A review on coastal urban ecology: Research gaps, challenges and needs

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# Abstract

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* which is consistent with the focus on 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 towards an ecology *of* and *for the cities*, in order to support coastal development in a diversity of countries and settings.

# 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 urbanisation 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 & 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 wellbeing (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, Wu 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 & Meyer 2001, Walsh et al. 2005), and organisms such as birds (e.g. Blair et al. 1996, Chace & Walsh 2006) or plants (e.g. Ulrich 1984, Donovan & 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 in 2017, 40% of the world’s population live less than 100 Km from the sea, and these cities have increased their population 6.6 times between 1945 and 2012 (Barragán and 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 (Benveniste et al. 2019, Torresan et al. 2008, Kumar et al. 2010). Despite recent interest on vulnerabilities, research has mainly focused on geomorphological contexts (Arns et al. 2017, Vitousek et al. 2017, [Luijendijk](javascript:;) 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 (Fig. 1), where the urban centre, 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. Grey-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 centres classification was modified from the United Nations (2014) and Barragán & Andrés (2015). This classification includes: 1) Non-urban areas, which have less than 100,000 inhabitants, 2) small cities, between 100,000 and 500,000 inhabitants, 3) medium cities, between 500,000 and 1 million, 4) large cities, between 1 and 5 million, 5) very large cities, between 5 and 10 million, and 5) 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 analysed 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 ( R Core Team 2020) using RStudio (RStudio Team 2019). For data analysis, packages tidyverse (Wickham 2017a), dplyr (Wickham et al. 2017), purrr (Henry and Wickham 2017), broom (Robinson 2017), and stringr (Wickham 2017b) 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 (Fig. 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 (Fig. 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 (Fig. 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 & Januszkiewicz 2019), and reviews 2.11% (e.g. Garden et al. 2006, Cohen et al. 2013, Branoff 2017).

General aspects 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. The most cited articles in this area have focus on urban impacts. For example, Castro et al. 1999 tested aerosol samples from urban, rural and coastal areas in Europe. They found air masses transported directly from the ocean and a clear seasonal dependence at both rural and urban environments, with minimum secondary organic carbon production during winter; Ip et al. 2007 collected surface sediments and sediment cores in an estuary and its surrounding coastal area. They found two hotspots of trace metal contamination at the mixed zone between freshwater and marine waters, which could be attributed to the deposition of the dissolved and particulate trace metals in the water column; and Stathopoulou & [Cartalis](http://apps.webofknowledge.com.pucdechile.idm.oclc.org/OutboundService.do?SID=6DlyjLg8BySqDjineDW&mode=rrcAuthorRecordService&action=go&product=WOS&lang=en_US&daisIds=28130916) 2007 used Landsat 7 satellite images in the thermal infrared to examine the thermal urban environment and urban heat island (SUHI) phenomenon in mayor urban areas in Greece . Social-ecological studies came second with 24.47%, where research has remained relatively constant during the years (an average 2.2 publications per year between 2005 and 2009, a 4.4 between 2010 and 2014, and a 3.8 between 2015 and 2019; Fig 3a). In this area, the most cited articles applied the Physiologically Equivalent Temperature (PET) index to thermal comfort studies: Johansson & Emmanuel 2006 with a discussion of the influence of street-canyon geometry on outdoor thermal in a coastal city (and they provide suggestions of how to improve [the outdoor comfort in a coastal city); and Cohen et al. 2013](javascript:;) with perceptions of human thermal sensation in the Mediterranean climate using subjective thermal sensation questionnaires. And environmental policies and planning studies, where its most cited articles have focused in developing guidelines for planning in order to contribute to the sustainability of the urban environment (Semadeni-Davies et al 2008 assessed the potential impact of climate change on water systems as an essential part of hydrological research; and Alcoforado et al. 2009 identified climatic needs in a coastal city with Mediterranean climate and discussed some of the problems that arise when applying climatic knowledge to urban planning).

Coastal ecology research has mainly considered spatial approaches searching for patterns based on differences in urban morphology. These spatial patterns include land cover land use (LCLU). (e.g. Hosannah et al. 2014 with the study of precipitation events in a coastal city, regarding aerosol particle size distribution) and coastal physical characterization (e.g. Kantamaneni et al. 2019 who considered beach width and coastal slope to determine the most critical physical parameters using GIS and created a map of coastal vulnerability. Study approaches have slowly included temporal dimensions since 1996 (Fig. 3b) Spatio-temporal studies included articles such as Grossmann (2008) who discusses the consequences of current global technological, organisational and economic developments for a port; and Clarkson et al. (1996) who described concentrations of benzene and toluene in New Zealand air including seasonality. Temporal studies included Jacobs (2011) with The Rotterdam Climate Proof program, which aims to ensure Rotterdam “climate proof” by 2025. through the implementation of new technologies and enhancing the safety and the quality of life in the city; and Priestley et al. (2018) with an inorganic and organic compounds measurement, where concentrations show changes during the day and could be affected by photolysis. In addition, experimental approaches through time included articles such as the study of Chabas et al. (2015) who simulated mechanisms involved in the weathering of the materials using an interaction chamber of environmental materials (CIME), obtaining the first results of the impact of gaseous pollutants on cultural heritage; and the study of Leclerc & Viard (2018), who studied how swimming predators influenced the early development of fauna associated with floating pontoons in marinas.

Quantitative studies have dominated the literature during the past 20 years and have focused on ecological approaches. For example many studies have assessed the measurement of polluting particles: Decelis & Vella (2007) determined the presence of compounds of butyltins in outdoor settled dust collected from several sites on the island of Malta, demonstrating the importance of the presence of this contaminant in the coastal urban environment and not only in seawater and on marine biota; and Theodosi et al. (2018) studied PM2.5 composition and its sources in aerosol samples, where the mayor source of contaminants was biomass burning. Qualitative studies represent 20% of the articles and these are mostly centered in using a social-ecology approach (e.g. Cleland et al. 2015 interviewed men and women from rural Tasmania and found that some urban environmental constructs were important, but some of them not: road safety or others not considered relevant- personal safety related to crime, availability of walkable destinations, or aesthetics; Chen et al. 2015 made a detail description of green roofs in Taiwan, and proposed a design and implementation for a coastal city), or focus on policy (e.g. Guerrero Valdebenito & Alarcon Rodriguez 2018 described tensions and threats to traditional small-scale artisanal fishing giving the coexistence with larger urbanized systems such as mega infrastructures, ports and cities. They propose to understand the socio-spatial transformation processes of coves, and their adaptation strategies to the effects of the neoliberal development model in Chile; Serre et al. 2010 described solutions that cities are using or will be able to use in the near future to anticipate the effects of global warming dealing with flood management, considering different types of flooding: fluvial, coastal, estuarial and pluvial). Modelling studies which include simulation of urban conditions, have begun to emerge in the past six years (Fig. 3c), these studies focus on a variety of issues such as urban heat island (Stathopoulou & [Cartalis](http://apps.webofknowledge.com.pucdechile.idm.oclc.org/OutboundService.do?SID=6DlyjLg8BySqDjineDW&mode=rrcAuthorRecordService&action=go&product=WOS&lang=en_US&daisIds=28130916) 2007 examined the thermal urban environment and urban heat island phenomenon in mayor urban areas in Greece), visualisation of realistic flooding scenarios (Su et al. 2019 related infiltration, sewer rehabilitation, and groundwater flooding in coastal urban areas), and use approaches which include ecology: social-ecology (Sahal et al. 2013 used of macro-simulators with graph-based and micro-simulators with multi-agent-based to select shelter points and choose evacuation routes for pedestrians located on the beach. With this, they showed evacuation capacities assessments to develop evacuation plans in case of tsunamis in French riviera; Song et al. 2016 analyzed urban environmental benefits among China’s prefectural cities. They divided cities in relatively developed group and cities in the undeveloped group, then defined areas of urban environmental benefits, and developed an assessment index system. To that year, they declared urgent for China to promote balanced improvement among areas of urban environmental benefits and between types of cities) and environmental policies (Alcoforado et al. 2009 by mapping Lisbon's physical features using a GIS with Digital Terrain Model, data of urban roughness, and Landsat image and field work; Storch & Downes 2011by quantifying current and future city-wide flood risks, combining climate change scenarios with urban land use scenarios).

When looking at the main research objectives it is interesting to note that the study of pollution and human impacts have dominated the literature (Fig. 3d). These articles mainly focus on the effects of stressors over coastal urban ecosystems and cities (e.g. Capaldo et al. 2000 simulated the atmospheric aerosol size/composition distribution presenting an approach to the modeling of the mass transfer of semi-volatile species; and Jartun & Pettersen 2010 collected sediments from urban stormwater runoff and analyzed for the content of various contaminants, showing that several active pollution sources are supplying the runoff systems). Habitat use (e.g. Holloway & Connell 2002 found a difference between fixed and floating structures in benthos; Eguchi et al. 2010 estimated abundance and survival rates for green turtles (*Chelonia mydas*) in a highly industrialized bay; Winzer et al. 2019 studied the geographical distribution, host species, impacts and management in Australia of the plant fungus *Austropuccinia psidii*) and city design are less frequent, but they have been increasing in the last 10 years (e.g Alcoforado et al. 2009 developed a series of climatic guidelines for planning, identifying climatic needs in a coastal city with Mediterranean climate and discussing some of the problems that arise when applying climatic knowledge to urban planning; Papatheochari & Coccossis 2019 provided a methodology for the development of a decision making tool, based on multi-criteria analysis and explores local stakeholders' perceptions in terms of priority actions for waterfront development).

According to study models (Fig. 4), a significant number of publications focused on physical aspects (48.10%) such as pollutants and risk towards natural hazards (e.g. Buggy & Tobin 2008, with a study of metals in surface sediment of an urban estuary; Dominick et al. 2018, with a characterization of airborne particle in a coastal-urban environment). The second most frequent study model was biological, centred on specific species (21.94%). In this group birds were the most studied (e.g. Kalinowski & 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), followed by invertebrates (marine: Galimany et al. 2013, ribbed mussels; Eddy & Roman 2016, epibenthic invertebrate species; and terrestrial: Bizzo et al. 2010, a drosophilid; Reyes-López & Carpintero 2014, ant communities) and plants (e.g Schwartz et al. with the study of rare plants 2013; Grisafi et al. 2016 with two species of Tamarix, Oliveira et al. 2019 with the endangered tree brazilwood), leaving other marine species such as fishes (e.g. Naidoo et al. 2016, Mugil cephalus; Bolton et al. 2017, fish community) behind. Studies centred on ecosystems (Ehrenfeld 2000, wetlands; Branoff 2017, mangroves), social (e.g. White et al. 2013, people who visit natural areas; Burger et al. 2017, perceptions of avian resources and beach restoration) and social-eco-technological systems (e.g.Wong 2011, Eco-cities in China; Conticelli & Tondelli 2018, a proposal for the coastal landscape) showed fewer articles published (less than 10).

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 less than 100,000 inhabitants presented only 10% of articles. These are dominated by articles from the USA (e.g. Kalinowski & Johnson 2010, Wolsko & Marino 2016).

Research in coastal urban ecology has focused mostly in near-shore terrestrial environments, presenting more than 68% of articles (e.g. Parzych et al. 2016, urban environments; Günel 2018, anthropogenic constructions; Callaghan et al. 2018, green areas; and Pinheiro & Hokugo 2019, and urban watersheds). Intertidal areas presented 17.30% of the publications (e.g. Jonkman et al. 2013, coastal defences; Kuwae et al. 2016, estuarine and shallow coastal systems; Naidoo et al. 2016, estuarine mullet in an urban harbour; and Greenwell et al. 2019, predation on a threatened coastal seabird), near-shore coastal benthic 3.38% (e.g. Holloway & Connell 2002, studying flooting structures in benthos, they found a difference between fixed and floating structures; Eddy & Roman 2016, studying epibenthic invertebrates they found that in this habitat, species assemblages and diversity differed significantly between wave-exposed and wave-protected sites; Bolton et al. 2017, studying trophic consequences of lighting on marine trophic interactions on fishes;Heery et al. 2018, studying spatial distribution patterns and habitat-use of the giant Pacific octopus (*Enteroctopus dofleini*), and those pelagic environments near the coast only 1.69% (mostly sea water studies: Zhen et al. 2007 and the use of ocean thermal energy; Wang 2010 and toxicity of cadmiun in various trophic saltwater organisms; Williams et al. 2016 microwaves in deep sea). 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).

## Coastal urban ecology *in*, *of*, and *for the city*.

Paradigms *in*, *of*, and *for the city* have been addressed globally (Fig. 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 & Roman 2016, Maguire & 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, Peng et al. 2011, Li et al. 2017), which is the highest number of papers in a country which addresses this paradigm.

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 subsequent tendencies (Fig. 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.

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 (Fig. 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 socio-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 (for example *ecology in the city*: Hosannah et al. 2014; *ecology of the city*: Bulleri 2006; *ecology for the city*: Santos & Freire 2015), followed by spatio-temporal approach (for example *ecology in the city*: Castro et al. 1999; *ecology of the city*: Serre et al. 2010; *ecology for the city*: Storch & 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 centred research on themes related to human adaptation (e.g. Wolsko & 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 adptations 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; and city design in Conticelli & Tondelli 2018 who proposed an urban regeneration of a coastal territory considering the local coastal landscape as a key element for boosting local sustainable growth) .

When analysing the whole database of coastal urban ecology articles, only 34 publications showed connections among citations, presenting a total of 24 interactions (Fig. 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 (Chen et al. 2018, Lopes et al. 2011), three cited the same article (Shepard et al. 2016, Washburn et al. 2013, Campbell 2010), or four cited the same article (Leclerc and Viard 2018, Heery et al. 2018, Bertocci et al. 2017, 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 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 (Fig. 3). Even when it seems that social dimensions have been integrated slowly during the years under the knowledge of human-nature coupling (Liu et al. 2007a, Lui et al. 2007b) 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 & 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 towards short time scale research (Fig. 3). Consequently, there is a shortfall in long-term dynamic perspectives in the study of coastal cities. Results demonstrate research is also biased towards quantitative approaches with few qualitative analyses (e.g. Giovene di Girasole 2014, Cleland et al. 2015, Guerrero et al. 2018, Villagra et al. 2016). 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 analysed, 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 & 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 CO2 emissions (Cole & 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. Wang 2010, Noble et al. 2006) and river basin pollution (4 articles: e.g. Mgelwa et al. 2019, Abdul-Aziz & Ahmed 2019), both important elements in coastal environments.

Risk assessments towards natural disasters and particularly flooding represented approximately 18% of the studies (Fig. 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 & 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 (Watson & Adams 2010, Serre et al. 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 towards 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 (Fig. 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 & 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 & 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 (Fig. 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 (Fig. 7). Only 20% of the articles in coastal urban ecology focused on interdisciplinary research such as socio-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 towards these interdisciplinary dimensions. Accordingly, coastal research in urban areas must advance toward an urban sustainability-centred 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 (Fig. 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.

# Conflict of Interest

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

# Author Contributions

GG, NN, JC, 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, 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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# Data Availability Statement

The datasets generated and analyzed for this study can be found in the CoastalReviewGit repository, https://github.com/GiorgiaGraells/CoastalReviewGit.

# Figures

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 3 categories: ecological paradigms *in*, *of*, and *for the cities*.

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 colour of the circle represents the size of the city given its population.

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

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.

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 colours from light to dark); Countries that not present coastal urban ecological articles are show in grey.

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* R2=0.656, p< 0.001, *of the city* R2=0.382, p< 0.05, *for the city* R2=0.460, p<0.05); colour areas represent the 95% confidence interval.

Figure 7. Proportional contribution of categories. Articles in coastal urban ecology were categorised 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*.

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

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# Table

Table 1. Classification of articles in coastal urban ecology.

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| Category | Classification | Description | Examples |
| Disciplinary focus | Ecological | Study of relationships and interaction between organisms and their coastal urban environment. | Tait *et al. (*2005), Smith & Munro (2010). |
| Social | Study of social behaviour, 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. | Dodman (2009), Cohen *et al.* (2013). |
| Environmental policy | Study of the environment with a focus in organization, law, regulations or policy solutions. | Alcoforado *et al.* (2009), Vye & Rousseaux (2010). |
| Social policy | Provides practical guidelines and principles to improve human welfare. | Guerrero Valdebenito & Alarcon Rodriguez (2018), Kuhnlein *et al.* (2003). |
| Study approach | Spatial | Focus on landscape, land cover or urban geomorphology changes. | Lim & Sodhi (2004), Cui & Yuan (2009). |
| Spatiotemporal | Landscape, land cover or urban geomorphology changes, including some changes over time on small scale. | Li *et al.* (2011), Grossmann (2008). |
| Temporal | Focus in changes over time. | Yu *et al.* (2019), Semadeni-Davies *et al.* (2008). |
| Temporal experiment | Focus in changes over time in a controlled environments and simulations. | Leclerc & Viard (2018), Chabas *et al.* (2015). |
| Experimental | Including all lab procedures. | Zhen *et al.* (2007), Charalambous *et al.* (2012). |
| Type of analysis | Qualitative analysis | Non-numerical descriptions and ethnographic studies. | Arif (2017), Gardner (2003) |
| Quantitative analysis | Collection and evaluation of measurable data of either social or environmental aspects. | Yamazaki, *et al.* (2007), Videla & Herrera (2017). |
| Modelling studies | Mostly computational simulations. | Sahal et al. 2013 , Santos & Freire (2015). |
| Main research object | City design | Mainly urban planning. | Kantamaneni *et al.* (2019), Alcoforado *et al.* (2009). |
| 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-Alvarez et al. (2018). |
| Habitat use | Variation in the distribution of species within cities. | Lim & Sodhi (2004), Reyes-Lopez & 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 *et al.* (2008). |
| Social | Social space comprises bioclimatic comfort, demographic, human activities and culural heritage, perceptions, public health, and sustainable development. | Human activities and culural heritage: Cleland *et al.* (2015).  Perceptions: Nunkoo & 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 & 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. | Whisson *et al.* (2015), Watson (2015). |
| Intertidal | Estuaries, deltas, mangrove forests, coastal lagoons, salt marshes, other coastal wetlands, marinas and ports. | Kuwae *et al.* (2016), Jonkman *et al.* (2013) |
| Near-shore coastal benthic | Seagrass beds, artificial structures and soft bottom environments above the continental shelf. | Eddy & 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 (1996), Dominick *et al.* (2018). |