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A Review on Coastal Urban Ecology: Research Gaps, Challenges, and Needs

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Coastal urban areas have dramatically increased during the last decades, however, coastal research integrating the impacts and challenges facing urban areas is still scarce. To examine research advances and critical gaps, a review of the literature on coastal urban ecology was performed. Articles were selected following a structured decision tree and data were classified into study disciplines, approaches, type of analysis, main research objectives, and Pickett's paradigms *in-*, *of-*, and *for- the city*, among other categories. From a total of 237 publications, results show that most of the research comes from the USA, China, and Australia, and has been carried out mostly in large cities with populations between 1 and 5 million people. Focus has been placed on ecological studies, spatial and quantitative analysis and pollution in coastal urban areas. Most of the studies on urban ecology in coastal zones were developed at nearshore terrestrial environments and only 22.36% included the marine ecosystem. Urban ecological studies in coastal areas have mainly been carried out under the paradigm *in the city* with a focus on the disciplines of biology and ecology. Results suggest a series of disciplinary, geographical, and approach biases which can present a number of risks. Foremost among these is a lack of knowledge on social dimensions which can impact on sustainability. A key risk relates to the fact that lessons and recommendations of research are mainly from developed countries and large cities which might have different institutional, planning and cultural settings compared to developing and mid-income countries. Scientific research on coastal urban areas needs to diversify toward an ecology *of* and *for the cities*, in order to support coastal development in a diversity of countries and settings.

Keywords: coastal urban ecology, marine urbanization, coastal cities, urban ecology paradigms, coastal urbanization

INTRODUCTION

The world's population is increasing annually. In 2018, 55% of the human population lived in urban areas and cities have been constantly growing in number and size, forming large cities. The so-called megacities have reached over 10 million inhabitants (according to the United Nations, 2018, presenting 33 settlements). The high levels of urbanization during the last decades have triggered increasing research and policy interest on the impacts and sustainability of these human-dominated ecosystems (Grimm et al., 2000; Griggs et al., 2013). Initial research hypothesized urban areas were not able to sustain wildlife and complex ecological processes. However, this began changing in the first part of the '70s when urban ecology began studying species distributions in cities and its drivers (Noyes and Progulske, 1974; Dorney et al., 1984; Sukopp, 1998; Grimm et al., 2008). Since then, urban ecology research topics have evolved to include ecological and social science approaches (Grimm et al., 2000) and currently, urban ecosystems are recognized as a complex coupling of ecological processes and human dynamics, as defined by Alberti (2008) and Pickett et al. (2008). Research on urban ecology is diverse and includes studies on biodiversity patterns [e.g., urban biodiversity in Faeth et al. (2011); biotic homogenization in McKinney, 2006], species distributions (e.g., birds in Marzluff, 2001), ecosystem functions (Groffman et al., 2004; Rosenzweig et al., 2018), development processes (e.g., Antrop, 2004), drivers of change (e.g., Grimm et al., 2008), ecosystem services (Bolund and Hunhammar, 1999; Daily, 2003), human well-being (Pacione, 2003; Van Kamp et al., 2003; Dallimer et al., 2012), social-ecological systems (Barthel et al., 2010; Grimm et al., 2013), and sustainability (Wu, 2008, 2014).

Pickett et al. (2016) introduced three phases in the way urban ecology has evolved. They provide a typology of paradigms for urban ecology, which are termed: *in*, *of*, and *for the city*. Each one of these paradigms exposes historical differences according to changes in urban ecology research, and resulted by the comparison of three variables: chronology, model approach, and complexity. Studies under the paradigm *in the city* fall mainly into using ecological approaches, studies *of the city* are mainly based on social-ecological interactions, and studies *for the city* represent research about environmental policies and planning. The urban ecology paradigms also represent increasing level of complexity of the system studied, where research which subscribe to the *of the city* paradigm include interdisciplinary research; the urban ecology *for the city* is more intricate and includes *in* and *of the city* studies, engaging scientific knowledge in practice for action (Pickett et al., 2016).

Most of the theoretical and empirical developments in urban ecology have used green areas (e.g., Chiesura, 2004; Tzoulas et al., 2007; Wolch et al., 2014), freshwater streams (e.g., Allan et al., 1997; Paul and Meyer, 2001; Walsh et al., 2005), and organisms such as birds (e.g., Blair, 1996; Chace and Walsh, 2006) or plants (e.g., Ulrich, 1984; Donovan and Prestemon, 2012; Donovan et al., 2013) as their preferred research subjects. Coastal settings and species have not received the attention they deserve, and only 5% of urban ecology research in Web of Science is focused in coastal or marine ecosystems. This is unfortunate because coastal cities present a variety of environments, including the land-marine ecotone interaction, and they are an important place for people to settle (Weinstein, 2009). According to the (United Nations, 2017), 40% of the world's population live <100 Km from the sea, and these cities have increased their population 6.6 times between 1945 and 2012 (Barragán and de Andrés, 2015). These factors and specific features such as interactions with watersheds in estuaries, the establishment of structures in ports (Cadenasso et al., 2006), and the social importance of access to the waterfront (Sairinen and Kumpulainen, 2006) reflect a particular vulnerability for coastal urban areas. During recent decades, studies on risks have increased due to predicted changes in winds, waves or sea-level rise due to climate change (Torresan et al., 2008; Kumar et al., 2010; Benveniste et al., 2019). Despite recent interest on vulnerabilities, research has mainly focused on geomorphological contexts (Arns et al., 2017; Vitousek et al., 2017; Luijendijk et al., 2018; Benveniste et al., 2019).

This article reviews scientific publications of coastal urban ecology with the aim of examining spatial and temporal changes in time and evaluating the evolution of urban ecology in these vulnerable areas through identifying the interconnection in existing literature given by the urban ecology paradigms (Pickett et al., 2016). Here, studies are classified according to theoretical and empirical dimensions of urban ecology. Biases in the literature are highlighted as a way to call attention to the needs for developing coastal urban ecology studies that can inform ongoing urbanization trends, especially in developing and mid-income countries.

METHODS

A review of the literature was performed through the Web of Science database (https://webofknowledge.com/). Eligibility criteria included any publication following keywords in the topic, using Boolean operators to combine concepts and keywords: ("urban ecology" or "urban environment*") and (coast* or marine). The period of the search included from 1975 until December 2019. We based our search on systematic mapping in order to collate, describe and catalog available evidence relating to the topic, allowing to address open-frame or closed-frame questions (James et al., 2016). Selection of articles was made with a decision tree (**Figure 1**), where the urban center, marine studies, and biodiversity approach had to be checked for any articles to be included. Fulfilling the requirement for inclusion, publications were classified in ecology *in the city*, ecology *of the city* or ecology *for the city* following the paradigms established by Pickett et al. (2016). Studies were counted just once for each paradigm. Gray-literature was not incorporated in the selection.

Each article collected was categorized by publication year, author's name, type of publication, author's affiliation country, study country, and study city. After examining each paper they were categorized according to disciplinary focus, study approach, type of analysis, main research object, study model, and coastal environment. A list of categories, their definitions and example references can be found in **Table 1**. Articles were classified by two of the authors independently. Results were then compared and discrepancies resolved with the participation of a third author. For each category, articles were counted just once.

City's population data were obtained from the United Nations (2019) compendium. Urban centers classification was modified from the United Nations (2014) and Barragán and de Andrés (2015). This classification includes: (1) Non-urban areas, which have <100,000 inhabitants, (2) small cities, between 100,000 and 500,000 inhabitants, (3) medium cities, between 500,000 and 1

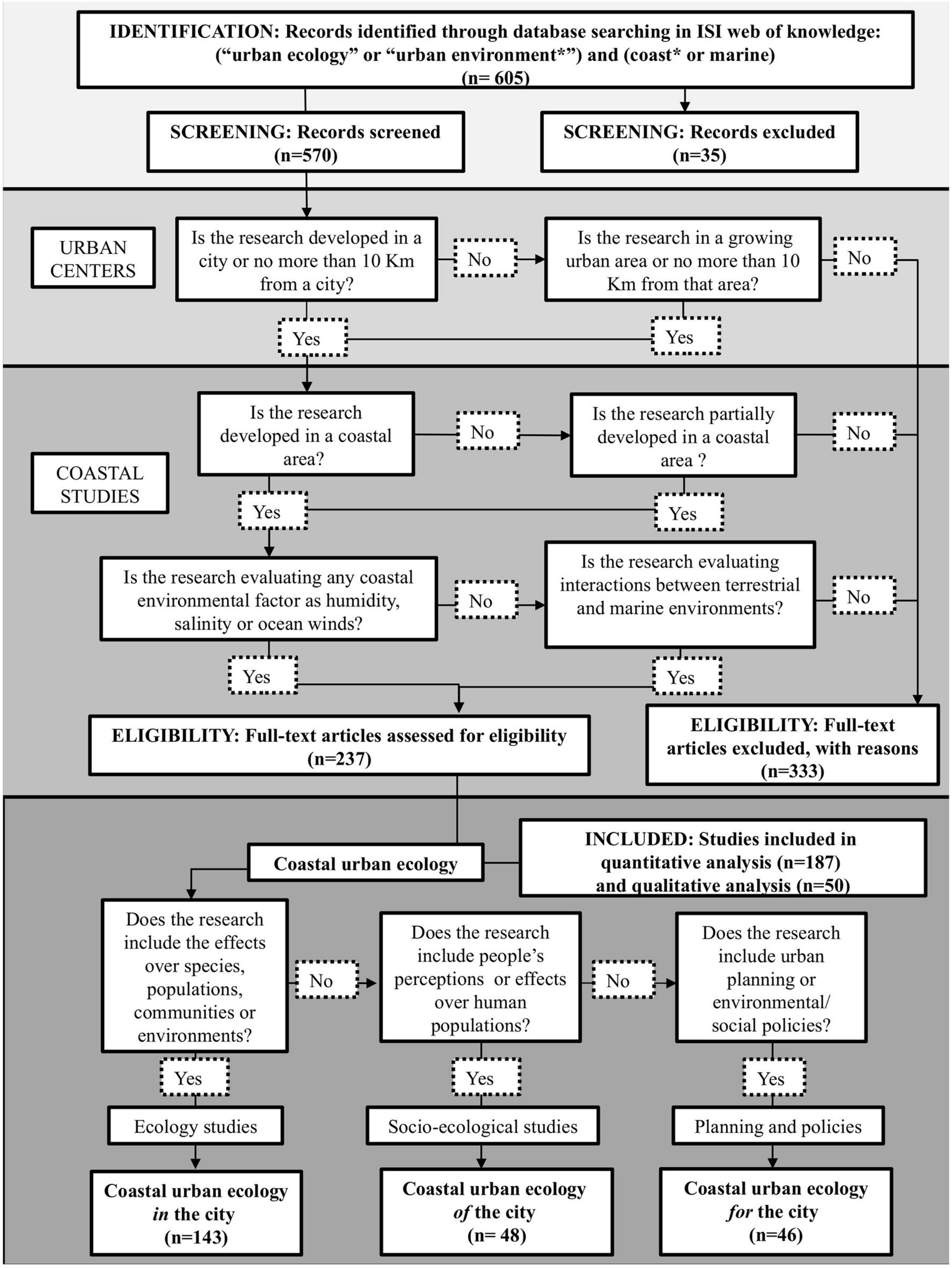

FIGURE 1 | Decision tree of articles selected based on a PRISMA flow diagram. Description of the selection process for articles in coastal urban ecology review. After four passes for selection filters, the remaining 237 studies where classified in three categories: ecological paradigms *in*, *of*, and *for the cities*.

million, (4) large cities, between 1 and 5 million, (5) very large cities, between 5 and 10 million, and (6) megacities, with more than 10 million.

Characterization of articles according to urban ecology paradigms included the number of studies found for each paradigm, countries, year of publications, disciplinary focus, research approach, type of analysis, and main research objective. To examine the interaction among articles' paradigms, we analyzed the co-citations to other articles in our data base using the Web of Science database, and carried out a descriptive analysis of the network. We did not used topological measurements of the network, but rather describe its directionality. This analysis was developed with package bibliometrix (Aria and Cuccurullo, 2017), which allowed modifications in the code to create a new relationship between articles and their co-citations. The analysis included extracting every reference from each article that was selected in this review and the selection of cited articles that were already part of the article selection. Consequently, there was a tagging for each article cited with corresponding paradigm classification and these were plotted to unveil the relationship among paradigms used.

Classification, data analysis, and figures were prepared in R Core Team (2020) using RStudio Team (2019). For data analysis, packages tidyverse (Wickham and Wickham, 2017), dplyr (Wickham and Wickham, 2017), purrr (Henry and Wickham, 2017), broom (Robinson, 2017), and stringr (Wickham, 2017) were used. Graphs and maps were plotted with ggplot2 (Wickham, 2009) and gridextra (Auguie, 2016).

RESULTS

Coastal Urban Ecology Tendencies

Coastal urban ecology studies that met selection criteria included a total of 237 articles (**Figure 1**) from 51 countries, involving 137 different coastal cities. Most of the research was carried out in three countries: USA presenting 38 articles published, which included 20 different cities, China with 20 articles from 10 different cities, and Australia also with 20 articles, including 10 different cities (**Figure 2**). The timeline of publications shows that urban ecology in coasts appeared for the first time with Barcelona in 1979, however, it was not until 1995 that another study related to the field was published with Punda-Polić et al. (1995). Between 1995 and 2005, the number of publications was below five articles per year (**Figure 3**). After 2005 more articles can be found, particularly in years 2016, 2018, and 2019, which showed more than 20 publications per year. According to the type of publication found at the Web of Science database, publications are mostly journal articles with 84.97% of the total, proceedings papers represented 9.7% (e.g., Kulkova et al., 2011; Giovene di Girasole, 2014; Fu et al., 2018), indexed book chapters 2.11% (e.g., Race et al., 2010; Wong, 2011; Juchimiuk and Januszkiewicz, 2019), and reviews 2.11% (e.g., Garden et al., 2006; Cohen et al., 2013; Branoff, 2017).

General findings and tendencies since 1995 are shown in **Figure 3**. The main disciplinary focus of research has consistently come from ecology with an average representation of 48.79% of studies for the whole study period. Among ecological studies, those where coastal urbanization have modified ecological patterns stand out. For example Way et al. (2004), tracked movement and activity patterns of coyotes in northeastern North America, demonstrating that these mammals used more urbanized areas than natural ones. Other studies have assessed diets and feeding habitats of coastal birds to assess the interplay between natural and anthropogenic factors in determining diversity patterns (Washburn et al., 2013). Social-ecological studies were the second most common disciplinary focus with 24.47% (an average 2.2 publications per year between 2005 and 2009, 4.4 between 2010 and 2014, and 3.8 between 2015 and 2019; **Figure 3**A). Social-ecological studies include those which focus on biodiversity and natural environment perceptions and human well-being. For instance, White et al. (2013) assessed human emotions toward different coastal environments and Burger et al. (2017) assessed human preferences toward protection and restoration. Environmental policy and planning studies have focused on developing guidelines for planning in order to contribute to the sustainability of the urban environment. For instance Alcoforado et al. (2009) identified climatic needs in a coastal city and discussed problems that arise when applying climatic knowledge to urban planning. Disciplinary focus of research showed high number of publications on traditional ecology, centered on how biodiversity patterns are affected by cities. However, despite noticeable exceptions, focus on human dimensions, such as studies which deal with perceptions and well-being associated to urban development and environmental footprint have received less attention. In addition multidisciplinary research on defining and designing solutions, associated to various forms of participatory approaches in order to move toward urban sustainability, are still scarce, showing a gap in knowledge.

Coastal ecology research has mainly considered spatial approaches searching for patterns based on differences in urban morphology. These spatial patterns include land cover and land use. For instance, research based on beach width and coastal slope that determine the most critical physical parameters to create coastal vulnerability maps (Kantamaneni et al., 2019). Study approaches have slowly included temporal dimensions (**Figure 3**B). Spatio-temporal studies included articles such as Grossmann (2008) who discusses the consequences of current global technological, organizational and economic developments for a port. Temporal studies included Priestley et al. (2018) who assessed inorganic and organic compounds and their relation to photolysis and Martin et al. (2007) who studied management approaches for a coastal urban pest (White Ibis) along the east coast of Australia. Studies which use experimental approaches through time represent <1% of the articles. They included articles such as the study of Leclerc and Viard (2018), who studied how swimming predators influenced the early development of fauna associated with floating pontoons in marinas. A significant higher number of publications considering spatial instead of temporal approaches could generate a static representation of what happens in coastal cities. This is particularly relevant in the face of climate change scenarios, where temporal variability becomes important.

TABLE 1 | Classification of articles in coastal urban ecology.

Category	Classification	Description	Examples
Disciplinary focus	Ecological	Study of relationships and interaction between organisms and their coastal urban environment.	Tait et al., 2005; Smith and Munro, 2010
	Social	Study of social behavior, including its origin, evolution and organization within a coastal urban environment.	Abarca-Álvarez et al., 2018
	Social-ecological	Study of interaction between humans and their coastal urban environment, using multidisciplinary approaches including anthropology, geography, sociology and ecology.	White et al., 2013; Burger et al., 2017
	Environmental policy	Study of the environment with a focus in organization, law, regulations or policy solutions.	Alcoforado et al., 2009; Vye and Rousseaux, 2010
	Social policy	Provides practical guidelines and principles to improve human welfare.	Jonkman et al., 2013; Guerrero Valdebenito and Alarcon Rodriguez, 2018
Study approach	Spatial	Focus on landscape, land cover, or urban geomorphology changes.	Garden et al., 2006; Yamazaki et al., 2007
	Spatiotemporal	Landscape, land cover, or urban geomorphology changes, including some changes over time on small scale.	Grossmann, 2008; Li et al., 2011
	Temporal	Focus in changes over time.	Semadeni-Davies et al., 2008; Yu et al., 2019
	Temporal experiment	Focus in changes over time in a controlled environments and simulations.	Chabas et al., 2015; Leclerc and Viard, 2018
	Experimental	Including all lab procedures.	Zhen et al., 2007; Charalambous et al., 2012
Type of analysis	Qualitative analysis	Non-numerical descriptions and ethnographic studies.	Gardner, 2003; Arif, 2017
	Quantitative analysis	Collection and evaluation of measurable data of either social or environmental aspects.	Galimany et al., 2013; Branoff, 2017
	Modeling studies	Mostly computational simulations.	Sahal et al., 2013; Santos and Freire, 2015
Main research object	City design	Mainly urban planning.	Alcoforado et al., 2009; Kantamaneni et al., 2019
	Demographic change	Variation in the population in terms of size, average age, life expectancy, family structures, or birth rates, among others.	Race et al., 2010, Abarca-Álvarez et al., 2018
	Habitat use	Variation in the distribution of species within cities.	Lim and Sodhi, 2004; Reyes-López and Carpintero, 2014
	Human adaptation	People's reaction to urban changes and creation of new spaces	Weinstein, 2009; Chen et al., 2015
	Natural disaster	City's risks or damage associated to floods, hurricanes, storms, tsunamis, or another geophysical process.	Yin et al., 2016; Su et al., 2019
	Pollution and human impacts	Effects of city growth and/or increase in urbanization as a measurement of contamination.	Ip et al., 2007; Arruti et al., 2011
	Shoreline changes	New infrastructure in the shoreline, waterfronts and other constructions.	Wu, 2007; Alberico et al., 2018
Study model	Physical	Physical space comprises research with aerosol, geomorphological elements, land structures, meteorological elements, pollutants, remote sensing data, risk models, seawater, surface deterioration, and water resources.	Pollutants: Pallarés et al., 2019 Remote sensing: Peng et al., 2017
	Social-ecological-technological.	Includes marine and green structures, eco-cities, and sustainable cities.	Marine structures: Gumusay et al., 2016 Eco-cities: Surjan and Shaw, 2008
	Social	Social space comprises bioclimatic comfort, demographic, human activities and cultural heritage, perceptions, public health, and sustainable development.	Human activities and culral heritage: Cleland et al., 2015 Perceptions: Nunkoo and Ramkissoon, 2010
	Biological-species	Biological in terms of studied organisms or their parts, including algae, antibiotics, bacteria, birds, fishes, invertebrates, lichens, mammals, and plants.	Birds: Belant, 1997 Fishes: Naidoo et al., 2016
	Biological-ecosystems	Biological in terms of studied ecosystems, including studies in diversity, ecological processes and patterns, ecosystems, and environmental management.	Environmental management: Tu and Shi, 2006 Ecosystems: Branoff, 2017
Study habitat	Near-shore terrestrial	Includes dunes, coastal xeromorphic habitats, rocky and sandy shores, urban, agricultural and industrial landscapes in the coast.	Watson, 2015; Whisson et al., 2015
	Intertidal	Estuaries, deltas, mangrove forests, coastal lagoons, salt marshes, other coastal wetlands, marinas and ports.	Jonkman et al., 2013; Kuwae et al., 2016
	Near-shore coastal benthic	Seagrass beds, artificial structures and soft bottom environments above the continental shelf.	Eddy and Roman, 2016; Bolton et al., 2017
	Coastal pelagic	Open waters above the continental shelf.	Zhen et al., 2007; Wang, 2010
	Coastal atmosphere	The aerial space.	Clarkson et al., 1996; Dominick et al., 2018

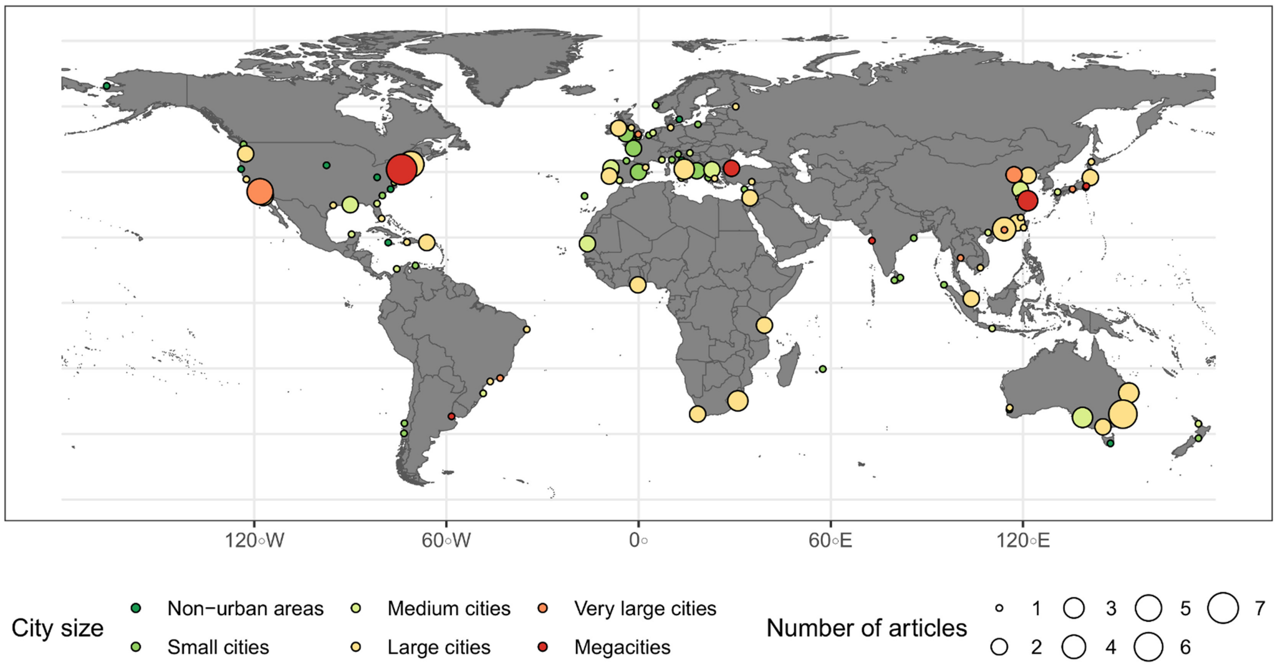

FIGURE 2 | Global distribution of publications. Articles in coastal urban ecology according to the city where the investigations were carried out, the population size of each city and the number of articles published in them. For each city the size of the circle is proportional to the number of articles published (from 1 to 7); the color of the circle represents the size of the city given its population.

Quantitative studies have dominated the literature during the past 20 years and have focused on ecological approaches. For example Tzortzakaki et al. (2018) studied the effect of the different land-cover types on bird species richness and abundance and concluded that open green spaces are the most significant factor favoring bird diversity in a coastal city in Greece. Qualitative studies represent 20% of the articles. These mainly use a social-ecological approach. Studies use qualitative interviews to assess urban coastal environmental constructs and preferences (Cleland et al., 2015). Other qualitative studies have been used to design green infrastructure in urban cities (Chen et al., 2015). Policy studies such as Guerrero Valdebenito and Alarcon Rodriguez (2018) used qualitative approaches to assess tensions and threats to traditional small-scale artisanal fishers coexisting with larger urbanized systems such as mega infrastructures, ports and cities. Modeling studies which include simulation of urban conditions, have begun to emerge in the past 6 years (**Figure 3**C) to address a wide variety of issues. For example, Stathopoulou and Cartalis (2007) modeled the thermal urban environment and urban heat island phenomenon in mayor urban areas in Greece. Su et al. (2019) used modeling to determine realistic flooding scenarios. Other modeling studies have contributed to assess social-ecological dimensions. Sahal et al. (2013) used macro-simulators and micro-simulators with multi-agent-based modeling to select shelter points and choose evacuation routes for future tsunamis. Song et al. (2016) modeled urban environmental benefits, such as green infrastructure, industrial upgrade, and environmental management, in China, testing social-economic and demographic variables. The use of modeling to inform environmental policies has been approached mainly through mapping and risk assessments. For instance, Storch and Downes (2011) quantified and mapped current and future city-wide flood risks, combining climate change scenarios with urban land use scenarios. A key finding is that qualitative research approaches have been underrepresented. This has important consequences especially when assessing how the general public engage with urbanization and its impacts in coastal zones. Accordingly, there are important gaps of knowledge in this area.

When looking at the main research objectives it is interesting to note that the study of pollution and human impacts have dominated the literature (**Figure 3**D). These articles mainly focus on the effects of stressors over coastal urban ecosystems and cities. For instance, Jartun and Pettersen (2010) collected sediments from urban stormwater runoff and analyzed various contaminants, showing that several active pollution sources are supplying the runoff systems. Studies that focus on habitat use in urban areas are also common. For example, studies have focused on differences in communities between fixed and floating structures (Holloway and Connell, 2002) or on abundance and survival rates of charismatic species in highly industrialized bays (Eguchi et al., 2010). Studies which focus on different aspects of city design are less frequent, but they have been increasing in the last 10 years. Some of these studies have developed climatic guidelines for planning and identifying climatic needs in coastal cities (e.g Alcoforado et al., 2009),

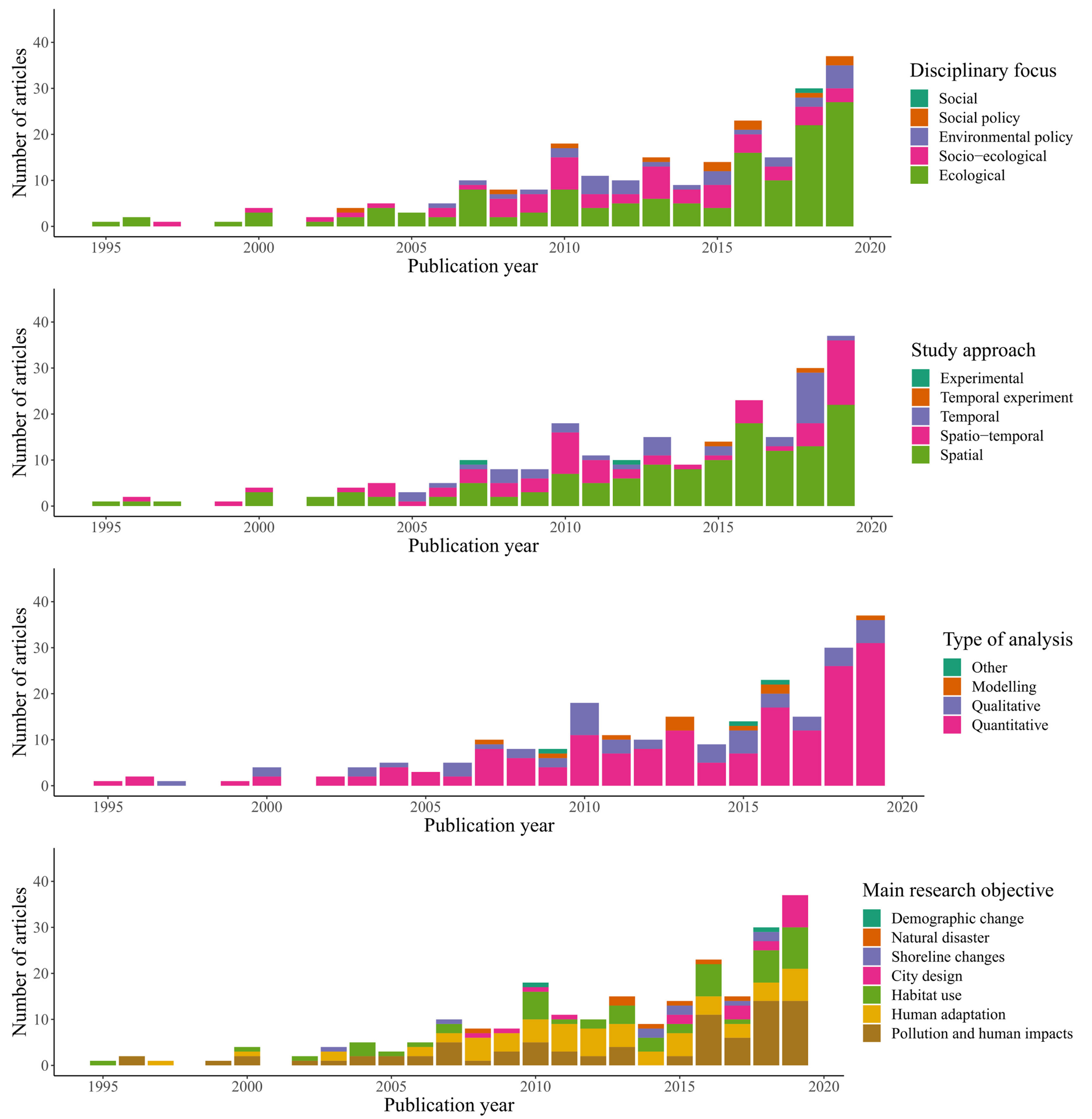

FIGURE 3 | Temporal distribution of categories. Articles in coastal urban ecology were categorized according to disciplinary focus, research approach, type of analysis, and main research objectives.

others have applied multi-criteria decision analysis to explore local stakeholders' perceptions in terms of priority actions for waterfront development (Papatheochari and Coccossis, 2019).

According to study models used (**Figure 4**), a significant number of publications focused on physical aspects (48.10%) such as pollutants and risk toward natural hazards (Buggy and Tobin, 2008; Dominick et al., 2018). The second most frequent study model was biological, centered on specific species (21.94%). In this group, birds were the most studied (e.g., Kalinowski and Johnson, 2010, studying a suburban bird community; Sainz-Borgo et al., 2016, studying the house sparrow; Blight et al., 2019, studying an urban-nesting gull population). Invertebrates were the second most studied group including marine (Galimany et al., 2013; Eddy and Roman, 2016); and terrestrial species (Bizzo et al.,

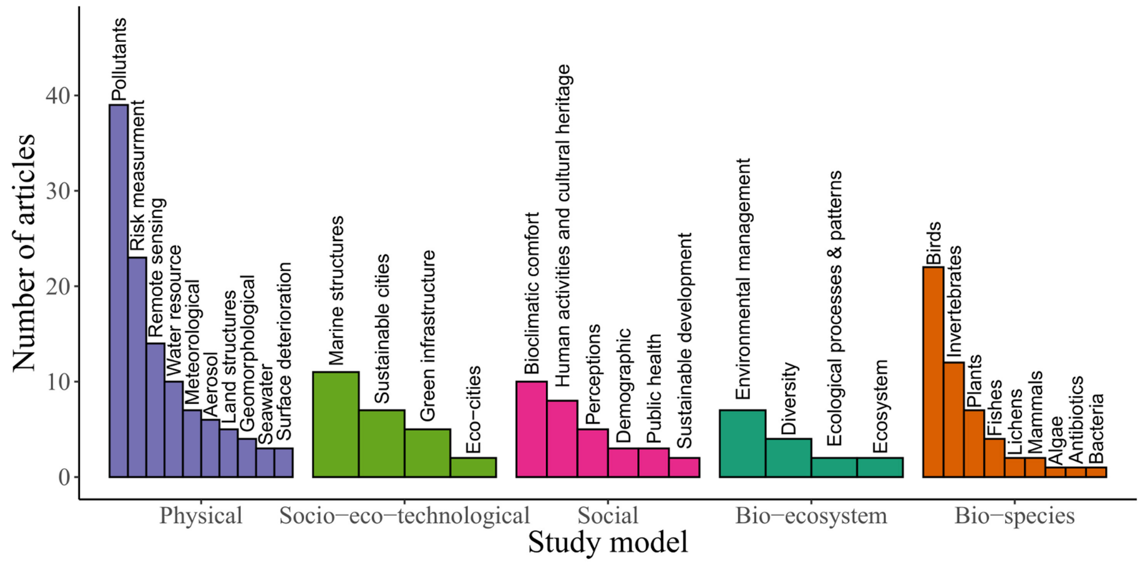

FIGURE 4 | Distribution of articles, according to study models of research. Coastal urban ecology models were grouped by Physical, Social-Ecological-Technological, Social, Biological-Ecosystem, and Biological-species.

2010; Reyes-López and Carpintero, 2014). While other marine species such as fishes received less attention, some noticeable examples include the study by Bolton et al. (2017) of fish communities. Studies centered on specific ecosystems (Ehrenfeld, 2000; Branoff, 2017) or social-eco-technological systems showed <10 articles published. Foremost among these are those on eco-cities (e.g., Wong, 2011). This evidence indicates that study models have been frequently replicated. The dominance of certain study models has allowed progress in the field on certain issues. But at the same time, there are some fields that have not progressed at all such as those that include organisms like algae or marine microorganism.

Most of the articles published in coastal urban ecology have been developed in large cities of 1 to 5 million inhabitants (41%), while other city categories do not exceed 18%. More than 55% of articles were carried out in cities with more than 1 million people, including very large cities such as Los Angeles in USA (Barcelona, 1979), Osaka in Japan (Yamazaki et al., 2007), Tianjin in China (Peng et al., 2011), Bangkok in Thailand (Burnett et al., 2007), and megacities with more than 10 million people such as Shanghai in China (Li et al., 2018), Tokyo in Japan (Krishnan et al., 2019), New York in USA (Washburn et al., 2013), Buenos Aires in Argentina (Cardo et al., 2014). Coastal areas with <100,000 inhabitants presented only 10% of articles. These are dominated by articles from the USA (e.g., Kalinowski and Johnson, 2010; Wolsko and Marino, 2016). There is a clear focus on large cities and important knowledge gaps remain in studying urbanization processes and differences associated to growth of smaller cities and the social-ecological complexities they confront.

Research in coastal urban ecology has focused mostly in near-shore terrestrial environments, presenting more than 68% of articles. These have focused on urban environments (e.g., Parzych et al., 2016), anthropogenic constructions (Günel, 2018), green areas (Callaghan et al., 2018), and urban watersheads (Pinheiro and Hokugo, 2019). Intertidal areas presented 17.30% of the publications. Some of these focused on coastal defenses (e.g., Jonkman et al., 2013), estuarine and shallow coastal systems (Kuwae et al., 2016), estuarine mullet in an urban harbor (Naidoo et al., 2016) and predation on a threatened coastal seabird (Greenwell et al., 2019). Near-shore coastal benthic habitats accounted for 3.38% and included studies such as those which assess community structure (e.g., Holloway and Connell, 2002; Eddy and Roman, 2016), impacts of light on communities (Bolton et al., 2017) and spatial distribution patterns [e.g., Heery et al., 2018 for the giant Pacific octopus (*Enteroctopus dofleini*)]. Studies which focus on pelagic environments near the coast account for only 1.69%. These relate mostly to sea water studies such as Zhen et al. (2007) and ocean thermal energy (Wang, 2010). Coastal atmosphere showed 8.86% of total articles published (e.g., aerosol: Castro et al., 1999; PM10 pollution episodes: Vicente et al., 2012; atmospheric deposition: Shanquan et al., 2016; and chemical composition of fine-aerosol fraction: Theodosi et al., 2018).

Current research evidence suggests studies in coastal urban systems deal greatly with pollutants and ecological implications, with emerging interests in planning and social interactions and responses. The ways in which these areas interact in time and space and across different city sizes and configurations could provide to be particularly novel research endeavors. Important issues such as the environmental footprint and social-ecological tradeoffs of coastal configurations of few large or a series of smaller cities settled along the coast are some key areas which need further development (Weinstein, 2009; Kaniewski et al., 2013; Barragan and Andres, 2015). Q19 Ultimately, coastal urban ecology still has important research opportunities in addressing the interactive effects of urban

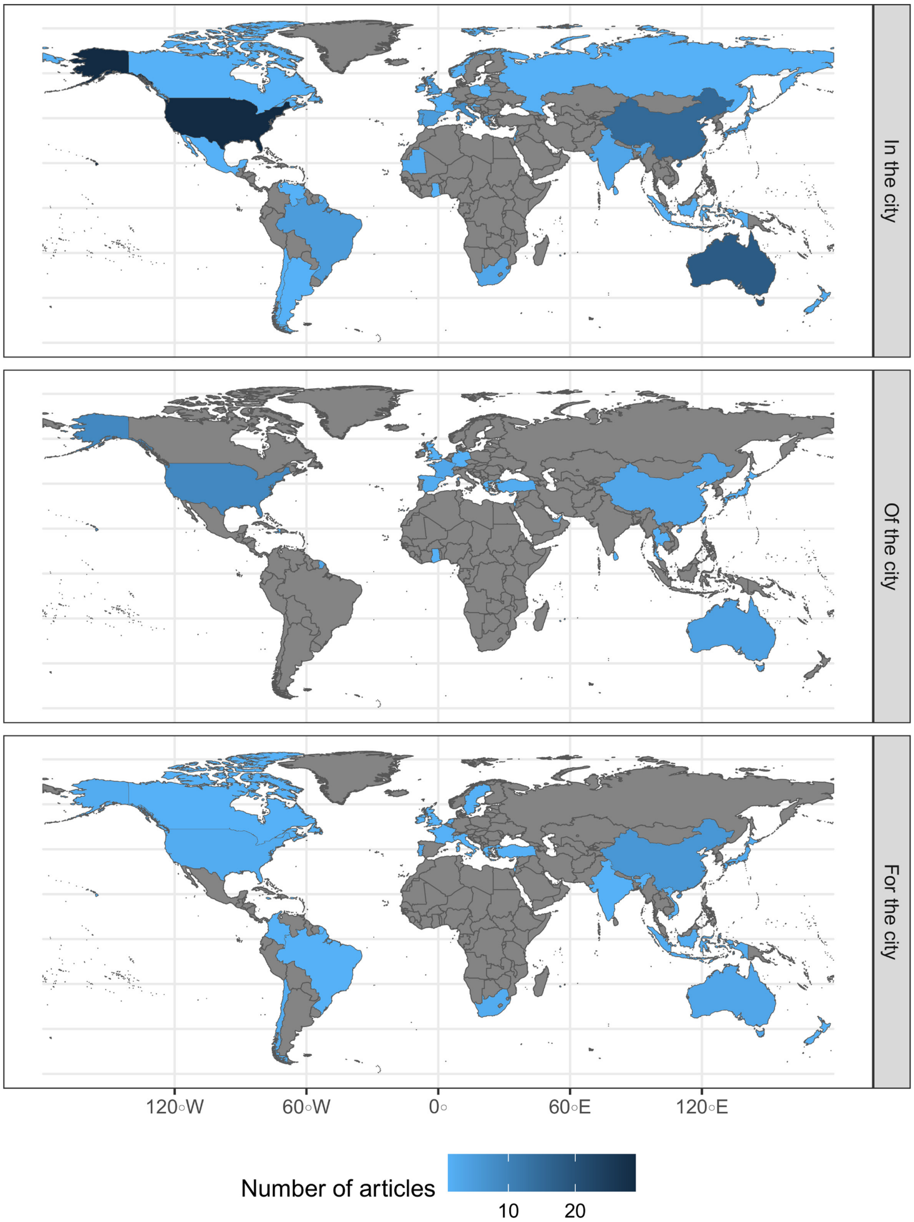

FIGURE 5 | Contribution of countries by paradigms. Coastal urban ecology studies ascribed to Picketts's paradigms *in*, *of*, and *for the city* (presented in blue colors from light to dark); Countries that not present coastal urban ecological articles are show in gray.

drivers, social-ecological responses and how planning processes accommodate these complex system dynamics.

Coastal Urban Ecology *in*, *of*, and *for the City*

Paradigms *in*, *of*, and *for the city* have been addressed globally (**Figure 5**). The focus *in the city* is represented in more than 60% of articles, including 37 countries. The US showed the highest number of articles with 29 publications (e.g., Way et al., 2004; Eddy and Roman, 2016; Maguire and Fulweiler, 2019). The focus *of the city* is shown at a lower percentage than the previous paradigm, with 20.25% of publications and performed in 21 countries. The US also dominated this paradigm with 9 articles (e.g., Gasper et al., 2011; Douglas et al., 2012; Burger et al., 2017). Research addressing the *for the city* paradigm represented 19.41% of total articles and came from 25 different countries. China presents six articles (e.g., Li et al., 2011, 2017; Peng et al., 2011), which is the highest number of papers in a country which addresses this paradigm. This result indicates that coastal urban ecology is dominated by research with a focus *in the city* and only few countries have attended to develop the three paradigms.

Paradigms *in*, *of*, and *for the cities* have shown differences, not only in the total number of articles published (143, 48, and 46, respectively) but also in their first year of publishing and

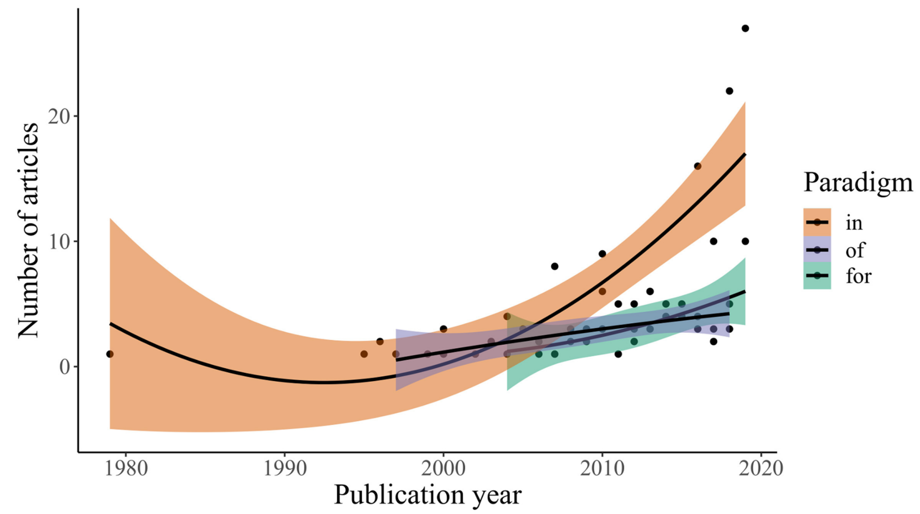

FIGURE 6 | Paradigms' temporal changes. Number of articles published considering paradigms *in*, *of*, and *for the cities*. Trend lines represent quadratic regression fit (*in the city* $R^2 = 0.656$, $p < 0.001$, *of the city* $R^2 = 0.382$, $p < 0.05$, *for the city* $R^2 = 0.460$, $p < 0.05$); color areas represent the 95% confidence interval.

subsequent tendencies (**Figure 6**). In this way, it is not until 2004 that the paradigm *for the city* appeared in coastal urban ecology studies (Patz et al., 2004). Before that, the paradigm *in the city* (since the beginning with Barcelona, 1979) dominated this research area, with some occurrence of the paradigm *of the city* since 1997 (Belant, 1997). The three paradigms show to be increasing in the number of publications during the last decade, although the paradigm *in the city* is doing it faster than the others. This could result in an even larger gap between the number of publications focused on each paradigm.

Evidence suggests that the three paradigms are different according to disciplinary focus, research approach, type of analysis, and the main research objectives presented in their articles (**Figure 7**). As expected, categorization by discipline showed that the paradigm *in the city* is mostly focused in ecological research, the paradigm *of the city* in social-ecological research, and paradigm *for the city* in environmental policies, and also some social-ecological and social policies. Research approaches are similar among paradigms, the spatial approach of studies is the most common (e.g., *ecology in the city*: Hosannah and Gonzalez, 2014; *ecology of the city*: Bulleri, 2006; *ecology for the city*: Santos and Freire, 2015), followed by spatio-temporal approach (e.g., *ecology in the city*: Castro et al., 1999; *ecology of the city*: Serre et al., 2010; *ecology for the city*: Storch and Downes 2011). Experiments and the interplay with temporal approaches are poorly represented in coastal urban ecology studies. Studies *in the city* presented mostly quantitative assessments, however, studies presented under paradigms *of* and *for the city* showed similar proportions between quantitative and qualitative analysis. The paradigm *of the city* has centered research on themes related to human adaptation (e.g., Wolsko and Marino, 2016, integrated research on disasters and climate change-induced migration with environmental psychology and the psychology of natural disasters), this topic also appears in the paradigm *for the city* in combination with city design, a consequence of the predominant focus on policy and planning implications of these studies. An example of human adaptations can be found in Villagra et al. (2016) who described the "resilience thinking" approach in urban planning, in order for a coastal city to adapt to extreme natural events such as tsunamis. Also, Conticelli and Tondelli (2018) proposed an urban regeneration of a coastal territory considering the local coastal landscape as a key element for boosting local sustainable growth.

When analyzing the whole database of coastal urban ecology articles, only 34 publications showed connections among citations, presenting a total of 24 interactions (**Figure 8**). These interactions varied in strength from one article citing a single article of the one included in our study, two cited the same article (Lopes et al., 2011; Chen et al., 2018), three cited the same article (Campbell, 2010; Washburn et al., 2013; Shepard et al., 2016), or four cited the same article (Campbell, 2010; Bertocci et al., 2017; Heery et al., 2018; Leclerc and Viard, 2018; Bugnot et al., 2019). Network analysis showed a marginal interaction among articles' paradigms. Here the paradigm *in the city* cited only seven *in the city* articles from a total of 16 citations, the paradigm *of the city* cited three articles *in the city* and one *of the city* from a total of seven citations, paradigm *for the city* cited only one article under the paradigm *of the city*. These results suggest that coastal urban ecology article citation have a subtle connection among publications, and it is not reinforced when the three paradigms are considered.

DISCUSSION

Coastal urban ecology encompasses a diversity of disciplines and research models aimed at understanding the links between the natural and built environments. Results show that coastal urban ecology has focused primarily on ecological studies and

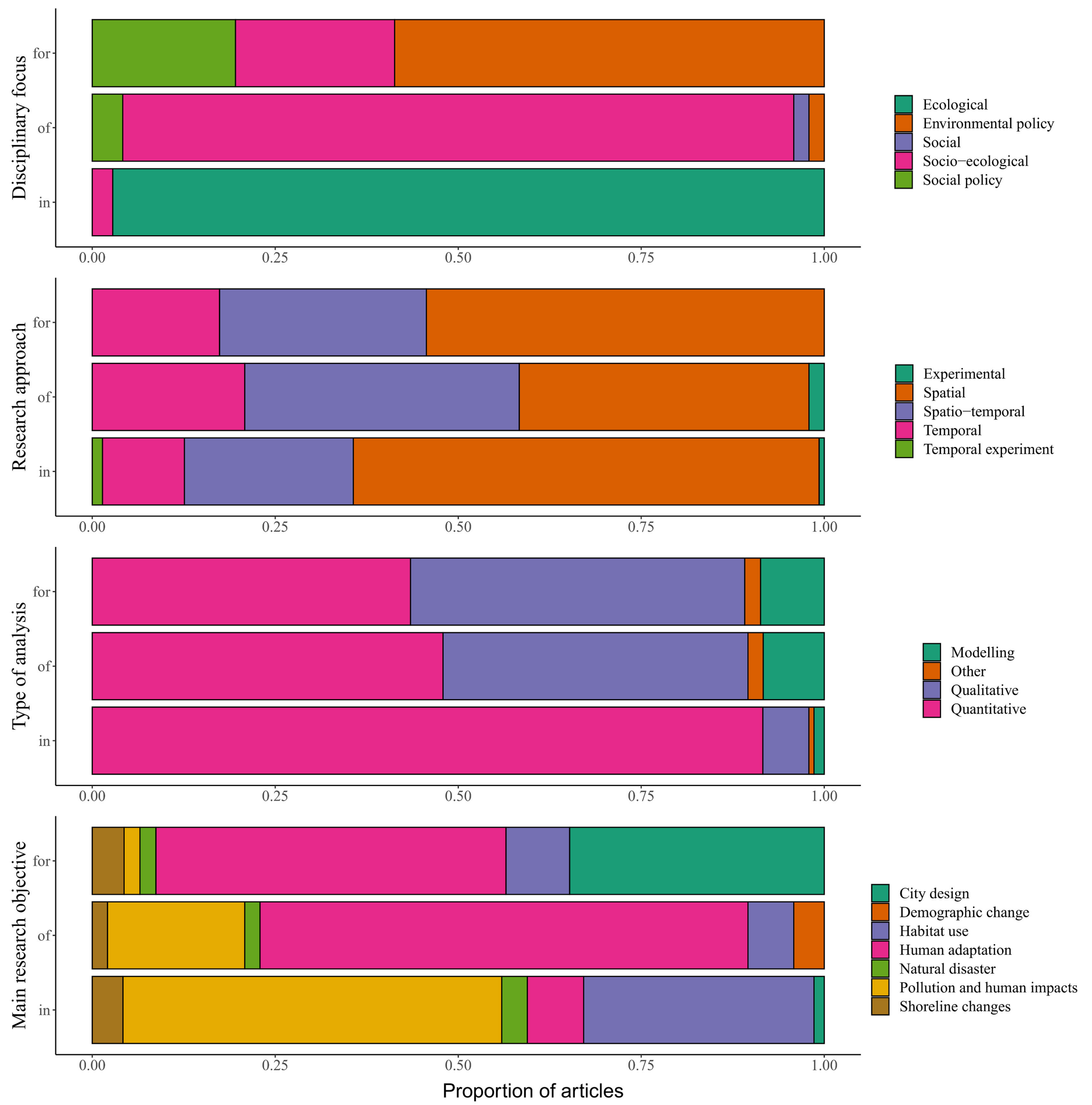

FIGURE 7 | Proportional contribution of categories. Articles in coastal urban ecology were categorized according to disciplinary focus, research approach, type of analysis, and main research objectives in coastal urban ecology studies ascribed to Picketts's paradigms *in*, *of*, and *for the cities*.

those studying physical characteristics of urban centers in coastal areas, dominated by research on pollution. However, there is an increasing contribution of studies on social dimensions. Studies that address coastal urban ecology from an *in the city* perspective have significantly increased during the last three decades. Interestingly, results show that coastal urban ecology is beginning to address issues which relate to planners and policy makers through some key studies on green infrastructure (Chen et al., 2015; Zhang et al., 2016; Conticelli and Tondelli, 2018), eco-cities (Surjan and Shaw, 2008; Wong, 2011), and sustainable cities (Pizarro, 2008; Song et al., 2016; Arif, 2017). Despite the diversity of research on coastal urban ecology, there are still important geographic and disciplinary gaps in research foci.

Coastal urban ecology research has drawn from ecological studies more than any other discipline (**Figure 3**). Even when it seems that social dimensions have been integrated slowly

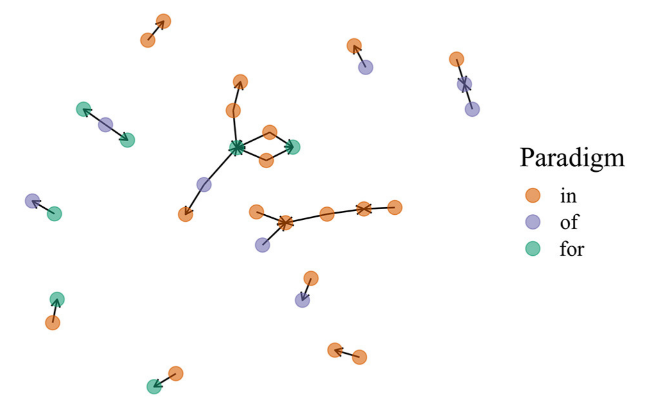

FIGURE 8 | Network analysis. Analysis for co-citations of articles presented in this coastal urban ecology review, considering the three paradigms proposed. Each dot represents a study and the color indicates the paradigms (*in*, *of*, and *for the cities*). Directed edges go from the article citing to the article being cited.

during the years under the knowledge of human-nature coupling (Liu et al., 2007a,b) and the importance to include people and their relationship with the urban environment (Redman et al., 2004), interdisciplinary studies are still infrequent. An interesting interdisciplinary line of research is emerging associated with designing new infrastructures in coastal cities aimed at the provision of sustainable alternatives as new habitats for protection and even promotion of biodiversity (Kates et al., 2001; Perkol-Finkel et al., 2018; Burt and Bartholomew, 2019). However, these interdisciplinary efforts have been performed in a few coastal areas (Morris et al., 2019), showing similar geographical bias.

Coastal urban ecology has centered mainly in understanding spatial patterns and variability, showing a bias toward short time scale research (**Figure 3**). Consequently, there is a shortfall in long-term dynamic perspectives in the study of coastal cities. Results demonstrate research is also biased toward quantitative approaches with few qualitative analyses (e.g., Giovene di Girasole, 2014; Cleland et al., 2015; Villagra et al., 2016; Guerrero Valdebenito and Alarcon Rodriguez, 2018). This supports the results which show little social science research based on methods such as grounded theory or ethnography, among others (Creswell et al., 2007). Coastal urban ecology would benefit from encouraging these long-term and disciplinary dimensions.

Many coastal urban ecology studies focus on pollutants. The focus on pollution has been maintained during the whole period analyzed, with 35% of total articles dealing with this issue. Accordingly, the effects of urbanization over sea breeze and the reactions of aerosols have had an important increase in this line of research (Castro et al., 1999; Mejia and Morawska, 2009; Shanquan et al., 2016; Pushpawela et al., 2018). A predominant focus on pollution is not difficult to understand in coastal urban ecology given urbanization and increases in CO_2 emissions (Cole and Neumayer, 2004). Water pollution also has an important number of articles published (27.7% from the total of articles that mentioned pollution), considering marine (23 articles: e.g., Noble et al., 2006; Wang, 2010) and river basin pollution (four articles: e.g., Abdul-Aziz and Ahmed, 2019; Mgelwa et al., 2019), both important elements in coastal environments.

Risk assessments toward natural disasters and particularly flooding represented approximately 18% of the studies (**Figure 4**; e.g., Goh, 2019; Patel et al., 2019), which were carried out mainly in the USA and Japan. Expansion of coastal cities undermine natural protection (Sherbinin et al., 2007), hence an increase in natural disasters and city's vulnerability (Chang and Huang, 2015). While research has been performed in developed countries, developing ones are the most vulnerable in terms of natural disasters in coastal zones, such as flooding events (Ogie et al., 2020) or in specific areas under risk of tsunamis (Villagra et al., 2016). This same tendency is repeated in relation to studies which address mitigation strategies, with projections to make cities more resilient to natural disasters (Serre et al., 2010; Watson and Adams, 2010; Aerts et al., 2014; Sutton-Grier et al., 2015; Morris et al., 2020) and even ecoengineered shoreline strategies as nature-based alternative design (Bergen et al., 2001; Mitsch, 2012; Morris et al., 2019; O'Shaughnessy et al., 2020). As a consequence, there is an urgent need to extend this type of research toward developing and mid-income countries.

Our review shows that research on coastal urban ecology has mainly focused in cities between 1 and 5 million people in 15 different countries. However, more than a half of articles have been performed in the USA, China and Australia (**Figure 2**). While results from these specific studies can be important to develop theoretical frameworks and assess specific impacts, the focus on these high GDP countries makes it hard to extend insights to other cities in developing and mid-income countries, where growth dynamics, institutional support and adaptive capacity are very different (Chauvin et al., 2017; Nagendra et al., 2018). For example, urban concentration (when country resources are over-concentrated in one or two large cities, raising cost of production of goods) is described as part of country development, and decreases as income rises (Davis and Henderson, 2003). This phenomenon is often presented in coastal cities, where there is a physical infrastructure capital. Urban concentration can be affected significantly by a range of political variables, including democratization, federalism, and whether a country was a former planned economy (Davis and Henderson, 2003). We therefore strongly advocate for the need to support programs for coastal urban ecology research in these settings. Research in cities smaller than 1 million inhabitants would extend the variety of conditions in terms of the size of the human group, transitioning to bigger cities, and configuration of environmental variables, considering by 2017 more than 60% of cities in the world have between 100,000 and 1 million inhabitants (United Nations, 2019, data compilation).

Research has been mainly performed in near-shore terrestrial environments, resulting in a lack of information in coastal-marine urban environments that reveals the limited integration in the coastal urban interface (seawater-land configuration and dimensionality). This bias can have negative consequences such as generating false dichotomies for conservation, where marine and terrestrial ecosystems could meet as two isolated systems (Bulleri, 2006), which can undermine the effectiveness and need for healthy marine ecosystems in urban areas (Bulleri, 2006; Shochat et al., 2006). It is key to extend research on the interaction between marine and terrestrial realms associated with urbanization.

Results show that more than half of the reviewed articles can be classified as belonging to the paradigm *in the cities*. Studies contributing to this paradigm have been growing in number, faster than the others, during the last years (**Figure 6**). This result synthesizes the main biases found in this review which relate to the predominant focus on ecological research, understanding urban impacts such as pollution, the non-human components, and in spatial and quantitative analysis (**Figure 7**). Only 20% of the articles in coastal urban ecology focused on interdisciplinary research such as social-ecological studies (included in the paradigm *of the city*). This represents an important research gap associated to the lack of social knowledge in a system where humans are both objects and subjects of urbanization, who use space to live, extract subsistence and non-subsistence resources, perform recreational activities, and deposit waste, among other activities (Weinstein, 2009). Because of that, a lack of research on people with nature represents the loss of understanding an integral part of the ecosystem (McDonnell et al., 1993; Rees, 1997; Collins et al., 2000), decoupling human dynamics and ecological processes of this urban ecosystem (Alberti, 2008). Lessons from urban ecology in other systems have shown the importance of transitioning toward these interdisciplinary dimensions. Accordingly, coastal research in urban areas must advance toward an urban sustainability-centered perspective, transdisciplinary in terms of focuses and approaches, with the ability to inform urban design and planning (Wu, 2014). Current imbalance among paradigms and the lack of interaction among research paradigms (**Figure 8**) can undermine urban coastal sustainability. Under Pickett's complexity of paradigms (Pickett et al., 2016), ecology *for the city* should include the knowledge generated by both *ecology in* and *ecology of the city*. In order to understand coastal urban ecological systems, coastal urban ecological paradigms need to build upon literature from each other.

While biophysical and ecological approaches to coastal urban systems are important, urban ecology necessarily operates in a human context. Results highlight the need for coastal cities to be seen from the point of view of people, their interaction with the environment and the implementation of concepts that contribute to sustainability in cities through public policies and planning. Developing regional learning platforms to address these dimensions should be a priority. Results of this review also recommend research needs to focus on the three paradigms equally. In addition, better consideration of the diversity of cities, the integration across marine and terrestrial ecosystems, and the inclusion of developing country coastal urban areas will allow to support ongoing urbanization trends and cultural settings in coastal zones across the globe. Clear research agendas that include trans-disciplinary collaborations will provide the opportunity to fill these knowledge gaps.

DATA AVAILABILITY STATEMENT

Q16 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: https://github.com/GiorgiaGraells/CoastalReviewGitandlt.

AUTHOR CONTRIBUTIONS

Q17 GG and SG contributed to design of the study. GG and NN organized the database. GG performed the statistical analysis and wrote the first draft of the manuscript. SG, NN, JC-D, NL, PP, and PM wrote sections of the manuscript. All authors contributed to conception and manuscript revision, read, and approved the submitted version.

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