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Decision-making with ecological process for coastal and marine planning: current literature and future directions

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Abstract Marine-protected areas are designated to reduce anthropogenic impacts on biodiversity and enhance fish production, but other ecological processes are inadequately accommodated in plans for coastal and marine ecosystems. We conducted a quantitative systematic literature review and meta-analysis on how researchers and decision-makers include ecological processes in coastal and marine conservation planning. Marine spatial planning ideally delivers representative protected areas systems that deliver persistence for ecosystems and species. Although several reviews have reported on incorporating connectivity as a process in marine spatial planning, to our knowledge, no one has yet published an inclusive review on how ecological processes are incorporated to help ensure persistence in coastal and marine planning. A total of 162 peer-reviewed journal research papers and 27 non-peer-reviewed papers (n = 189) were identified that included ecological processes in coastal and marine conservation planning between 2000 and 2019, the number of papers integrating ecological processes peaked in 2013 followed by a declining trend to 2019. We attribute the trend to the complexity of the problem of integrating dispersal and demographic objectives alongside other management goals. The results of our statistical analysis uncovered that incorporating ecological processes in conservation planning is important for coastal and marine ecosystems across the literature (p-value < 0.001). However, there was significant variation in scope and choice of method in planning assessments. Dispersal was the process most frequently incorporated in spatial plans, followed by demography and flows of nonliving materials. Identifying appropriate ecosystem objectives and incorporating multiple sources of uncertainty into conservation planning for coastal and marine ecosystems remain important areas for future research. This review highlights the need for greater awareness among planners of the relevance of ecological

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processes in conservation planning for coastal and marine ecosystems.

Keywords Ecological processes · Systematic conservation planning · Marine spatial planning · Persistence · Dispersal

Introduction

Although Aichi Target 11 of the Convention on Biological Diversity sets a 10% target to conserve coastal and marine areas globally by 2020, to date only 7.6% of the World's Exclusive Economic Zones and Territorial Seas are under management by designated marine spatial plans (UNEP-WCMC, IUCN 2018). Target 11 of the Strategic Plan for Biodiversity calls for "coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, to be conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas including other effective area-based conservation measures, and integrated into the wider landscapes and seascapes". The Strategic Plan commits governments to establish marine protected areas (MPAs) as a critical defence against biodiversity loss in the world's oceans. MPAs in coastal waters are key management tools delivering marine ecosystem services such as food, climate regulation, flood protection, and recreation and thus contribute to human well-being (Small et al. 2017). However, MPA planning requires a wide range of environmental, social, and economic information on the distribution and status of coastal and marine features (e.g. habitats and species, spatial scale, sea water properties, substratum) (Green et al. 2014; Cheok et al. 2016). Furthermore, understanding how ecological processes influence coastal and marine habitats is fundamental to appreciate the flow of ecosystem services (Saunders et al. 2017). In addition, MPAs should retain their ecological integrity and be ecologically representative, containing adequate samples of the full range of ecosystems and ecological processes in natural condition (Convention on Biological Diversity 2012; Jones et al. 2018). Perversely, countries use percentage targets to designate large, remote MPAs with the least value for extractive uses and little or no conservation benefits, subverting Aichi Target 11. For example the Australian Commonwealth MPAs were established in 2012 where they are least controversial and least costly (Devillers et al. 2015; Grech et al. 2015; Visconti et al. 2019).

Systematic conservation planning (SCP) is a process for prioritising conservation actions on the ground, with the goal of optimising the trade-offs between biodiversity conservation and socio-economic values (Groves and Game 2016; McIntosh et al. 2017; Sinclair et al. 2018). Prioritising actions for coastal and marine regions to maintain essential ecosystem functions involves a quantitative description of the planning problem and an explicit designation of the trade-offs and outcomes. Decision support for spatial actions is informed by spatially explicit information on biodiversity that represents the full range of marine ecosystems, focal species, and persistence (the long-term survival of species or other elements of biodiversity, including ecological processes) (Moilanen et al. 2009; Pressey and Bottrill 2009; Barr and Possingham 2013).

Networks of MPAs are an important strategy for biodiversity conservation and fisheries sustainability (Frazão Santos et al. 2019). Network planning that includes marine reserves (no-take areas) is significantly more successful at achieving conservation objectives (Sciberras et al. 2015). Despite the recent escalation in placement of MPA networks globally (Laffoley et al. 2019), evidence suggests that MPAs that do not include full protection engender perverse outcomes (Giakoumi et al. 2017; Sala et al. 2018; Rodríguez-Rodríguez 2019) and are often inadequate to protect the world's oceans and nearshore regions. Variability in the effectiveness of networks has resulted from the subjugation of ecological goals in favour of political ones leading to less successful conservation outcomes (Boonzaier and Pauly 2016).

Prioritising for the persistence of species should mean the MPA planning process explicitly incorporates ecological processes but, evidence suggests targeted feature representation, conserving a sample of all habitats and species, is unlikely to support ecological processes as those processes require large areas or particular spatial configurations (Olds et al. 2012; Edgar et al. 2014; Martin et al. 2015). Further, despite decision-makers recognising the importance of processes as a criterion in spatial planning there is limited availability of tools and operational frameworks to facilitate collaboration between process scientists and spatial planners (Kool et al. 2013; Balbar and Metaxas 2019). In addition to technical barriers, successful MPA design is complicated by the difficulties in quantifying the dispersal trajectory of organisms and in comprehending the spatial and temporal scales of ecological processes (Treml and Halpin 2012; Rossi et al. 2014).

In this review, we consider seven broad categories of ecological process. The seven categories were derived from the conservation planning and general marine ecology literature:

(1) Catastrophic disturbance (an extreme disturbance event involving considerable mortality, habitat loss, or acute ecosystem dysfunction) (Game et al. 2008; Mumby et al. 2011; Maynard et al. 2015).
(2) Demography (birth, death, and migrations of individuals) (Figueira 2009; Magris et al. 2016).
(3) Dispersal (the exchange of individuals as larvae, juveniles, or adults among marine populations (Olds et al. 2016; Krueck et al 2017).
(4) Primary productivity (a functional indicator that is a measure of ecosystem health e.g. nutrient cycling, ecosystem metabolism) (Ulloa et al. 2006; Grantham et al. 2011).
(5) Flows of nonliving materials (transmission of nutrients, pollutants, or sediments between locations by passive transport via water currents (Crist et al. 2009; Sale et al. 2010; Klein et al. 2012).
(6) Physiology (the response of organisms, populations, and ecosystems to environmental change and stressors (Lombard et al. 2007; Cooke et al. 2013).
(7) Lineage diversification (ecologically driven divergent selection where the biological properties of a species lineage determine its capacity to diversify and generate natural selection within or across community settings, given rapid and multifarious environmental change (Mumby et al. 2011; Wellborn and Langerhans 2014; Coleman et al. 2017).

We lack a quantitative synthesis of how ecological processes are incorporated in spatial plans, the value of ecological processes to planners, and the role of uncertainty. Whereas several reviews have reported on connectivity as a process in coastal and marine spatial planning (Magris et al. 2014; Balbar and Metaxas 2019; Manel et al. 2019), to our knowledge, no one has yet published an inclusive review on the role of all ecological processes in coastal and marine planning. We reviewed the peer-reviewed and grey literature for systematic conservation planning analyses that included ecological processes. We determine what ecological processes are considered in the research, the methods by which the processes were incorporated into the planning, and the impact of spatial scale on the methods. In doing so, we explore how uncertainty was incorporated in spatial planning. Notwithstanding the various types of uncertainty, it is important to assess the robustness of study conclusions because of limitations in data, knowledge, or modelling outputs (Hamel and Bryant 2017). In addition to evaluating ecological processes in the research, we examine the attributes shared among successful cases. An application is successful if it explicitly presents and implements ecological processes in a conservation planning analysis. Further, we quantify the value of ecological processes in spatial planning in relation to the protection of threatened species and ecosystems in the coastal and marine environment. Finally, we discuss what gaps are revealed in the literature.

We created a database of systematically assessed papers from June 2000 to June 2019 with relevant criteria. (Supplementary Materials). The database consists of criteria outlining the key findings, methods, and strengths/limitations of each study, as well as summarises how ecological processes and uncertainty were incorporated in systematic conservation planning for coastal and marine ecosystems. Based on the results of this review, we then provide recommendations for researchers and decision-makers on the inclusion of ecological processes in coastal and marine planning.

Materials and methods

We used a systematic quantitative literature review and meta-analysis approach to find papers that address the question of how the inclusion of ecological processes in coastal and marine SCP has been covered in the literature and what knowledge gaps are present. We followed the protocol developed by the Preferred Reporting Items for Systematic Review Recommendations (PRISMA) (Page et al. 2021). We compiled a database of peer-reviewed studies and the grey literature (including journal papers, book chapters, conference proceedings) using established framework. Accordingly, we searched two carefully selected specialist websites, three web-based search engines (including Google Scholar, Findarticles.com, and Duck Duck Go Search); the databases ISI Thompsons Web of Science, Scopus, and Science Direct; and the hidden web. We searched the hidden web using directories to find full text grey literature. All permutations and combinations of keywords were used: 'systematic conservation planning', 'marine spatial prioritisation', 'marine reserve selection', 'marine conservation plan*', 'marine protected area', 'marine reserve', 'decision support tool', 'Marxan', 'Zonation', 'biophysical dispersal model*', 'metapopulation model*', 'ecological process*', 'demography', 'primary productivity', 'physiology', 'flow*', 'disturbance', 'climate change', 'lineage'. (Table S1 in Supplementary Materials). Reference sections of these documents and relevant review articles were cross-checked to identify articles that were not found using the search strategy. Papers written in English encompassing the last 19 years (June 2000–June 2019) were assessed (n = 732).

Our systematic literature search was designed to find studies related to the integration of ecological processes in coastal and marine conservation planning in both tropical and temperate regions. We used three levels of screening to isolate articles on this topic from the literature. At the first level of screening titles and abstracts were scanned to identify and exclude articles that did not identify a priority area in the sea for expansion or action, presented theoretical methods, used theoretical data, were a review concept paper, opinion paper, or gap analysis (n = 610). The second level of screening excluded papers that failed to fulfil two criteria: (1) the use of SCP concepts (e.g. decision support methods/tools; conservation actions; discussion of uncertainty); (2) the inclusion of ecological processes. Our search initially identified 206 peer-reviewed and grey literature papers meeting the search criteria. Full text articles were then scanned, and the next level of screening was applied. Articles were excluded that did not fulfil the criteria: (1) presented original research on the design and/or implementation of marine conservation activities under the SCP framework; (2) acknowledged, documented (i.e. case study) and/or explicitly applied methods to incorporate ecological processes (n = 189, Fig. 1 and Supplementary Materials). We created a database of papers to collate information pertinent to different aspects of the analyses. We analysed the database to detect patterns in the literature. There were five aspects of the findings: the nature of the research and who conducted it; the ecological processes described in the literature for coastal and marine planning; the methods of incorporating ecological processes into the spatial plan; the study scale; and recognition of uncertainty. Rather than covering the multitude of articles that have been published in an exhaustive fashion, we attempt to analyse the databases of studies and synthesise some of the main insights, highlighting those issues that appear to advance the field. With the advent of innovative methods and techniques in the marine conservation field, it is timely to synthesise this information.

In our database of papers, we recorded how systematic conservation planning was included according to whether they were qualitative or quantitative: qualitative studies were based on theoretical guidelines, case studies and discussion papers; quantitative studies presented and implemented ecological processes in a conservation planning exercise. The quantitative papers were further subdivided into those that implicitly acknowledged ecological processes and those that explicitly applied ecological processes. *Implicit* is defined as identifying or discussing one or more processes as important in spatial planning, but not explicitly quantifying the process/s or integrating them into the planning analysis. *Explicit* consideration of ecological processes is defined as explicitly using information about ecological processes in the planning analysis outcome (Dade et al 2019). The systematically selected papers (n = 189) were assessed on how each article envisaged ecological processes in the context of coastal and marine conservation planning and the biodiversity and fisheries elements required in the planning exercise to operationalise the objectives (Fig. 1 and Supplementary Materials).

To answer the research questions, key items of information were recorded in the database from each paper (Table S2 in Supplementary Materials). We recorded the article details, article content, and information relevant to our analysis. For example, we recorded the approach used in the systematic conservation planning context, that is, if the objectives envisaged design and/or implementation. Further, we included key findings of the study, that is, if ecological

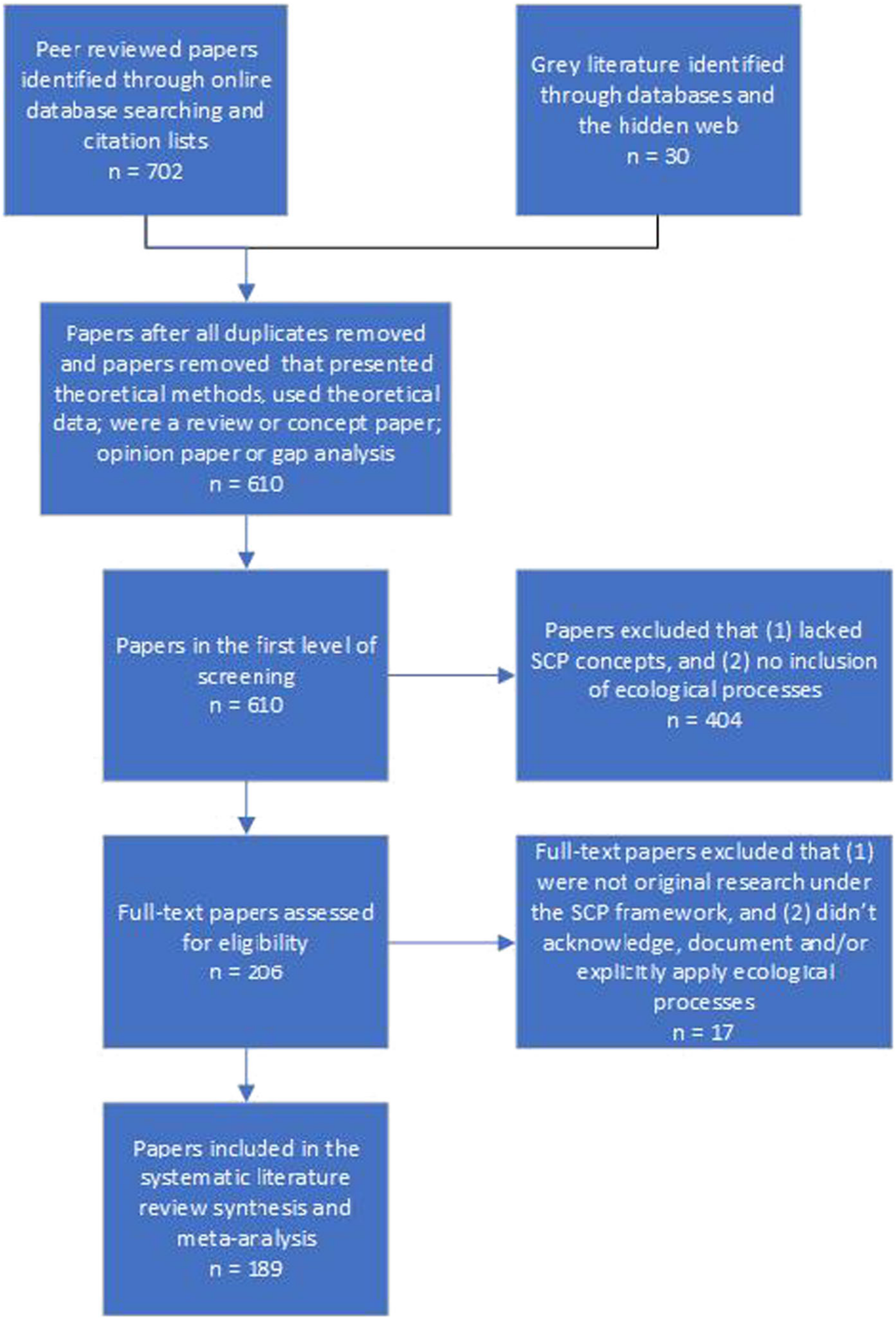

Fig. 1 Flowchart outlining the methods used in this study to organise the systematic quantitative literature review

processes were explicitly included in conservation planning and what methods were used to investigate ecological processes for coastal and marine seascapes. Finally, we extracted uncertainty considerations, the spatial extent, and the significance and implications of the research. The database reflects a primary motive for producing a comprehensive review- to contribute an analytical approach that would be available to scholars and decision-makers of coastal and marine conservation management.

For each paper in the review, we collected data addressing six response variables that answered our research questions. We used a set of compiled questions to extract data from the papers for input into a meta-analysis (Table 1). The data extraction questions (n = 13) assist in addressing our research questions (Table S3 in Supplementary Materials), which are: (1) identify gaps in the literature relating to the context of coastal and marine spatial conservation planning; (2) quantify the value of incorporating ecological processes in spatial planning; (3) determine the methods and software used to incorporate ecological processes; (4) ascertain what attributes were shared among successful cases to inform effective coastal and marine conservation planning; (5) determine how uncertainty was considered. Through the survey questions, we identified gaps in the contexts of the spatial plans by extracting data on the geographical location and spatial scale of the study—research question (1). Additionally, if the spatial plan included an integrated approach (estuarine/coastal habitats) this information related to research question (1). Information on the scope of the study and the type of ecological processes included was extracted for research question (2). With this data, we were able to quantify the value of incorporating ecological processes in planning for threated species and ecosystems in coastal and marine environments. A question relating to the methods and software used in each study to incorporate ecological processes assisted with data extraction for research question (3). For the meta-analysis, methods and software data were grouped into the categories: geographic information systems (GIS); prioritisation software; statistical model; process model; expert elicitation. A question on the main attributes for a successful outcome in the plan design and/or implementation related to research question (4) to determine what attributes were shared among successful cases to inform effective coastal and marine conservation planning. Finally, we determined if uncertainty was acknowledged, explicitly considered, or ignored in the studies. If uncertainty was considered, we recorded the method and source of uncertainty. It is important to include uncertainty in a spatial planning analysis because there are important trade-offs to consider when accounting for error and uncertainties in conservation planning (Tulloch et al. 2017). Where uncertainty was applied explicitly, we investigated the type of uncertainty i.e. whether stochastic or epistemic, and how this was dealt with

Table 1 Structured questions with categories used to extract data from the journal articles. Each category relates to the review's research questions (1)–(5)

Category	No	Research question	Survey question
Filter	1	–	Does the paper identify a priority coastal and/or marine area for planning action using a systematic conservation planning framework?
	2	–	Does the paper incorporate ecological processes?
Study area	3	(1)	Spatial scale of planning area?
	4	(1)	Location of planning area?
Integrated approach	5	(1)	Was an integrated approach used (estuarine/coastal habitats)?
Ecological processes	6	(1)	Which ecological processes were considered?
	7	(2)	How does the scope of the study determine the inclusion of ecological processes?
	8		Did the incorporation of ecological processes benefit the planning result?
	9		What was the impact on cost of including ecological processes in planning for the coastal and/or marine environment?
Methods and software	10	(3)	What methods and software were used?
Shared attributes	11	(4)	What were the main attributes of the planning process that led to a successful outcome (design and/or implementation)?
Uncertainty	12	(5)	Was uncertainty considered?
	13	(5)	What was the source of the uncertainty and what methods were used to incorporate it in the planning assessment?

in the studies. This information related to research question (5).

We performed an ordinal regression analysis via a cumulative link mixed model (CLMM) using the package Ordinal 2019.12–10 (Agresti 2018; Christensen, 2015, 2019) in the statistical software R v. 3.6.2. Cumulative logit models can handle multiple explanatory variables, which can be quantitative and/or categorical (Agresti 2018). To ensure independence among observations, a normally distributed random effect was accounted for in the model using the intercept for the study ID. The ordinal categorical variable, study scope (i.e. qualitative, implicitly acknowledged, explicitly applied) was used as the response variable to assess the value each study placed on ecological processes in spatial planning of coastal and marine ecosystems. Ecological processes (i.e. catastrophic disturbance, demography, dispersal, flows of nonliving materials, physiology; primary productivity, lineage diversification), methods (i.e. geographical information systems, prioritisation software, expert elicitation, statistical or process models), spatial scale, and uncertainty were the predictor variables. We assessed the goodness of fit with the likelihood- ratio test. Prior to the analysis we tested for collinearity among predictor variables using Cramer's V, a metric that is independent of sample size and is generalizable across contingency tables of varying size, for each pair of predictor and response variables (Mangiafico 2015). As predictor variables had non-mutually exclusive levels (e.g. one study could have multiple methods), we created a binary variable for each level of the variable. We considered any study characteristic with $V > 0.3$ as having a moderate (V value range 0.3–0.5) association among all variables. The main objective is to examine the effect of study scope on the type of ecological processes incorporated in the conservation planning study. Hence, this information provides insight into the value planners attribute to ecological processes.

Results

Spatial distribution

A total of 162 peer-reviewed journal research papers and 27 non-peer-reviewed papers ($n = 189$) were identified that included ecological processes in coastal and marine conservation planning between 2000 and 2019 (Supplementary Materials). Surprisingly, the number of papers integrating ecological processes peaked in 2013 followed by a decline to 2019 (Fig. 2 and Fig. S1 in Supplementary Materials). Despite papers acknowledging or including ecological processes in coastal and marine planning from 36 countries much of the research is from Australia (18%); USA Pacific Northwest coast (the coast of Washington and Oregon); USA Middle Atlantic Bight; USA northern California (17%); Coral Triangle (14%); Mediterranean region (10%); Central Coast of British Colombia, Canada (6%) (Fig. 3). Twenty-three papers (12%) only used qualitative data i.e. theoretical guidelines, case studies, and discussion papers (e.g. Bullimore et al. 2014; Knowles et al. 2015; Foster et al. 2017). Studies that implicitly acknowledged ecological processes (i.e. acknowledged without an explicit measurement) were 68% of the total. Papers that explicitly recognised and incorporated ecological processes were 20% of the total (Fig. 4) and decreased in number from 2016 to 2019 (Fig. 5). We found that the studies considered a diversity of spatial scales with most studies in the range 1000–100,000 km^2 (Fig. 6). From the total of 189 coastal and marine conservation planning studies, Oceania had the highest number of plans at 60 by 2019 (sharp increase from 2008), next highest was North America at 46 (outstripped Oceania until 2013 then peaked at a lower level), followed by Europe at 37, Asia 19, South America 14, and Africa 12 (Fig. 7). The studies focussed on a wide range of taxonomic groups but are strongly biased towards ray-finned fishes (Actinopterygii) and corals (Anthozoa). Other groups represented in our database of papers are crabs and lobsters (Malacostraca), followed by mussels (Bivalvia), barnacles (Maxillopoda), and cockles (Gastropoda).

Identification of temporal pattern

Overall, the regression slope of the number of studies incorporating ecological processes increased from 2000 to 2013 then weakened from 2014 to 2019 indicating a declining trend in studies that included ecological processes (Fig. 2).

Ecological processes in coastal and marine spatial planning.

Unsurprisingly, dispersal is the most studied ecological process in our database of papers for coastal

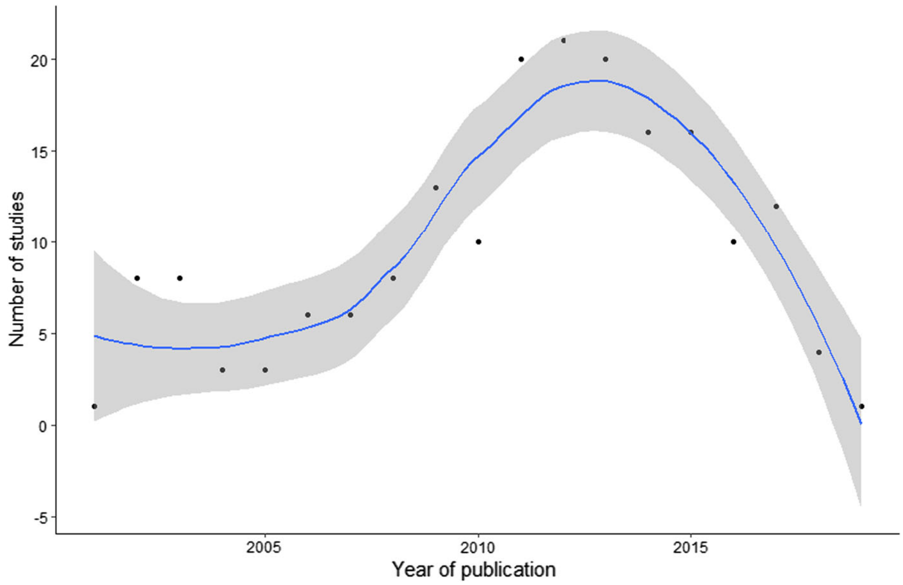

Fig. 2 Frequency of studies with each year of publication (includes the grey literature we discovered). Shaded area is 95% confidence interval

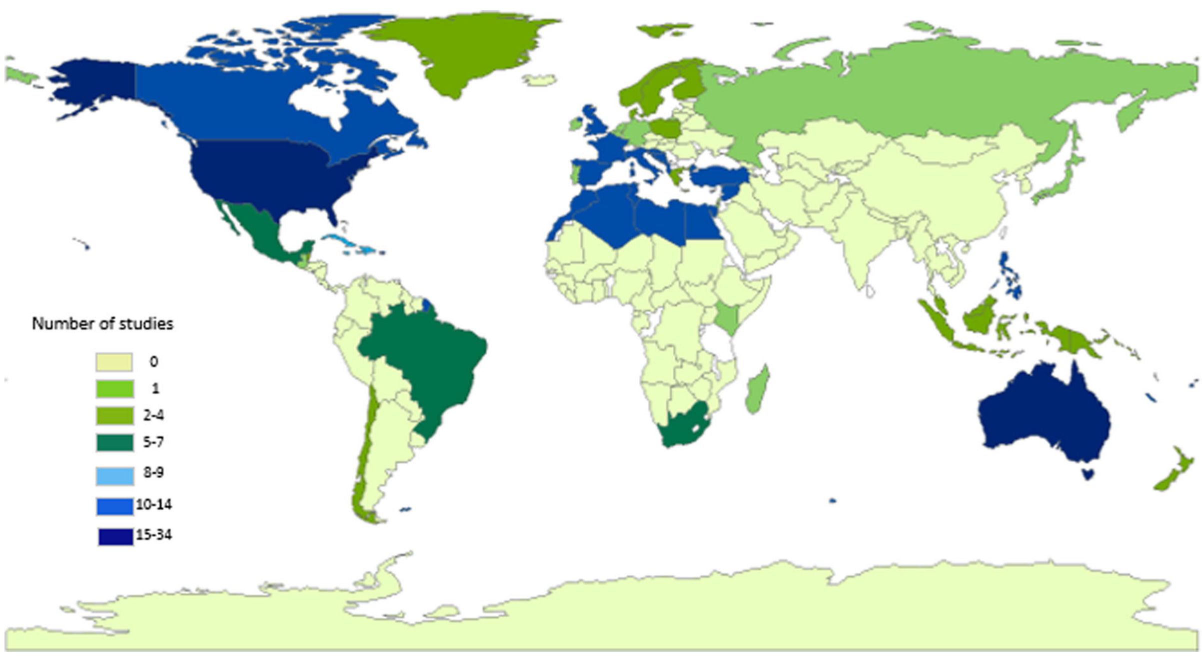

Fig. 3 Global distribution of studies incorporating ecological processes in coastal and marine conservation planning

and marine conservation planning (78% of the total). Papers including dispersal peaked from 2011 to 2013 but show a declining trend thereafter (Fig. 8). There was no distinct temporal pattern in the inclusion of demography in spatial planning—often termed "demographic connectivity" or "population connectivity" in the literature (Fernandes et al. 2012; White et al. 2014; Bode et al. 2016). The relevance of metapopulation persistence and recovery from disturbance in MPA design and/or implementation was

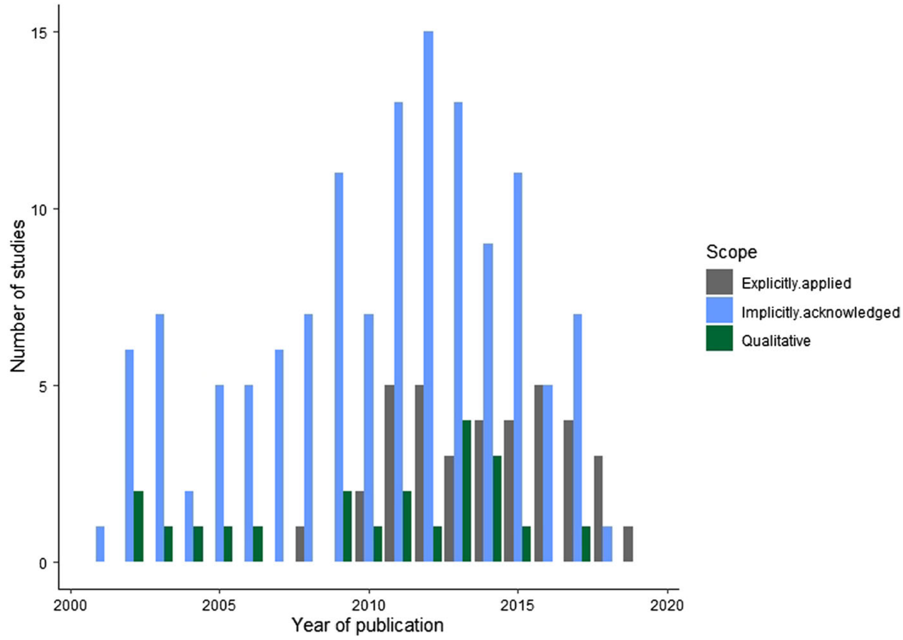

Fig. 4 Scope of journal articles per year of publication between 2000 and 2019: qualitative; implicitly acknowledged; explicitly applied

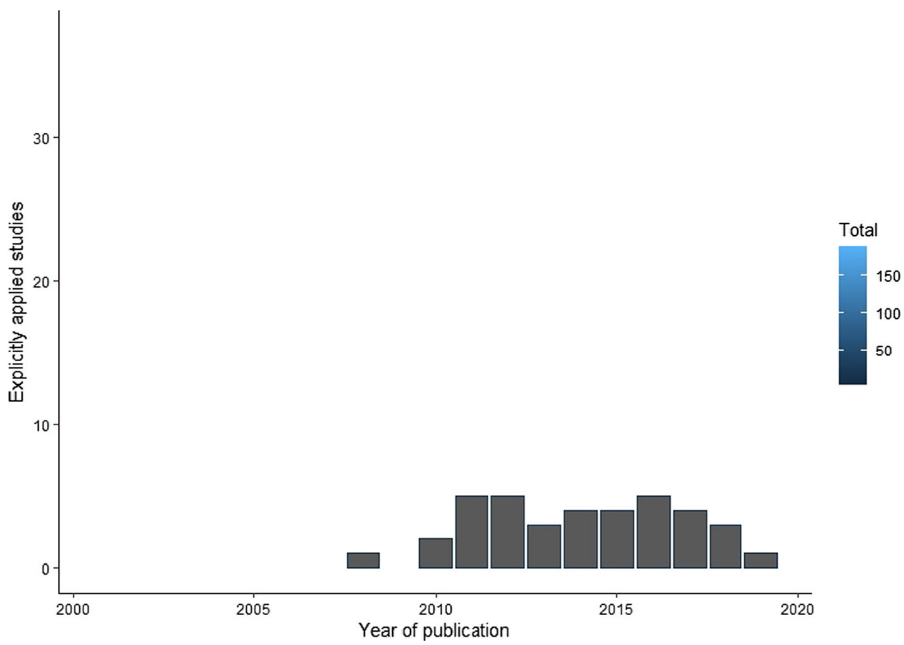

Fig. 5 Year of publication of explicitly applied studies (n = 37) in relation to the total number of studies (n = 189)

recognised and included as a fundamental mechanism in 32% of studies. We found flows of nonliving materials was a sporadic occurrence in publications but consistent occurrence across the time period of the review (12% of studies) indicating that the transmission of materials via water currents was considered by planners as somewhat important in MPA planning (Maina et al. 2015; Boon and Beger 2016; Gilby et al.

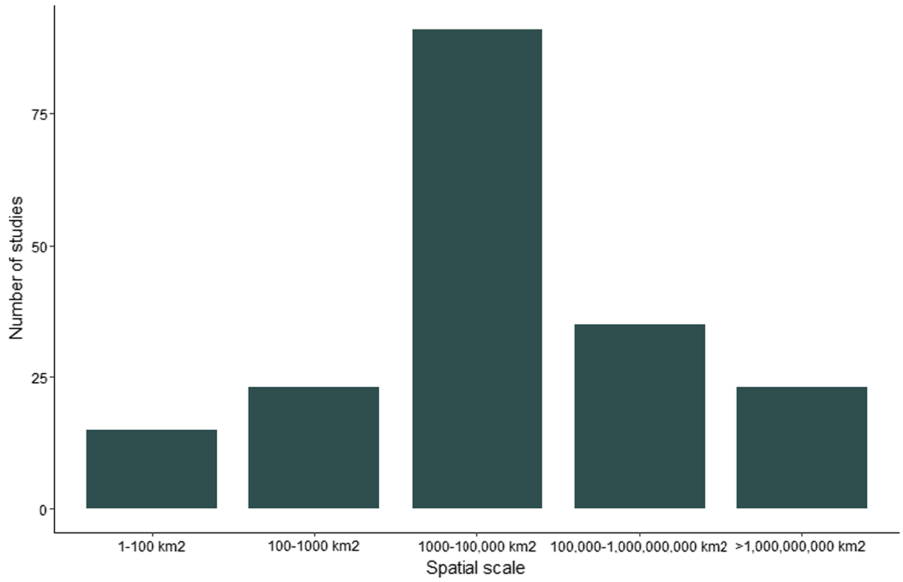

Fig. 6 Frequency of each spatial scale

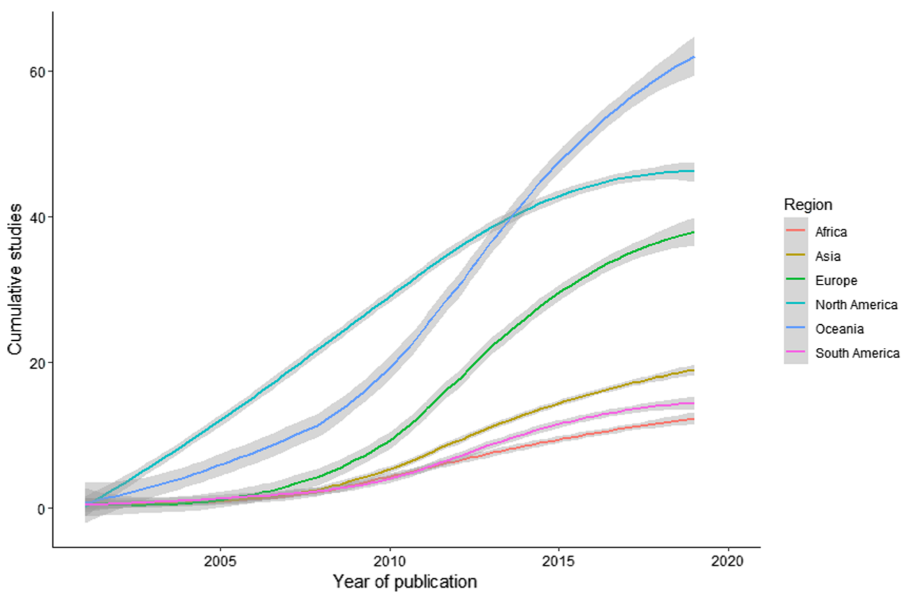

Fig. 7 Minimum cumulative number of 189 coastal and marine conservation plans in the published and grey literature between 2000 and 2019

2016). Catastrophic disturbance was prominent in studies as an ecological process from 2011 to 2019 (5% of studies) demonstrating an increasing awareness of climate change effects e.g. thermal stress, ocean acidification, coral bleaching, (Allnutt et al. 2012; Coll et al. 2012; Levy and Ban 2013; Magris et al 2016). The three remaining ecological processes; primary productivity (3% of studies); physiology (2% of studies); and lineage diversification (0.5% of studies) albeit important, rarely informed MPA planning (Lombard et al. 2007; McGowan et al. 2013; Mumby et al. 2011).

An objective of our review is to examine the effect of study scope (i.e. qualitative, implicitly

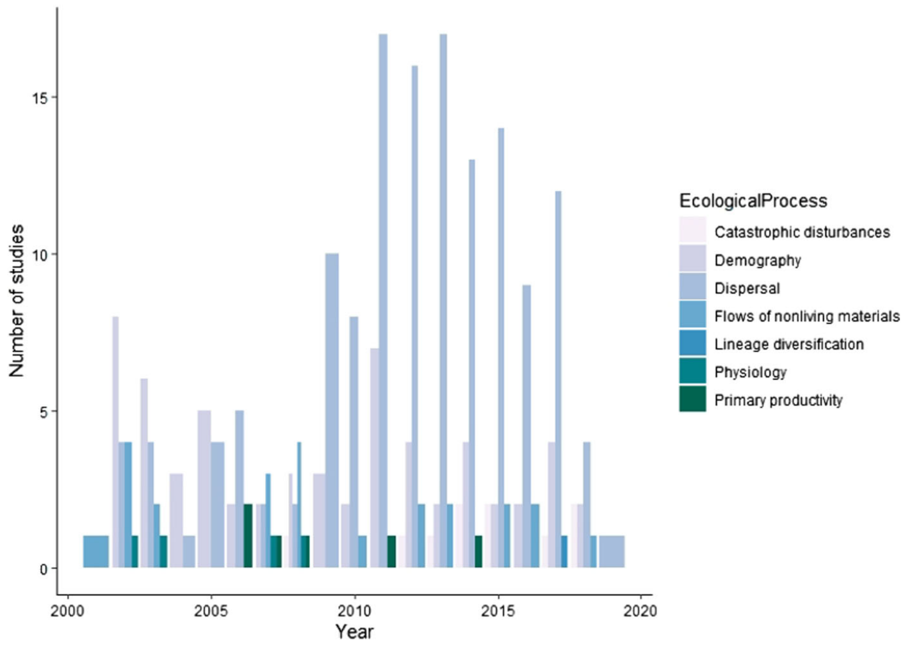

Fig. 8 Frequency of ecological process categories captured by conservation planners in our database of papers

acknowledged, explicitly applied) on the type of ecological processes incorporated in the conservation planning study. This information provides insight into the value planners attribute to ecological processes. The results of the cumulative link mixed model analysis for the explanatory variable, ecological processes, show that this variable was statistically significant (p-value = 0.0003, Table S4 in Supplementary Materials) indicating that conservation planning with ecological processes is important for coastal and marine ecosystems throughout the literature. The test for goodness of fit showed ecological processes were valued significantly in planning (likelihood-ratio test, p-value < 0.0002, Table S5 in Supplementary Material). In contrast, spatial scale of the study region, had no influence on the inclusion of ecological processes in conservation planning (Table S6 in Supplementary Material). The test for collinearity among variables using Cramer's V resulted in a moderate association (V range value 0.3–0.4).

Methods and software

Of the 166 papers using quantitative data, researchers considered ecological processes with 33 different methods or tools. Papers that implicitly acknowledged ecological processes primarily used geographic information systems (GIS), statistical models, and prioritisation software (78%). Papers that explicitly applied ecological processes largely used process models and GIS in combination with prioritisation software (e.g. Marxan, Zonation) (22%) (Fig. 9).

In their review, Alvarez-Romero et al. (2018) concluded that SCP has advanced considerably because of the methods and tools developed by Australian organisations, for example the most widely used conservation planning tool, Marxan. In Marxan, connectivity can be incorporated as a discrete feature or by replacing the boundary length modifier with connectivity values (Beger et al. 2010; Makino et al. 2013; White et al. 2014; Balbar and Metaxas 2019; Daigle et al. 2020). Another spatial planning tool, Zonation performs connectivity transformations to optimise for connections through corridors or applies penalties based on boundary lengths (Lehtomäki and Moilanen 2013; Pickens et al. 2017). Of the 69% papers that implicitly acknowledged processes, 66% used Marxan and/or Marxan relatives (Marxan with Probability, Marxan with Zones), with 1.5% using the Zonation software. Papers that explicitly acknowledged processes used Marxan and/or relatives in 41% of studies whereas Zonation was the method of choice in 11% of papers. Two authors compared Marxan and Zonation outputs and concluded that the insights

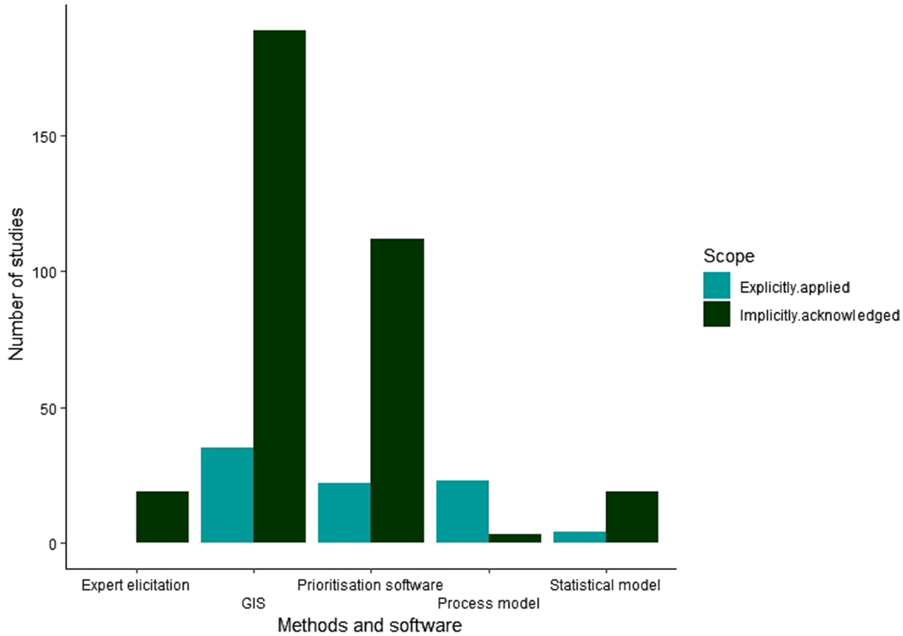

Fig. 9 Frequency of method and software categories used in our review according to the study scope

gained into biodiversity patterns and interactions were valuable, but socio-economic considerations within the study region rather than the type of conservation software had the greatest influence on the results (Allnutt et al. 2012; Delavenne et al. 2012).

Graph theory is increasingly being used as a means of estimating habitat connectivity to assign conservation value to individual sites emphasising patterns of regional marine connectivity based on the site's role in contributing to this connectivity (Treml et al. 2008; Kool et al. 2013; Alvarez-Romero et al. 2017). Particularly, useful in MPA design are metrics such as local retention, betweenness centrality and node outflux (Figuera 2009; Burgess et al. 2014; Magris et al. 2018). Studies that explicitly used dispersal in the planning process commonly employed network-based tools, for example; individual-based biophysical modelling approaches (41% of papers) yielding: dispersal trajectories (Grantham et al. 2011; Mumby et al. 2011; Krueck et al. 2017); connectivity matrices (Watson et al. 2011; Bode et al. 2012; Garavelli et al. 2014; Magris et al. 2018; Kininmonth et al. 2019); and dispersal kernels (Abesamis et al. 2016). Some studies tailored metrics to taxa with different life-history strategies in spawning and larval dispersal and further combined them in a multispecies approach to inform MPA design (White et al. 2014; Schill et al. 2015). While graph-theoretic approaches vary in their complexity depending on the application, graph-theoretic methodology has combined spatially explicit connectivity outputs with the decision support tool Marxan to target self-persistence, and highly central habitat patches to improve the design and implementation of networks of marine reserves (Alvarez-Romero et al. 2017; Magris et al. 2018). Alternatively, and at the high end of the complexity spectrum, customised optimisation algorithms integrate the strength and diversity of dispersal connections generated through biophysical modelling directly into MPA design (Mumby et al. 2011; Krueck et al. 2017).

An objective of our review is to examine the effect of study scope (i.e. qualitative, implicitly acknowledged, explicitly applied) on the type of method used to incorporate ecological processes in the conservation planning study. We assigned a value-based criterion to the study scope, that is, the diversity (or number) of ecological processes incorporated in a spatial plan depends on whether the plan was qualitative or quantitative, the methods also reflecting the qualitative or quantitative designation. This information provides insight into the value planners attribute to ecological processes. The results of the cumulative link mixed model analysis, showed that the type and number of methods used to incorporate ecological processes influenced the results significantly (*p*-value = 0.0179) indicating that the extent of incorporation (and value amount) of ecological processes in which planners incorporated ecological processes was reflected in the scope of the conservation plan. The methods reflect the scope (either qualitative, implicitly acknowledged, or explicitly applied) to which planners expect to include persistence constraints (Table S4 in Supplementary Materials).

Uncertainty

Few papers discuss the importance of uncertainty around ecological processes in coastal and marine planning. Of the 67 (35%) papers that discussed uncertainty, epistemic uncertainty describing incomplete knowledge or limitations of data, was commonly mentioned. However, only four papers explicitly included a method for dealing with uncertainty. Maina et al. (2015) and Tulloch et al. (2017) employed the conservation planning tool Marxan with Probability to accommodate uncertainty measures in the analyses such as information on the probability that habitats or species distribution is accurate. Wood et al. (2007) used multicriteria evaluation and fuzzy sets to facilitate outcomes for potentially conflicting resource use objectives at an ocean basin scale, and Assad et al. (2018) ensured a precautionary approach with data redundancy to evaluate and expand an MPA system at both a regional and national level.

Discussion

Our focus in this review is on ecological processes in coastal and marine conservation planning and determining the value of these processes to scientists and decision-makers. This work has relevance to the maintenance of biodiversity and ecological processes because it explores: (1) gaps in the literature relating to the context of coastal and marine planning; (2) methods that have been used to capture ecological processes; (3) the relevancy of ecological processes to planners, and (4) attributes of successful cases.

We found that after a peak in the overall number of studies in 2013 there are now relatively few studies including processes in spatial plans. We attribute this declining trend to the complexity of the problem of integrating dispersal and demographic objectives with other management goals. Bryan-Brown et al. (2017) identified that research trends often reflect the availability and uptake of technologies, demonstrated in our review by the increased development of biophysical modelling and genetic techniques for measuring effective larval dispersal, that is, dispersal of propagules with reproductive success. A common theme throughout our review is that optimal spacing of marine reserves in a network is strongly influenced by the spatial scale of movement of the target species' life-history characteristics, usually larvae, and there is a wide variation in larval dispersal distances (Fernandes et al. 2012; Green et al. 2014). The scales of larval movement can determine the distance between marine protected areas that allow for demographic connectivity (Cowan and Sponaugle 2009; Puckett and Eggleston 2016). However, a decline in the number of papers that included dispersal occurred after 2013, although dispersal is the most studied ecological process in our database of papers. Consequently, the movement of species remains a major uncertainty in spatial management (Moffitt et al. 2011).

Research based on empirical studies continues to develop our understanding of larval connectivity patterns particularly on theories of self-recruitment (the proportion of recruits that remain in the same population) in marine reserves and the export of offspring to adjacent fished areas (Gaines et al. 2010; Harrison et al. 2012; Almany et al. 2013). A challenge for MPA design—apparent in the irregular output of explicit studies with ecological processes in our review—is that planning for conservation objectives with larval dispersal data is focussed on self-recruitment, in contrast to planning for fisheries objectives where the focus is on larval spillover (the export of larvae from reserves to fishing grounds) (Brown and Mumby 2014; Krueck et al. 2017). The need to understand larval dispersal patterns has been driving the research in the field, but most studies in our review acknowledged processes without using an explicit method to include them in the spatial plan. Additionally, a critical issue is to build spatial plans for many species that have greatly differing dispersal patterns. We found that formulating and operationalising quantitative objectives for population persistence explicitly has lagged the development progress of contextual larval dispersal approaches. Empirical studies of genetics have not translated into process-based objectives for coastal and marine conservation planning.

Our results highlight a gap between the increasing volume of research on persistence criteria and its integration into marine spatial planning. Geographical bias in the distribution of research was apparent, in that particular ecoregions (Spalding et al. 2007) had a high concentration of studies: the Northeast Australian Shelf (including the Great Barrier Reef); Cold Temperate Northwest Atlantic (USA); Cold Temperate Northeast Pacific (USA and Canada); Western Coral Triangle; Northern European Seas; Western Mediterranean and Ionian Sea. The imbalance possibly results from several factors: (1) on-ground conservation programmes in these ecoregions by international conservation non-government organisations; (2) statutory mandates for development of plans e.g. Great Barrier Reef Marine Park Zoning Plan (Great Barrier Reef Marine Park Authority 2014); California Marine Life Protection Act (Saarman et al. 2013; White et al. 2014); Canada's Oceans Act (Horsman et al. 2011; Ban et al. 2013); (3) the field of SCP originated in Australia then progressed to the USA spreading to other countries, such as UK, the Baltic countries, South Africa, and Brazil (Ribeiro and Atadeu 2019); (4) proximity of an ecoregion to expertise in marine conservation planning. In contrast to the findings of Alvarez-Romero et al. (2018) we found some areas with high anthropogenic impacts had a consistent level of planning e.g. Lusitanian Province and the Eastern Caribbean. Studies in these disparate regions are progressive as the conservation plans address the challenges of marine spatial management in spatially limited and isolated coastal habitats that are extensively used by fisheries and recreational pursuits.

Among the explicit studies in our review there was a strong argument that by using a variety of methods and software, planning for processes allowed robust and actionable outcomes to be reached thereby advancing the field of coastal and marine conservation planning. The potential for biophysical dispersal models using simulated dispersal patterns to incorporate demographic connectivity are insightful. However, more empirical studies on individual species and their dispersal kernels (the probability distribution of larvae as a function of their starting location) is required to fine-tune the input of biological data for ground truthing these models (Moilanen 2011; Jones 2015; Manel et al. 2019). We found strong evidence for a linkage of method choice with study scope, suggesting that planners varied in the value they placed on ecological processes in planning assessments. Attributing relevance to explicitly defining processes in conservation plans is important for persistence values. Particularly, quantifying patterns of demography and dispersal (and other ecological processes) is crucial to our ability to manage coastal and marine systems effectively. Combining many processes in a single planning approach (aside from GIS and prioritisation software which is a common approach) is rare, but has the advantage of ameliorating limitations as shortcomings in one method can be addressed by other methods (Bryan-Brown et al. 2017). Additionally, greater methodological integration is required not only for data from advanced genetic techniques in process models, also to provide more robust outputs in persistence values from the planning analyses.

Our review revealed that several studies acknowledge uncertainty, although few studies consider uncertainty explicitly in coastal and marine conservation planning (Wood et al. 2007; Maina et al. 2015; Tulloch et al. 2017; Assad et al. 2018). Tulloch et al. (2017) explain that incorporating uncertainty can produce a larger and therefore more costly MPA system, the trade-off involves certainty in meeting targets against the combination of economic (e.g. impact to fishers) and biodiversity objectives. The dynamic nature of coastal and marine environments results in frequent shortfalls in biological data especially for ecological processes, evidenced by widespread consensus of epistemic uncertainty throughout the database of papers. Shifting baselines, under pressure from cumulative threats contribute to the challenge of identifying appropriate and sufficiently resourceful ecosystem objectives (Bullimore et al. 2014). Therefore, building on sources of biological data and incorporating multiple sources of uncertainty into conservation planning for coastal and marine ecosystems remain important areas for future research.

Our findings identify the unique challenges planners confront to incorporate ecological processes in coastal and marine planning: (1) there is a deficiency in data and multispecies models, and (2) it is an ambitious task to integrate process models with planning tools. Subsequently, our results demonstrate that most of the currently applied approaches fail to accurately represent crucial ecological processes.

There remains a critical need to better understand approaches to setting objectives for incorporating ecological processes, enabling decision-makers to proactively design and deliver better strategies. Defining goals explicitly related to persistence in combination with target feature representation is important to consider, notwithstanding different area and spatial configuration requirements (Edwards et al. 2010; Metcalfe et al. 2015). To elaborate, there is a lack of tools and serviceable frameworks to facilitate collaboration between process scientists and spatial planners. Firstly, relevant biological data is often absent e.g. reproduction and larval mortality rates (Riginos and Liggins 2013). Secondly, temporal or scale mismatch for demographic connectivity relative to genetic connectivity is challenging to describe but is commonly encountered in marine organisms (Leis et al. 2011; Green et al. 2014). Finally, methodological integration within studies is scarce, those studies that accomplished the task explored seascape genetics in combination with biophysical dispersal models explicitly e.g. connectivity matrices (Treml and Halpin 2012; Burgess et al. 2014; White et al. 2014; Abesamis et al. 2016; Selkoe et al. 2016; Magris et al. 2018). Nevertheless, many studies corroborated the perception that including ecological processes in marine spatial planning is integral to functional ecosystems particularly under changing environmental conditions (Agostini et al. 2015; Schmiing et al. 2015). Moreover, additional studies are needed to clarify the ecological processes underpinning ecosystems that are not being considered in conservation planning of coastal and marine seascapes. Further, this review reflects a primary motive for conducting a literature survey–to contribute a comprehensive information source that would be available to policy makers and managers considering conservation planning of coastal and marine ecosystems. Hence, by highlighting key gaps in the literature, the review sets the agenda for future research.

Limitations of the study

While this review enabled us to provide a thorough summary of the current knowledge on ecological processes in coastal and marine conservation planning, there were some limitations in its scope. Results of meta-analyses across studies may be affected by bias due to the absence of results from studies that should have been included in the synthesis (Higgins et al. 2021). Publication bias also occurs when the conclusions of the review may be compromised—decisions about how, when, and where to report results of eligible studies are influenced by the nature and direction of the results (Jennions et al. 2013). This leads to results systematically missed from syntheses, which can lead to syntheses over-estimating or under-estimating the effects of an intervention (Haddaway et al. 2017). We created a database of systematically collected papers to collate information pertinent to different aspects of the analyses. In this way we cross-referenced studies, avoiding contradictions in formulating categories and recording results, with the purpose of circumventing publication bias as much as possible and producing a definitive review.

Conclusion—critical research gaps and ways forward

Representation of habitats in MPAs alone does not ensure long-term protection of species and ecosystems. On the contrary, instigating actions for representation and species persistence can contribute to a concrete measure of biodiversity protection. However, incorporating processes into multispecies planning for coastal and marine seascapes is especially complex as data and models for species of interest are unavailable, complicated, and time-consuming to develop. Conservation decisions such as where to place MPAs should be influenced by knowledge of local ecological processes pertaining to the focal species, a critical gap in our review. An issue of paramount importance in spatial management still to be resolved is the movement of species, particularly incorporating many species into spatial plans that have greatly differing dispersal patterns, although research on larval connectivity patterns of self-recruitment and spillover in marine reserves provides optimism. Formulating and operationalising quantitative objectives for population persistence explicitly has lagged the development progress of contextual larval dispersal approaches. Aside from dispersal, most ecological processes are not sufficiently included into coastal and marine spatial planning. This review highlights the need for greater awareness among planners of the relevance of ecological processes in conservation planning for coastal and marine ecosystems, a value that translates to explicitly meaningful assessments.

Author's contributions HPP and DAC jointly conceived and designed this study. SRP provided input into the contents of the paper, suggestions for analysis and editing of the draft and final versions. DAC processed and analysed the data and led the writing of the paper with all authors making contributions.

Declarations

Conflict of interest The author declared that there is no conflict of interest.

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