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EDITED BY
Sharif A. Mukul,
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Laval University, Canada
Parvez Rana,
Natural Resources Institute Finland (Luke),
Finland

*CORRESPONDENCE
Gemma Cobb
gemma.cobb@griffithuni.edu.au

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Global trends in geospatial conservation planning: a review of priorities and missing dimensions

Gemma Cobb[1*], Johanna Nalau[2] and Alienor L. M. Chauvenet[1]

[1]Centre for Planetary Health and Food Security, Griffith University, Nathan, Australia, [2]Adaptation Science Research Group, Cities Research Institute and School of Environment and Science, Griffith University, Southport, Australia

Introduction: Biodiversity underpins resilient ecosystems that sustain life. Despite international conservation efforts, biodiversity is still declining due to ongoing anthropogenic threats. Protected areas have been widely adopted as a strategy for conserving biodiversity. The use of spatial conservation planning, which prioritizes areas for protection based on geo-referenced biodiversity and ecological information as well as cost of action and their feasibility, has gained popularity in the conservation discipline in the last few decades. However, there remain gaps between plans and implementation, and negative social impacts on local communities can occur, such as tension and conflict between differing priorities, perspectives, and views.

Methods: To better understand the state of the spatial conservation field and support translating research into practice, a mixed-method approach of bibliometric (n=4133 documents) and content analysis (n=2456 documents) was used to analyze and identify key research priorities, collaborative networks, and geographic and thematic patterns.

Results: We identified that research conducted by westernized nations dominated the field, with the United States, the United Kingdom, and Australia being responsible for almost two-thirds of the research globally, with research interest exponentially growing since 2010. Additionally, while there has been some refinement over time of algorithms and models, Zonation and Marxan methods developed in the 2000s remain the predominant choices of software, with a majority focus on marine ecosystems, birds, and mammals. We found a major gap in the use of social dimensions in spatial conservation case studies (only n=146; 6%).

Discussion: This gap highlights a lack of collaboration in conservation science between researchers and local communities who are affected by management decisions. We recommend including spatially explicit social dimensions from the onset of projects through participatory approaches, along with the acknowledgement by researchers of the importance of including diverse views in conservation planning to enhance implementation and outcomes that are relevant in local contexts. We suggest an increased reflection on types of data used for conservation but also on researchers' personal values, biases, and positionality to encourage more ethical, applicable, and collaborative conservation science.

KEYWORDS

conservation, review - systematic, spatial prioritization, VOSviewer, social dimensions

1 Introduction

Biodiversity is integral to functioning and resilient ecosystems (IPBES, 2019). The persistence of ecosystem services sustained by functioning ecosystems provides the stability needed to support life (Mooney et al., 2009; Sandifer et al., 2015). The importance of conserving biodiversity and ecosystems for societal well-being has become evident with the creation of a multitude of governing bodies, agreements, and goals such as Convention on Biological Diversity (CBD) to the creation of the Sustainable Development Goals (SDGs) (UN, 2015). Beginning in 1992 with the signing from 150 government leaders, the CBD now hosts a range of action agendas, frameworks, conferences, partnerships, protocols, and programs that are updated over time all pertaining to supporting the needs of global biodiversity (CBD, 2022). However, the health of ecosystems is deteriorating and biodiversity is declining (MEA, 2005; IPBES, 2019) despite local, national, and international efforts to meet conservation targets (Butchart et al., 2010; Johnson et al., 2017). As the planet continues to warm and becomes dangerously close to crossing climate-induced tipping points (Brovkin et al., 2021; IPCC, 2022), effective management of landscapes is needed now, more than ever.

Although decisions and actions for managing landscapes have existed for millennia through Indigenous custodianship (Roos et al., 2018; Fletcher et al., 2021a; Roberts et al., 2021), protected areas and other area-based conservation actions, in particular, have recently been adopted widely, at an increasing rate, by industrial society and contemporary scientific disciplines as a strategy for conserving biodiversity (Radeloff et al., 2013; Gillespie, 2020). Protected areas are defined as a clear, defined, recognized, dedicated geographical space that is managed through legal or other effective means for the long-term conservation of nature associated with ecosystem services and cultural values (Day et al., 2019). Protected areas make up 17% of terrestrial and inland water and 10% of marine and coastal areas protected formally (UNEP-WCMC and IUCN, 2021). These numbers are expected to increase in response to global initiatives like “30 by 30” that aims to designate 30% of Earth as formally protected areas by 2030 (CBD, 2022). While strict protection categories for protected areas exist (Dudley et al., 2010), there is debate about whether they are more effective than non-strict areas with multi-use management strategies (Elleason et al., 2021). While some studies have found strict protected areas are more effective (Carranza et al., 2014), others have found that non-strict areas can contribute to climate change mitigation by reducing tropical forest fires (Nelson & Chomitz, 2011) and biodiversity conservation by providing habitat for vulnerable species (Chauvenet, 2023).

To achieve desired conservation targets, spatial conservation planning approaches for identifying where to put new protected areas have gained popularity in the conservation science discipline in the past two decades (Sarkar et al., 2006; Kukkala & Moilanen, 2013; Alvarez-Romero et al., 2018). These approaches identify areas of high ecological importance using spatial information about characteristics of a landscape including, but not limited to, irreplaceability, distribution, and abundance of species, (Margules & Pressey, 2000; Wilson et al., 2009; Wiersma & Sleep, 2016). Spatial conservation approaches have been excellent at integrating ecological data and biophysical processes into spatial prioritization models (Pressey et al., 2003; Harris et al., 2019), and more recently, they have begun to embrace the importance of incorporating climate change data (Jones et al., 2016). Despite seeking to provide answers to questions about how to distribute limited conservation resources and identify priority locations (Wilson et al., 2007), geospatial conservation approaches have yet to fully bridge the gap between planning and implementing conservation activities (Knight et al., 2008; McIntosh et al., 2018).

In systematic conservation planning the impact on stakeholders can be considered through cost variables, such as the cost of acquiring land for a protected area (Kukkala & Moilanen, 2013) or opportunity costs (Adams et al., 2010). However, the unexpected consequences of designing protected areas on stakeholders remain somewhat unaddressed (Shafer, 2015; Larrosa et al., 2016). These include more abstract and difficult to account for situations such as negative social impact and creation of conflict between differing interests for local communities (West & Brockington, 2006; West et al., 2006). Additionally, decision-support tools are reflective of the inputs, settings, and decisions about methodology, and hence, they can favour certain interests and introduce bias into research outputs (Game et al., 2013). Considering social dimensions in conservation planning, like landscape values or cultural and social ecosystem services, has the potential to overcome some of these inadvertent ramifications of technologically heavy approaches. For example, in-person PPGIS workshops with stakeholders were used in the Upper Peace River Watershed to identify overlapping hotspots for non-economic priorities during the decision-making process for a hydroelectric dam (Darvill & Lindo, 2015).

As post-2020 global biodiversity targets are considered (Xu et al., 2021; Leadley et al., 2022), it is crucial to evaluate assumed benefits by assessing the on-ground effectiveness of management decisions. In this paper, we do this by assessing the research trends to understand, quantify, and consolidate the current state of geospatial conservation planning including knowledge gaps. To achieve this aim, we used a mixed method approach including bibliometric and content analysis to assess temporal, thematic and geographic patterns in the literature (Hood & Wilson, 2001; Van Eck & Waltman, 2014). Specifically, we assessed who published the research, where does this research occur, and what methods, themes and topics are prioritized. Finally, we evaluate the main considerations and concerns for future spatial conservation research.

2 Materials and methods

2.1 Bibliometric analysis

To evaluate the growing body of knowledge on geospatial conservation planning, bibliometric data on relevant publications was assessed to provide insights about key research priorities, collaborative networks, and research trends and gaps (Van Eck & Waltman, 2010; Waltman et al., 2010). The bibliometric review method is becoming more popular (Mingers & Leydesdorff, 2015) and has been used more recently to assess global research efforts for environmental topics such as in mountain regions (Verrall &

Pickering, 2020), adaptation to climate change (Nalau & Verrall, 2021), climate change research in the Arab world (Zyoud & Fuchs-Hanusch, 2020), marine spatial planning (Chalastani et al., 2021) among others. To understand the complexities of landscape decision-making processes, it is necessary to first assess how the geospatial conservation planning discipline has evolved, including evaluating priorities focused on when making decisions about the future.

Since it is challenging to identify all research documents on a topic with a single literature search, interactive query formulation was used. This involved collecting and screening preliminary results to ensure that a comprehensive final search term was used to systematically search for relevant literature (Wacholder, 2011; Verrall & Pickering, 2020). We used common geospatial terms paired with specific systematic conservation planning terms to gather a database that was representative of the body of literature in both breadth and depth. The final document search was conducted in the Scopus and Web of Science databases (Falagas et al., 2008) on July 30th, 2021 (Figure 1). This search yielded 4079 and 3407 documents from Scopus and Web of Science respectively and bibliometric data were downloaded for data cleaning in Microsoft Excel (2019). Next, duplicates and some miscellaneous document types were removed (i.e., note, letter, survey, and editorial materials) before topical abstract screening was used to remove any untargeted and unintentional results that were outside of the conservation scope of this review (i.e., applied mechanics and engineering). Even if it is impossible to collect 100% of relevant literature, systematic type reviews provide a framework for identification that is both reproducible and transparent (Moher et al., 2009; Mingers & Leydesdorff, 2015).

A final document count of 4133 peer-reviewed journal articles, books, book chapters and conference papers were included in the

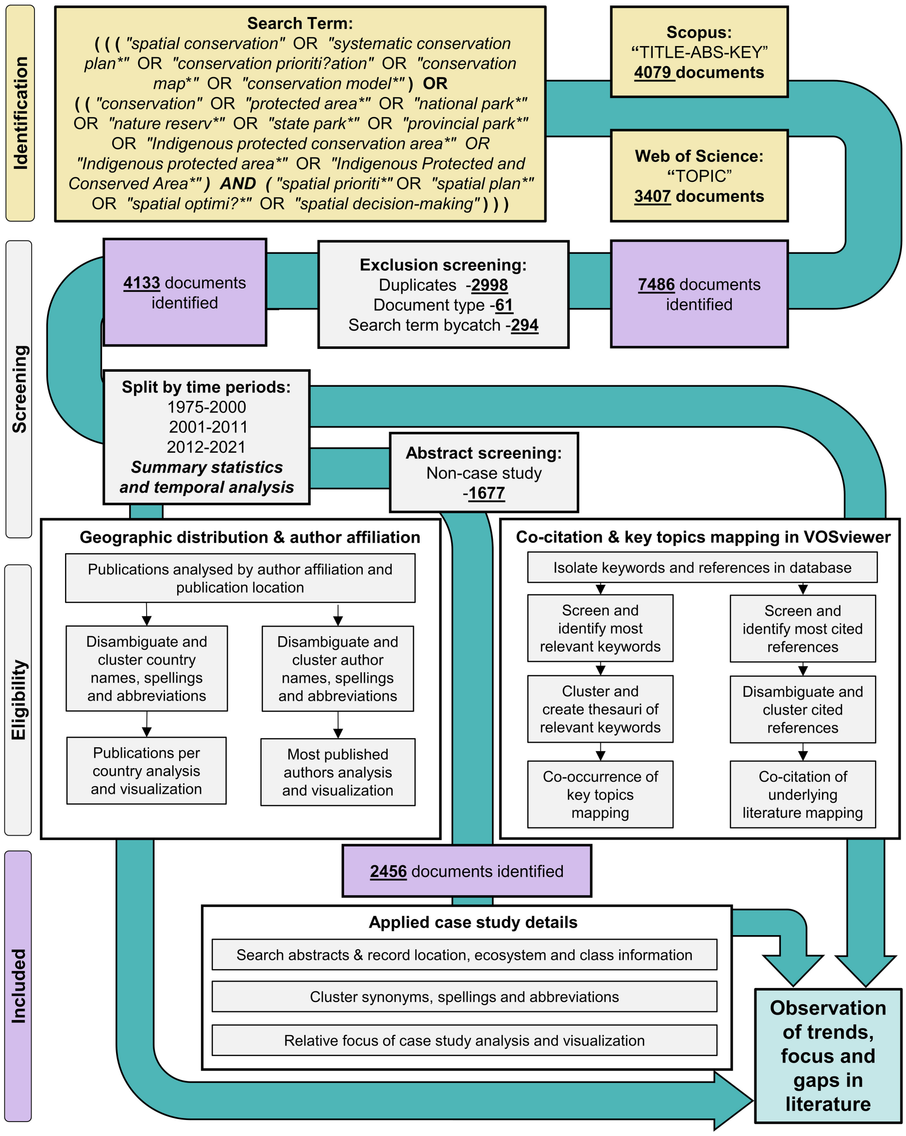

FIGURE 1
Methodological overview of study design including search term, screening process, and analysis summary for all time periods (1975-2000, 2001-2011, 2012-2021).

final bibliometric analysis (Figure 1). Prior to analysis, the final database was split into three time periods that correspond with the introduction of protected area targets from the Convention on Biological Diversity (CBD; 1975-2000, 2001-2011, 2012-2021) to assess the evolution of predominant research trends in the geospatial conservation planning discipline. To assess the literature database author key words, geographic spread of research, underlying co-cited literature, and leading researchers were analyzed in the bibliometric program VOSviewer (Van Eck & Waltman, 2010; Waltman et al., 2010). Some bibliometric data were clustered prior to final analysis by the creation of thesauri to reduce ambiguity (i.e., 'gis' and geographic information systems, 'mammal' and 'mammalian'), where a smart-moving algorithm was used to identify relationships and patterns within the dataset (Van Eck & Waltman, 2017) (Table S1). There is an overlap of terms within these categories due to the targeted nature of the search term, however through the clustering of common words used together, there are certain trends that can be identified. These relationships are visualized through nodes and lines where size and thickness are proportionate to the relative number of occurrences (Waltman et al., 2010).

2.2 Case study and content analysis

To better understand how this discipline is applied on the ground, the literature database was systematically assessed to identify articles that were appropriate for content analysis. The criteria we used to identify these articles was 1) they must be peer-reviewed case studies, 2) they employed geospatial conservation planning methods, and 3) they needed to be tied to a specific time and place, as opposed to theoretical and hypothetical models (Figure 1). Abstracts were screened to assess their relevance to the case study criteria to identify eligible documents for sub-set content analysis (Figure 1; Table S2). There were 32 publications excluded for lack of abstract, 131 because they were books or book chapters and 1515 documents excluded for not meeting the case study criteria of employing geospatial methods to a specific time and place, leaving 2455 documents remaining for content analysis (Table S2). Case study details were recorded in Microsoft Excel (2019); this included coding for region, nation, environment, ecosystem, organism type, organism class, endemicity, invasiveness and incorporation of social dimensions (type and method of collection). We included social dimensions that were spatially explicit, collected in a participatory manner, and integrated into spatial models such as landscape values (e.g., Karimi & Hockings, 2018). We used the author's own classification of ecosystems and location when recording details where possible and recorded where any of the data was not present. Finally, prior to final content analysis, author classifications of ecosystems were clustered into broader ecosystem type categories (e.g., 'bog', 'fen' and 'marsh' grouped to singular 'wetlands' category; 'prairie', 'plain' and meadow' grouped to singular 'grass- and arid-lands'; Table S3) to reduce ambiguity and improve comparative assessments to identify more detailed research trends presented in the following results.

3 Results

3.1 Characteristics of the literature over time

The initial results of the database searches yielded a total of 4133 relevant documents that were divided into three time periods early (1975-2000), recent (2001-2010) and emerging (2011-2021), with 83.7% of the literature falling in the latter, suggesting a recent increase in interest on this topic (Table 1; Figure 2). Most of this literature was published predominantly in English (n=3909; 94.6%) with the remaining published languages covering >2% of the overall documents (Table 1; Table S4). This database consisted mainly of peer-reviewed journal articles (n=3501; 84.7%; Table 1). Collectively, there were 1776 sources that published on geospatial conservation planning with Biological Conservation (n=231; 5.6%), Marine Policy (n-150; 3.6%) and Conservation Biology (n=122; 3%) leading the database for the journals with the greatest number of documents (Table S4). There were a few publications that were heavily cited. For example, 19 of 25 of the most cited authors were co-authors on a single document that has 3650 citations overall (Halpern et al., 2008) compared to the highest cited document in the emerging time period (2011-2021) (Chan et al., 2012) (512). Of the 4133 documents that were examined, 2456 case studies were identified where spatial conservation methods were applied to a specific time and geographic location (Figure 2).

3.2 Geographic trends and priority ecosystems

The database included papers by authors from 154 countries, however, 30 of these countries have only published once (Table S4). From these countries there were 13999 individual authors who have contributed to this body of literature, of which 80.2% have only published once (Table 1). Almost 60% of the literature has been published by authors associated with only three countries (n=2464); United States (26.4%), Australia (16.8%) and United Kingdom (16.4%) (Table 1). Of the top 25 published countries, only six are outside of North America and Europe (Table S4). The number of countries publishing on this topic has increased steadily over the three time periods (20 to 77 to 149). Similar to other global reviews (Verrall & Pickering, 2020; Nalau & Verrall, 2021), on a continental scale, authors from organisations in many countries are represented at some level but large gaps still exist in Central and Northern Africa, Western and Central Asia, Central America and the Caribbean (Figure 3A). While comparing the distribution of published research versus location of the case study areas, there are similar trends in terms of where receives the most attention (Figures 3A, B). Of the 2456 documents with a case study approach, there were 4486 specific geographic locations on which data was recorded, with more countries represented compared to where the studies were published (232 vs 154) (Table 1; Table S7).

Similarly, there are ecosystems that have received more attention than others, most notably marine environments (n= 758; 30%), specifically open water marine ecosystems (n= 489;

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TABLE 1 Bibliometric overview of publications split by time periods.

Categories	1975-2000		2001-2010		2011-2021		Total	
	#	%	#	%	#	%	#	%
Publications	105	2.6	568	13.7	3460	83.7	4133	100
Article	90	86.7	447	78.7	2964	85.7	3501	84.7
Proceedings Paper	11	10.5	50	8.8	207	6.0	268	6.5
Review	4	3.8	43	7.6	176	5.1	223	5.4
Book Chapter	0	0.0	24	4.2	97	2.8	121	2.9
Book	0	0.0	4	0.7	16	0.5	20	0.5
Language								
English	88	83.8	535	94.2	3286	95	3909	94.6
Chinese	1	1	4	0.7	71	2.1	76	1.8
German	9	8.6	8	1.4	19	0.5	36	0.9
Spanish	0	0	3	0.5	29	0.8	32	0.8
Polish	5	4.8	4	0.7	7	0.2	16	0.4
Country								
United states	28	26.7	160	28.2	904	26.1	1092	26.4
Australia	5	4.8	77	13.6	611	17.7	693	16.8
United Kingdom	8	7.6	86	15.1	585	16.9	679	16.4
China	1	1.0	14	2.5	302	8.7	317	7.7
Canada	4	3.8	34	6.0	265	7.7	303	7.3
Most Published Authors								
Possingham, HP	0	0.0	21	3.7	98	2.8	119	2.9
Moilanen, A	0	0.0	17	3.0	55	1.6	72	1.7
Pressey, RL	1	1.0	15	2.6	53	1.5	69	1.7
Klein, CJ	0	0.0	9	1.6	26	0.8	35	0.8
Hermoso, V	0	0.0	0	0.0	34	1.0	34	0.8
Most Cited Authors								
Pressey, RL	3368	58.5	1982	6.6	1635	3.1	6985	7.9
Halpern, BS	0	0.0	3560	11.9	1981	3.8	5541	6.3
Possingham, HP	0	0.0	1828	6.1	3532	6.7	5360	6.1
Micheli, F	0	0.0	3560	11.9	534	1.0	4094	4.6
Margules, CR	3368	58.5	592	2.0	0	0.0	3960	4.5
Citations								
Total	5757	6.5	29963	34.0	52535	59.5	88255	100
Most Cited	3368	–	3560	–	512	–	3560	–
Average	55	–	53	–	15	–	21	–
Number of Authors								
Total Authors	208	1.5	1729	12.4	12565	89.8	13999	100
Authors with only one publication	200	96.2	1544	89.3	10100	80.4	11233	80.2
Authors per publications	2.0	–	3.0	–	3.6	–	3.4	–

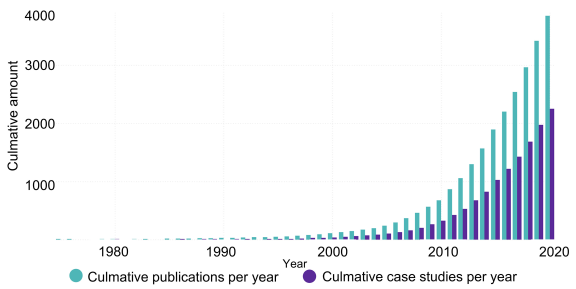

FIGURE 2
Cumulative publications and case studies over time.

19.4%) (Table 2). This may be attributed to a significant focus on the Mediterranean Sea (e.g, Kyprioti et al., 2021). Alternatively, freshwater environments (n= 341; 13.4%), specifically wetland ecosystems (n= 73; 2.9%), have received less attention despite their significant importance worldwide (Moomaw et al., 2018). The most studied ecosystem in terrestrial environments were forests (n=243; 9.6%) and were also the most studied ecosystem in South and Central America (Figure 4A). Anthropogenic landscapes were studied in 13.4% of all case studies (n=339) most often when focused on areas of historic and current human settlement (n= 339; 13.4%) which were the most studied ecosystem in Eastern & Southern Asia region (Figure 4A). There were however many cases of studies focusing on non-specific ecosystem (n= 558; 22.1%; Table 2), instead focusing on areas defined by geo-political boundaries that may make up multi types of ecosystems or range of species across a landscape (e.g., Botello et al., 2015).

3.3 Key topics and themes

Synonymous words were grouped to produce a total of 7593 author keywords used to illustrate key themes within the literature (Figure 5; Table S1). Keywords were grouped by VOSviewer based on their frequency of use, co-occurrence, and connection to each other to illustrate general research themes within the database. We named these sub-categories into five broad research themes: 1) sustainability and land-use planning; 2) spatial conservation planning; 3) habitat suitability and distribution 4) marine spatial planning and management and 5) ecological conservation and prioritization (Figure 5A) based on the relatedness of clustered keywords. While there is an overlap of terms within these categories due to the targeted nature of the search term, there are certain trends that can be identified. Category 1 (Figure 5A), there was a clear clustering of keywords that focused on landscape-level management approaches in socio-environmental systems centered around 'ecosystem services' and 'spatial planning'. The inclusion of 'governance', 'stakeholders' and 'urbanization' showcases a potential human-centric focus for this research (e.g., Kabisch, 2015). Expectedly, the largest cluster (2; Figure 5A) was centered around designing, planning, and analyzing protected areas using complex spatial tools and methods (Figure 5A; Table S#). Variations of 'Marxan' appear to be the predominant software choice for prioritization to support meeting 'conservation targets'

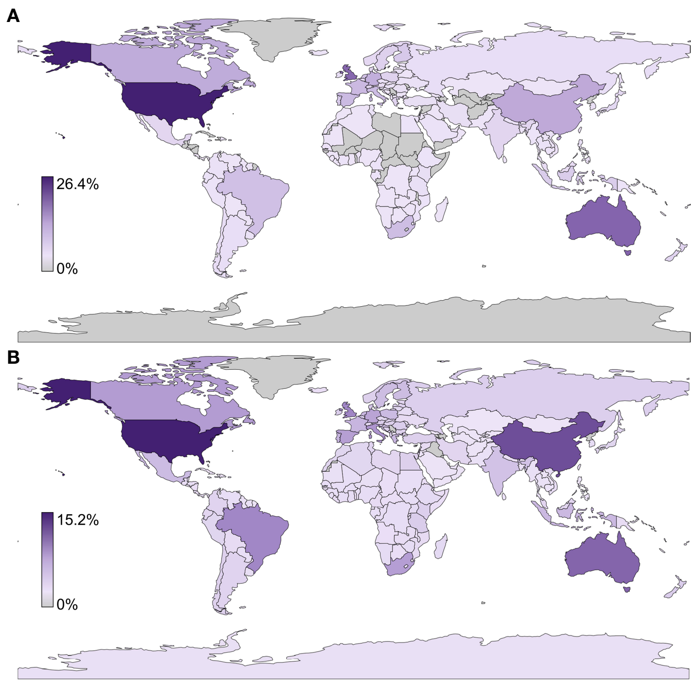

FIGURE 3
(A) Geographic distribution of published literature in the spatial conservation discipline over all time periods (1975-2021) and **(B)** Geographic distribution of case studies in the spatial conservation discipline over all time periods (1975-2021).

TABLE 2 Occurrence of environments of focus and ecosystem types.

Environment type	Ecosystem	#	%
Marine		*758*	30.0
	open water	489	19.4
	coastal	166	6.6
	reef	91	3.6
	mangrove	7	0.3
	non-specific	5	0.2
Terrestrial		*530*	21.0
	forest	243	9.6
	mountain	96	3.8
	grassland	80	3.2
	tropical & rainforest	*45*	1.8
	island	*37*	1.5
	tectonic & exposed rock	*5*	0.2
	non-specific	24	1.0
Freshwater		*341*	13.5
	riverine	149	5.9
	watershed	118	4.7
	wetland	73	2.9
	non-specific	1	0.0
Anthropogenic		*339*	13.4
	historic and current human settlement	158	6.3
	agriculture	116	4.6
	energy	65	2.6
Non-specific		558	22.1

such as 'natura 2000' and other 'protected area' targets (e.g., Kukkala et al., 2016). The next biggest cluster (4; Figure 5A) was focused on marine spatial planning and environments despite the search term not specifically targeting this literature (Figure 1; Figure 5A). There was a secondary focus on resource management and making decisions about balancing multiple preferences with the inclusion of terms like 'fisheries', 'marine reserves', and 'zoning' that consider 'local and traditional knowledge' (e.g., Bennett et al., 2018).

The two smallest clusters; 'habitat suitability and distribution' (3) and 'ecological conservation and prioritization'(5), contained highly specialized terms such as 'species distribution modelling' and 'phylogenetic ecology' (Figure 5A; e.g., Cadotte & Jonathan Davies, 2010). These keywords may not be necessarily specific to spatial conservation planning in their application like the other clusters, but the context of the research is inherently spatial because it included studies about the way flora and fauna interact with the landscape. The broadness of these disciplines over time and landscapes may explain the inclusion of comprehensive terms like 'climate change' and 'biodiversity' as top keyword in this is research theme category, which relative research focus has increased over time (Table S8). Figure 5B represents the time period of the largest change in research focus in this body of literature occurred between the years 2014 and 2017 (Figure 5B) where research shifted from optimizing reserve design and selection to focusing on the concepts that motivated conservation initiatives such as 'ecosystem services' and 'biodiversity'. Additionally, this has been a move to including more of a human element with terms like 'socio-ecological systems' and 'human impact' becoming more popular (e.g., Lazzari et al., 2019).

Examining these ecological attributes of flora, fauna and fungi at the case study level can provide insight into research priorities in terms of the specific organisms. About half of the case studies focused on at least one species of vertebrates (n=924; 34.6%), invertebrates (n=190; 7.1%) or vegetation (n=241; 9%) (Table 3). Most of the research on vertebrates was focused on birds, mammals, and fish (79.4%), while amphibians and reptiles were not as commonly studied (Table 3). When reptiles were studied however, they were more likely than other vertebrates to be studied in the context of being rare, endangered, or threatened (35.8%), particularly when it came to turtles (e.g., Shillinger et al., 2010). Terrestrial plants and invertebrates were more likely to be studied than their aquatic counterparts (Table 3). Terrestrial vegetation was the most studied rare, threatened, or endangered organism (n=67; 23.5%) and the most studied invasive organism (n=12; 50%).

3.4 Influential literature, institutions, and methodological choices

To understand how a body of knowledge influences future research, it is important to first identify the fundamental concepts and ideas that are driving it. Overall, the network of the top 25 most cited and co-cited publications is well-connected; meaning the field is cohesive as there are no major concepts and theories evolving separate from much of the literature. Instead, the documents that are cited most often, are widely and consistently cited throughout this whole body of literature (Figure 6). Of these 25 publications, 84% were published in the 2000s, implying that this is currently the most influential period for the discipline (Figure 6; Table S5). Australian institutions such as the University of Queensland and James Cook University have contributed the most over time to this body of literature with 251 and 114 documents respectively (Table S9). Nelson Mandela Metropolitan University, Conservation International and Duke University were among the earlier key contributors, while Deakin University, Imperial College London and University of Western Australia have been rapidly contributing post-2017 (Figure S1).

There was a clear use of method manuals in research such as Moilanen et al. (2009) and key papers such as Margules & Pressey (2000), demonstrating that these technical works has been pivotal in guiding the research and application of spatial conservation (Figure 6). This popularity could be because these books include

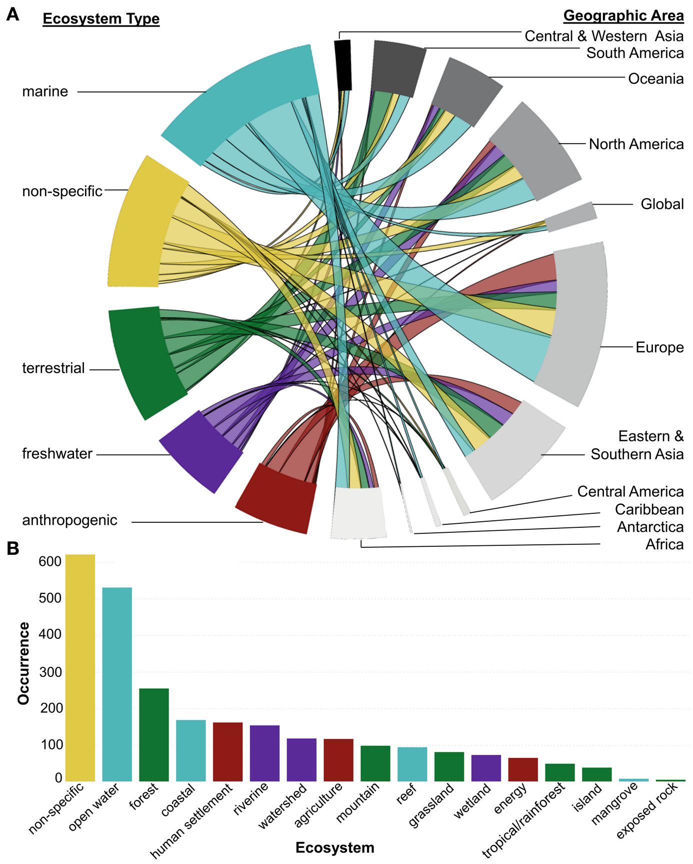

FIGURE 4
(A) Relative focus on environment type by case study region and **(B)** occurrence of ecosystem for case studies over all time periods (1975-2021).

many chapters of different methods that can be cited separately in a range of spatial conservation applications. While 22 of the 25 most co-cited documents were journal articles, they provide the basis of common methods and theories that are used within current geospatial conservation planning discipline (i.e., Watts et al., 2009), and within broader ecological and climate research (i.e., Hijmans et al., 2005).

While the technical aspects of conducting spatial conservation mapping and modelling are well represented, human dimensions and societal implications of the application of these types of approaches are largely missing. When it came to applying these methods on the ground, we found of the 2456 case study applications only 146 (6%) incorporated social dimensions collected through a participatory approach into their models (Table S6). Most often this research has occurred in Oceania (n=32), Africa (n=29), North America (n=26) and Europe (n=26) and has focused on marine ecosystems (n=58; i.e., Buscher et al., 2021). Additionally, there has been an increase in use of this type of method over time, with 54% of instances occurring from 2015 (n=79). Unsurprisingly, the most common type of social dimension that was integrated into research methodologies was preferences and priorities (n=98). Values, which were often conceptualized as ecosystem services to participants, were the next social dimension to be most often integrated (n=35) including situations of multiple or single values at a time (Table 4). Local knowledge was integrated into case studies 25 times, such as local fishers' knowledge on species and habitats (Pittman et al., 2018) and Indigenous Traditional Ecological Knowledge (TEK) (Noble et al., 2020). Finally, human perception was integrated only 8 times into case studies possibly because of the abstract nature and difficulty quantifying qualitative information into models (i.e., landscape changes, threats).

The number of times each data collection method was used was relatively uniform across the options however, interviews were used the most (n=55) followed by participatory mapping (n=54). This included 30 times non-digital (i.e., paper, or laminated maps with stickers, drawing or stackers) and 20 times digitally (both in person via tablets and via online interactive interfaces), and were often used in conjunction (ie., Kockel et al., 2020). Workshops and focus group settings were used 40 times followed using surveys and questionnaires to elicit data to be included in analysis. It is important to note that only one method was used 47 times, while the remaining occurrences used multiple forms of data collection (i.e., an interview that included a one-on-one mapping exercise; Noble et al., 2021). There were some cases where the method of collection was undisclosed (n=28). While authors noted a participatory process and included data collected in their model, the focus of research was on the model and it was not elaborated on how the data was collected (i.e., stakeholders were

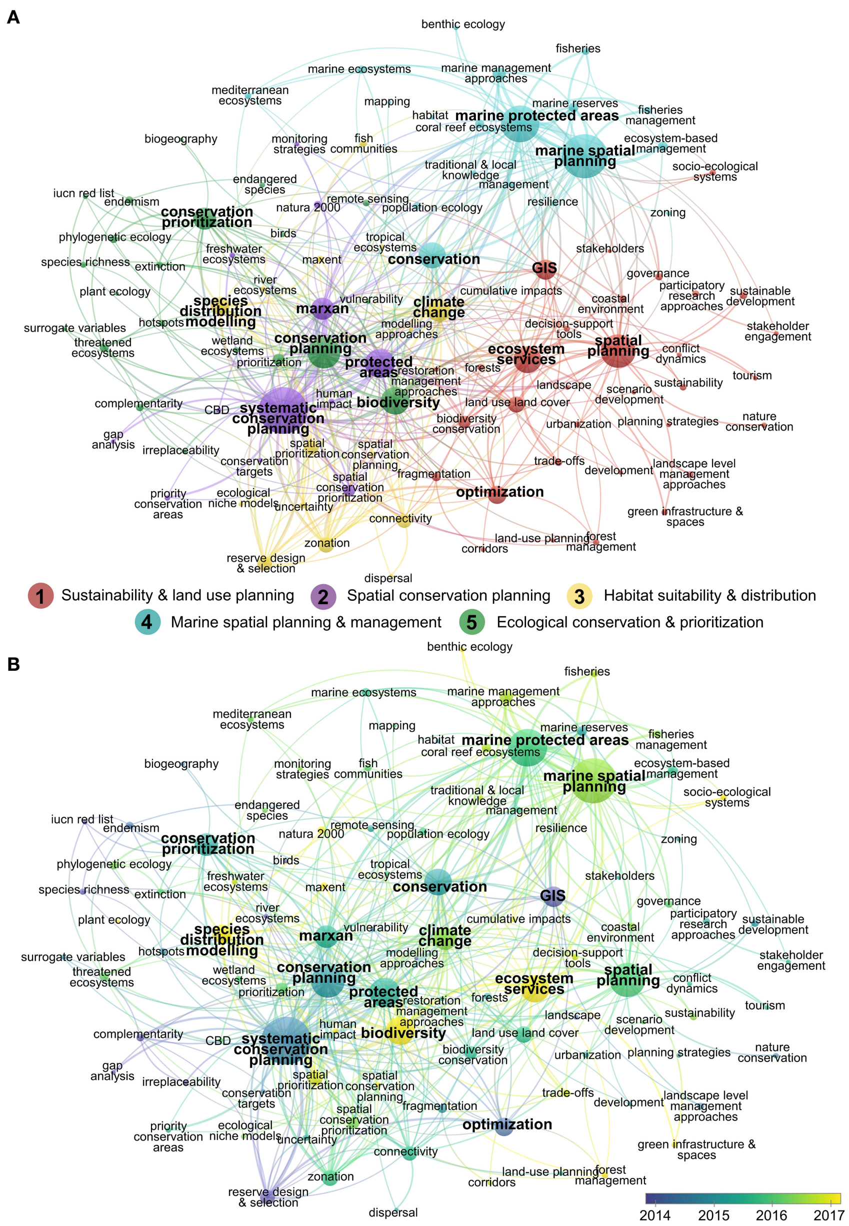

FIGURE 5
VOSviewer map of keywords for top 100 with 25 occurrences and 5 document minimum line strength with **(A)** theme titles and **(B)** the period of most thematic change (2014-2017) over all time periods (1975-2021) where purple represents common keywords pre-2014 and yellow represents common keywords post-2017 as current research focus.

"brought together" or priorities were developed by a stakeholder working group).

4 Discussion

This investigation has provided a comprehensive overview of the general trends in peer-reviewed geospatial conservation planning literature. Our analysis has examined bibliometric characteristics of the literature and foundational theoretical concepts as well as geographic trends in authorship and case study application, research priorities and key themes within the discipline. At this juncture, we focus on understanding how these trends have contributed to the evolution of knowledge within the discipline and how geospatial methods have been applied on the ground against the background of a technological and theoretical discipline.

4.1 Characteristics of research and global priorities

4.1.1 Inception and evolution over time

This review provides insight into the field of spatial conservation planning as a sub-discipline of conservation biology,

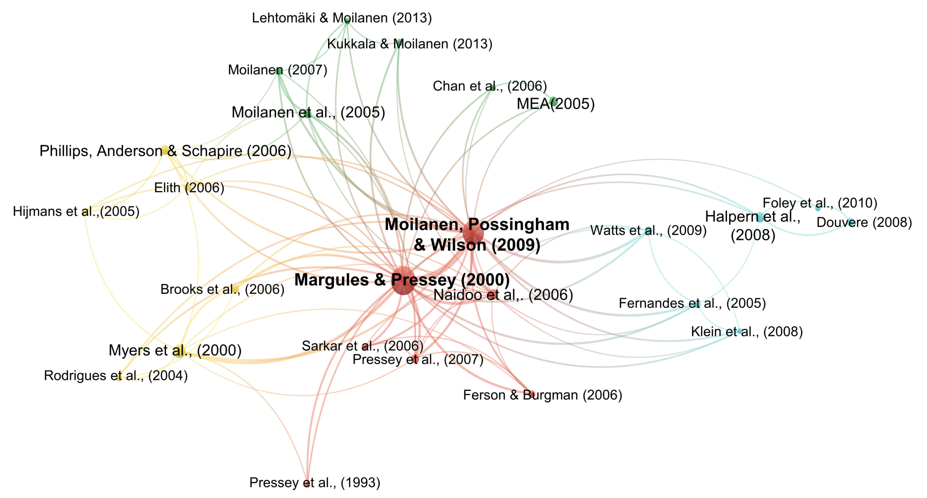

FIGURE 6
VOSviewer map of underlying co-cited literature for top 25 most cited documents with 25 occurrences or more for all time periods (1975-2021).

TABLE 3 Occurrence of taxonomic grouping and class and conservation status for case studies.

Taxonomic grouping	Class	#	%
Vertebrates		924	34.6
	Birds	261	9.8
	Mammals	249	9.3
	Fish	224	8.4
	Reptiles	81	3.0
	Amphibian	70	2.6
	Non-specific	39	1.5
Invertebrates		190	7.1
	Terrestrial	111	4.2
	Aquatic	77	2.9
	Non-specific	2	0.1
Vegetation		241	9.0
	Terrestrial	221	8.3
	Aquatic	16	0.6
	Non-specific	4	0.1
Other			
	Fungi	4	0.1
Non-specific		1315	49.2
Conservation status		#	%
	Endangered, rare, or threatened	328	12.3
	Invasive, noxious, or exotic	27	1.0

and how it has grown over time, especially in the past decade. Following the publication of '*Systematic Conservation Planning*' in 2000 (Margules & Pressey, 2000), and coinciding with systematic conservation planning principles being adopted in the CBD's Strategy for Biodiversity in 2002, there was increasing application of geospatial approaches for nature conservation. The tools that are being used to help conservation practitioners and researchers plan for protected areas are increasingly becoming more sophisticated from a technological standpoint since the centralization of approaches by key methodological publications (Moilanen et al., 2009; Watts et al., 2009). Interestingly, while the amount of research has rapidly increased over the past two decades, the main tools being employed have remained mostly constant. Marxan and Zonation are undoubtedly the primary choices of software for carrying out this type of analysis (e.g., Lehtomäki et al., 2015; Rivers-Moore et al., 2021), with the emergence of web-based tools and program extensions like 'prioriztr' in R (e.g., Southee et al., 2021). Choices in conservation planning support tools can influence the output and should be chosen based on the overall goals of the planning process. These decisions enable researchers and practitioners to make informed decisions about how to achieve their desired goals whether that be, but not limited to, cost-effectiveness, resource allocation, stakeholder engagement, threat mitigation, or corridor design and connectivity. For example, between Marxan and Zonation, both can support different overall goals such as more efficient results for the former and greater connectivity for the latter as demonstrated in a case study from the English Channel (Delavenne et al., 2012). Even though the main choices of methodology have remained dominant for the past two decades, there has been some refinement through changes to existing software as they have been applied more (i.e., from Marxan to Marxan with Zones), pointing to some reflection and advancement within the discipline about methodological choices.

TABLE 4 Examples of the integration of social dimensions from reviewed case studies including the type of dimension, method of participatory collection, software or program used and recommendations for future use and research.

Type	Examples from review	Collection	Software/ program	Recommendations for application
Values	Raymond et al. (2009)	Interviews, participatory mapping (in-person, non-digital)	GIS	-Improve methods in eliciting community input to effectively identify and map atmosphere asset values, associated supporting services, and threats, emphasizing the importance of developing a modified typology for a more comprehensive understanding of supporting services for participants.
	Ruiz-Frau et al. (2011)	Interviews, participatory mapping (in person, non-digital)	ArcGIS	-Adopt a more flexible approach in future Marine Protected Area (MPA) studies, allowing participants to select smaller areas that align with their preferences, as the current methodology of forcing the choice of larger, highly protected MPAs led to concerns about potential impacts on specific societal sectors. -Include a higher number of participants in interviews to capture variation in opinion with and between different stakeholder groups. -Give more attention to the potential disproportional representation of different sectors and possibly apply weightings to final valuation maps.
	Bryan et al. (2011)	Interviews, participatory mapping (in-person, non-digital)	GIS	- For effective co-management decisions, ecologists should engage in a two-way process with local communities, particularly in areas of low ecological value and high social value, by transcending normative aspects and providing evidence-based tools to enhance collaboration.
	(Jarvis et al., 2016)	Crowdsourced Voluntary Geographic Information (VGI)	ArcGIS, RStudio	-Ask participants how they had heard of the opportunity to participate in the study to determine the effectiveness of different recruitment types i.e., print, online, and/or news media. -Encourage participants to initially identify areas of personal importance before identifying values to effectively capture value diversity, including anthropocentric, biocentric, and anthropocentric–biocentric orientations at each point.
Perceptions	(Paloniemi et al., 2018)	Surveying/ questionnaire, interviews, workshops	Zonation	-Engage in iterative communication with planners, landowners, and stakeholders to scale up the prioritization, with emphasis on the importance of collaboration throughout the prioritization process i.e., discussion overall aims, analysis and findings more openly, to improve ownership. -Offer alternative prioritization analyses to present to stakeholders in workshops, aiding in the identification of specific areas for targeted marketing of voluntary conservation through subsequent local meetings and personal communication.
	(Goodman et al., 2006)	Workshops	Remote sensing, ArcGIS, Marxan	- Include, collect, and supplement the system with a wider range of data and biodiversity elements to refine targets for conservation and improve the chance that the plan will be implemented.
Preferences/ priorities	(Brown et al., 2019)	Surveying/ questionnaire, participatory mapping (digital online)	Custom Google maps application, ArcGIS	-Broaden survey recruitment efforts to improve representation, particularly in rural and remote areas, and consider alternative social data collection methods that are potentially more preferred i.e., face-to-face interviews. -Validate ecological data in locations identified as having both high quality habitat and social acceptability. -Include estimated land values for the economic feasibility of prioritization outputs. -Devise a manner to account for "super mappers" who can potentially influence overall results i.e., limiting the number of markers.
	(Teh et al., 2013)	Interviews	Protected Area Suitability Index (PASI)	-Pay attention to power dynamics in the participatory process, particularly where financial, scientific, and technological resources are uneven, to avoid influencing of pre-defined objectives by seemingly more powerful stakeholders. -View index scores as relative to each other and not as absolute values. It is the user's interpretation of the score in the local context that matters the most.
Local knowledge	(Leroux et al., 2007)	Interviews, participatory mapping (in-person, non-digital)	GIS, Marxan	-Caution given to the scaling of datasets to avoid the overestimation of overlap between heritage sites and protected areas. Make comparisons at a finer scale where possible and appropriate. -Develop co-operative working groups with local organizations to better facilitate exchange of information between researchers and the community and incorporate community interests.
	(Pittman et al., 2018)	Surveying/ questionnaire, participatory mapping (digital online)	Custom Google maps application, ArcGIS, MaxEnt	-Consideration of caveats for future use i.e., that the tool will need to be updated periodically and future users will need to assess the weight of evidence and uncertainty for each scenario.

(Continued)

TABLE 4 Continued

Type	Examples from review	Collection	Software/ program	Recommendations for application
	(Noble et al., 2020)	Interviews, participatory mapping (in person, non-digital)	ArcGIS	-Develop better coordination and mechanisms to prioritize addressing conflicting issues between stakeholders i.e., land council's management of the land-sea connection involved beach sand replenishment whereas other stakeholders felt this was damaging to habitat and could reduce cultural and community well-being. -Address and acknowledge the potential that some stakeholders may not feel comfortable giving responses due to their positions in government that may misrepresent the governments agenda particularly conversations involving contentious issues or topics. -Give value to local and Indigenous knowledge along with scientific information through a communicative process that addresses local concerns. Visual aids like maps could be used as a starting point to facilitate this knowledge exchange.

Assessing the evolution of a research body overtime can provide insights into the potential trajectory of research in the future. Overtime, the areas of focus in this body of research have also diversified including shifts from single species (e.g., Pyke, 2005) through ecosystem level and multi species conservation plans (e.g., Osipova & Sangermano, 2016) to integrating complex issues in socio-ecological systems, like climate change impacts, ecosystem function, and the value of ecosystem services (Anderson et al., 2021). This is aligned with recent calls to integrate climate change into geospatial decision-support tools and has been recognized as an important consideration as the climate continues to warm and species and ecosystems are faced with novel threats (Jones et al., 2016). The context in which these tools are applied, however, is becoming increasingly more diverse with wider application, as the amount of case studies is also rising as the discipline grows. Applying and connecting these approaches on broader geographic scales are important to avoid fragmented and isolated conservation efforts that reduce biodiversity (Haddad et al., 2015), which may hinder the ability to reach conservation targets.

4.1.2 Geographic mismatches

While there are several trends and central themes that have emerged in this review, there were imbalances in who is conducting the research versus where research is being conducted. Similar to many studies that have taken a broad approach to understand how research evolves over time, we found a clear inclination towards publications from westernized nations, with almost two thirds of the research driven by three countries. While the USA and United Kingdom are consistently recorded as leading nations when it comes to peer-reviewed published research (e.g., Hill et al., 2021), Australia surprisingly made up a large portion (16.8%) of the locations where research is conducted (e.g., Hermoso et al., 2012). This may be because some of the most cited and published authors are or have been affiliated with Australian research institutions (e.g., Possingham, H. P.; Pressey, R. L.; Klein, C. J.).

When it came to where research was conducted or applied in case studies, trends were still skewed towards North America and Europe but there was a greater diversity of nations represented. Central African and Western and Central Asian nations were not represented in terms of authorship but species and ecosystems inside their borders were represented at the case study level (e.g., Memariani et al., 2016). This trend was also apparent when examining highly studied regions such as the Mediterranean. While research was conducted at a scale that included the entirety of the Mediterranean Sea, publication credit was dominated by European nations over non-European nations, particularly in Northern Africa and nations of the Arabian Peninsula and Levant. This is not uncommon in peer-reviewed academic literature, specifically in the Arab world (Zyoud & Fuchs-Hanusch, 2020), but creates the potential that western researchers can perpetuate "helicopter" research by conducting research in the Global South without involvement from local collaborators (Haelewaters et al., 2021; Pettorelli et al., 2021). This poses a potential blind spot in managing conservation problems by excluding local and traditional knowledge systems and ideologies that are outside of westernized and colonial worldviews in regions by non-western governance systems. Potential strategies or solutions to overcome this trend could include building higher research capacity in non-western nations through funding of truly collaborative and meaningful research partnerships with western nations who have high conservation research capacity (Zhang et al., 2023).

Whether it was at the bibliometric or case study level, a key biogeographic theme that emerged was that marine environments were the most studied. This preference for marine ecosystems within the geospatial literature is not reflected in the proportion of formally protected areas globally, with more terrestrial and inland water protected (17%) in comparison to marine and coastal areas (10%) (UNEP-WCMC and IUCN, 2021). This imbalance in protected areas may account for this discipline evolving with such a heavy focus on protecting marine ecosystems, as Marine Protected Areas (MPAs) can be difficult to implement and barriers to implementation remain poorly understood (Schultz et al., 2022). Furthermore, some of the lesser studied terrestrial ecosystems such as mountains and wetlands provide important ecosystem services like fresh water and climate regulation that are integral to the survival of society (Moomaw et al., 2018) but remain under-studied in comparison to their importance. As there is increasing pressure with global change, understanding, and conserving these ecosystems and associated services will become increasingly important.

4.1.3 Species vs. ecosystem focus

This review identified two distinct areas of focus when it came to applying geospatial conservation planning. In general, the case studies examined here either focused on the ecosystem for its overall value, or on species and their habitat range. While it is important to consider the protection of individual species in the landscape, it is also important to acknowledge that species do not exist in isolation and certain interactions and assembles affect the stability of complex ecological communities (Qian & Akçay, 2020), mostly comprised of vegetative structures. Furthermore, vegetation forms the primary structural components of most terrestrial ecosystems but was studied far less than the fauna that often depend on vegetation for habitat and resources here. This is a broader problem in ecology and society with the manifestation of the plant awareness disparity, or the inability of people to notice plants in their environment (Parsley, 2020).

Understanding how biodiversity dynamics operate on the landscape is also an integral part of the geospatial conservation planning process. However, there has been a long-recorded mismatch between conservation areas and biodiversity globally (Brum et al., 2017; Willer et al., 2019). This was demonstrated in our analysis, with a dominant focus on specific species of flora and fauna. Prior research has demonstrated that human emotions can influence support to protect mammals and birds, over invertebrates and reptiles (Prokop & Fančovičová, 2013; Castillo-Huitrón et al., 2020), which may explain why birds and mammals were chosen to be studied over reptiles, amphibians and invertebrates overall in this review. However, there is also the potential that the ease of visual access to studying mammals and birds could be a contributing factor as to why researchers choose to focus on them. There was one exception to this trend with the majority of the studies that focused on reptiles, focusing on sea turtles specifically. Though this may be due to their popularity as charismatic mega-fauna and vertebrates often receive more funding for conservation (Mammola et al., 2020). In contrast, aquatic and terrestrial invertebrates are integral to the functioning of healthy ecosystems and provide many ecosystems services that are vital to ecosystem stability (Prather et al., 2013; Chen, 2021) but received relatively little focus here, with some exceptions (e.g., Gormley et al., 2015). Understanding this phenomenon is critical for conservation researchers and practitioners to understand and avoid the creation of "paper parks" that fail to meet conservation needs and targets (Dudley & Stolton, 1999).

4.2 Translating research into practice

Though we can learn from the quantitative insights provided through this investigation, we can also gain insights and learn from the observations made during the literature review process. Such generalized social science insights may equally inform and guide better research and management priorities and actions (Bennett et al., 2017).

4.2.1 Considerations for application

While systematic approaches to geospatial conservation planning provide structure to complicated technological processes, researchers and practitioners still need to take caution when creating these plans. Overall, the conflicting interests of users and the active selection of which data to include demonstrates that plans are not neutral. Since plans and maps can be designed to be reflections of the people involved in making them (Wood, 2010; Sonbli & Black, 2022), it is important to consider the influence and reflect on the wider implications of scientific practice by researchers when developing conservation plans and policies (Pasgaard et al., 2017). Though geospatial conservation planning is focused on nature, decision-support tools that assign dollar value to landscapes can create situations that struggle to balance economic costs with ecological or social benefits. For instance, the focus on cost-effectiveness by spatial conservation prioritization has led to a bias towards placing MPAs in areas that are least threatened (Boon & Beger, 2016).

Moreover, such methodological decisions can enforce or support existing political and societal tensions that have effects for local communities. For example, this review found the coastal areas of the Mediterranean have been a focus, but most studies chose to acknowledge Israel as an independent state while referring to Palestine as a territory, without acknowledgement of its occupation (e.g., Mazor et al., 2013), when it was even acknowledged. Biases, whether conscious or unconscious can have an impact on the chosen research design, data interpretation and decision-making throughout a project, impacting the overall outcomes (Pannucci & Wilkins, 2010). Introspection on one's positionality, whether in a social, cultural, or political context, can help researchers to understand how their own situations may shape research priorities and methodological choices. Reflecting on our own personal values, biases, and positionality may help to encourage more ethical, applicable and collaborative conservation science (Beck et al., 2021).

Severe cases where social aspects of conservation is not considered can manifest in the form "green-grabbing", the dispossession of lands for the sake of conservation (Fairhead et al., 2012). One example is the displacement of the Stoney Nakota Peoples for the creation of Banff National Park (Dang, 2017), one of the oldest, most iconic and the most visited protected areas in Canada (Parks Canada, 2008). Nevertheless, the input of Indigenous Peoples is integral to the conservation of nature worldwide, with 80% of remaining biodiversity protected and managed by just 6% of the world's population who identify as Indigenous (Garnett et al., 2018). While few studies explicitly acknowledged the local history of landscapes that predate colonization (e.g., Leroux et al., 2007; Benner et al., 2019), arrangements that aim to return land back to Indigenous Nations in the form of conservation areas provide a potential solution that can support the righting of previous wrongs (Indigenous Leadership Initiative, 2021). Additionally, land management practices like Indigenous fire stewardship can reduce climate-driven catastrophic bushfires through cultural burning (Fletcher et al., 2021b) and can lead to an increased rate of biodiversity (Hoffman et al., 2021). Considering the importance of Indigenous stewardship worldwide, conservation planning must strive to include diverse perspectives into future conceptualization, designation, and management of protected areas.

4.2.2 Enhancing implementation and outcomes

Our results demonstrated a plethora of geospatial conservation plans across the planet. What is not clear is if these plans came to fruition. Considering geospatial conservation planning is centered around the idea of using resources wisely, it is important to consider the time, knowledge, and funding of the researchers as a resource too. A review by McIntosh et al. (2018) that examined the outcomes of 1200 systematic conservation planning projects discovered that there were only 43 case studies that reported outcomes of implementation. Additionally, there are common mistakes that inhibit sufficient conservation priority setting including not acknowledging conservation plans as prioritizations, poor articulation of problems and ignoring the risk of failure (Game et al., 2013). Understanding why these projects have not made it to the implementation phase and how they can be implemented at an increased rate are important questions to answer if prioritization methods are to be used for effective and tangible conservation.

While this review found there has been some progress in integrating more holistic and interdisciplinary approaches into conservation planning with keywords like 'stakeholder' and 'socio-ecological systems' as an increasingly popular research topic over time. They were, however, rarely linked to the technical approaches (e.g., Marxan or Zonation) and were instead clustered among the marine environments section. This may be due to the high volume of marine studies examined in this review, though, a recent review of marine spatial planning (MSP) reported that that 50% of plans used qualitative methods to conduct MSP (Chalastani et al., 2021). One way to overcome the subjugation of biophysical interests in geospatial conservation planning might be to include social dimensions from the onset of projects (Strickland-Munro et al., 2016), which were only included in models 6% of the time in this review. Although it can be useful to focus on ecological elements and umbrella or flagship species for a cost-effective way of maximizing biodiversity representation (McGowan et al., 2020; Ward et al., 2020), gathering information and perspectives of local stakeholders and incorporating them into prioritization scenarios could move proposed systematic conservation planning past the theoretical phase into the implementation era (Knight et al., 2010).

4.3 Limitations and recommendations

4.3.1 Scope and nature of reviews

While this review was able to identify trends in geospatial conservation planning, there are certain limitations to the scope of analyzing such a large quantity of literature. To start, there are certain biases in the methodological framework used here including the tendency for databases used to favour certain geographic locations, types of knowledge, and languages (Hamel, 2007; Pickering & Byrne, 2014). This includes not accounting for knowledge and terminology used outside of this specific scientific discipline and only analyzing academic uses of geospatial conservation planning examined here that excludes grey literature and traditional knowledge (Franceschini et al., 2016; Mongeon & Paul-Hus, 2016). While bibliometric reviews are powerful at analyzing thousands of publications and identifying broad themes in a literature (Vinkler, 2010), they are restricted to the level of detail contained within bibliometric data (i.e., title, abstract, keywords etc.). While the deeper look into the subset of case study analysis was conducted partially overcome this challenge, we were still limited by our own ability to only comprehend English language case studies, and how and what authors chose to report in their findings. For example, there is the potential for more details about a project to exist, but not be reported in published literature, and therefore not included in this analysis. Nevertheless, this research was a worthwhile exercise despite the limitations and has made substantial contributions to understanding how geospatial conservation planning has evolved. As environmental impacts intensify with global change, is important that the geospatial conservation planning discipline evaluates its trajectory before research trends stray from tangible on-ground management actions.

4.3.2 Recommendations for future research directions

With access to the right technology, data and knowledge, spatial prioritization approaches have a history of being a viable method to create conservation plans that support effective decision-making for managing landscapes to preserve biodiversity and ecosystem services (Wilson et al., 2007). Future research, however, should focus on integrating more social dimensions and participatory approaches into the planning process. Even though there has been some instances identified in this review it is still not common practice to include social dimensions beyond demographic and economic surrogates, into these models despite the effort made by some researchers to use participatory methods to collect this information (e.g., Karimi & Hockings, 2018; Noble et al., 2020). For this to be a viable option for integrating perceptions into landscape research, the social data such as landscape values or locations of social and cultural ecosystem services, collected needs to be spatially explicit in order to be functional (Dorning et al., 2017). However, such an approach requires pre-planning and intentional data capture on the part of researchers through collaboration with the local communities where the research is taking place. To do this, taking a more stakeholder focused and bottom-up approaches can allow space for alternate forms of governance and models of land management to be considered in and becoming part of planning processes (Ban et al., 2013; Cornu et al., 2014; Whitehead et al., 2014; Noble et al., 2019) and allow time and space for social values to be translated to operational spatial information. Finally, to overcome the research-implementation gap that exists in conservation prioritization (Knight et al., 2008), more detail on design choices, and implementation results and outcomes of projects could be better reported to share insights with others who are considering this type of research.

5 Conclusion

Spatial conservation prioritization approaches are becoming increasingly popular over time. While there remains a clear focus on certain geographic regions, ecosystems and species, approaches are beginning to take into consideration more than just ecological data like climate data and social information and knowledge. To ensure that these spatial prioritization approaches are successful they should be situated in a larger conservation effort that is inclusive of local values, perspectives, and histories. Since social and ecological systems are coupled, focus should be placed on continuing the momentum for more participatory methods that integrate social dimensions with ecological values. Paying special attention to how we address power imbalances, particularly the ways in which we promote inclusive and ethical participation, and what types of knowledge and information we are prioritizing in decision-making tools is vital to the progress of this discipline.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: The datasets analyzed for this study can be found at https://doi.org/10.5281/zenodo.7787297.

Author contributions

Conceptualization, GC and AC. Methodology, GC and AC. Validation, GC and AC. Formal Analysis, GC. Investigation, GC. Data Curation, GC. Writing – Original Draft, GC. Writing – Reviewing & Editing, GC, AC, and JN. Visualization, GC. Supervision, AC and JN. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1209620/full#supplementary-material

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