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Urbanization indices development and use in the coastal ecological realm: a review

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Human populations are moving to coastal regions at a rapid pace, and growing populations are creating large impacts on ecological systems through the development of infrastructure and resource use. Urbanization indexes (UI) are used for a wide range of purposes related to understanding how urban growth impacts both urban development and ecological systems. Most UIs are developed using different factors, and there is a lack of standardization across studies even within the same study system. We reviewed the existing literature that utilizes a UI in the context of ecological questions within coastal regions to determine their utility in assessing how ecological impacts vary across coastal environments and are useful in identifying how urban growth is affecting ecosystems and species. We found that existing variation in UI development hampers the ability to make comparisons across studies and systems. To more fully understand the impacts of urbanization we recommend that UIs used in future studies be standardized to facilitate comparisons across time and studies. We offer guidance on how this can be done.

KEYWORDS

urbanization, urban impacts, urbanization index, coast, beach, intertidal, ecological impacts

Introduction

Human populations are increasing exponentially, and urban growth is necessary to accommodate the associated spatial and resource needs of the population (Huang and Chen, 2005; NOAA). Globally, urban development is growing at a faster rate in low-elevation coastal zones, 10 meters above sea level or lower, than in any other area type (Seto et al., 2011). This urban growth is accompanied by a significant increase in coastal populations residing in these low-elevation coastal zones (Neumann et al., 2015). China, Africa, and India have undergone the highest rates of urban land expansion, and North America has experienced the largest change in total urban area size (Seto et al., 2011). With 40% of the population within the United States now residing in the USA's coastal regions, representing just 10% of the total available land mass (Barragán and De Andrés, 2015).

Globally, 2.15 billion people reside in near-coastal zones, with 898 million inhabitants in low-elevation coastal zones immediately adjacent to the ocean (MacManus et al., 2021; Reimann et al., 2023).

To accurately understand how urban development is influencing the environment, it is necessary to examine urban impacts within coastal and marine systems (Todd et al., 2019). Urban development produces a wide range of ecological impacts, including the alteration of land use and cover through resource extraction, increasing agricultural lands, and the building up of cities (reviewed in Pickett et al., 2011), with additional impacts on biogeochemistry, biodiversity, hydrological systems, and alterations to the local and global climate (Grimm et al., 2008; Wang et al., 2022; Sempere-Valverde et al., 2023; Sharma and Khan, 2023). Habitat degradation and modification are associated with urban expansion as coastal areas have increased infrastructure development to accommodate human population growth and resource needs. Urban and marine sprawl also facilitate increased effects of pollution, seen with sewage, runoff, temperature increases, and light and acoustic pollution (Alter et al., 2021; Gilby et al., 2023). Urban centers are additionally associated with increased levels of transportation and industry, creating sources of carbon dioxide and other greenhouse gas emissions (Molina and Molina, 2004; Pataki et al., 2006). Further contributing to urban climate change impacts is the increased areas of impervious surfaces, leading to altered albedo and an increase in radiative heat gain and heat capacity, allowing for higher minimum and maximum temperatures around urban areas, known as heat islands (Deilami et al., 2018; Xu et al., 2019; Ouyang et al., 2022). This increase in impervious surfaces additionally impacts the hydrological systems surrounding urbanized areas. Artificial alteration of streams, rivers, and associated water systems in conjunction with increased impervious surfaces can lead to the funneling of pollution from buildings and roadways into the water system (Pearson et al., 2018). The building of urban structures and the alteration to surrounding temperatures and water systems also impact local biodiversity by increasing patch fragmentation found around urbanized areas (Cadenasso et al., 2007). These alterations to the environment have led to a decrease in species richness and evenness of biotic communities and create conduits for the spread of disease between organisms (Paul and Meyer, 2001; McKinney, 2008; Chatelain et al., 2023; Sempere-Valverde et al., 2023), though the effects on diversity appear to be influenced by general climatic conditions in the region (Szabó et al., 2023).

Research surrounding these impacts of urbanization has focused primarily on terrestrial systems, demonstrating that in these systems, urbanization often reduces biodiversity. In contrast, research on the impacts of urbanization in marine systems has been much more modest, and suggests that urbanization can have more variable effects across marine systems (Alter et al., 2021; Samhouri et al., 2022; Hammerschlag et al., 2022). However, as in terrestrial environments, biodiversity loss in marine systems is caused by habitat fragmentation, pollution, and altered resource availability near urbanized areas (Graells et al., 2022). Despite these processes extending to marine systems, the study of marine urbanization lags behind the study of urban impacts in terrestrial systems (Graells et al., 2021).

Recognizing that different levels of urbanization can create a gradient of impacts, a large body of literature has examined ecological impacts of urbanization across urban gradients. In their review of this literature, McDonnell and Hahs (2008) note that only a small minority of the 300 studies they examined clearly describe how they quantified the degree of urbanization. However, this deficiency is not universal, and many researchers have attempted to more clearly quantify urbanization. One of the most widespread tools that has been used to accomplish this is the use of urbanization indices (UIs). These indices are used to assess and quantify the level of impacts coming from factors associated with urban areas and to measure how much each factor influences different sites or study regions. A variety of methods have been used to create UIs, and different methods may vary in their effectiveness. Yet the primary goal of UIs is usually the same: to aid in understanding urban impacts within ecological systems and to aid cities in policy-making decisions. To most effectively achieve this goal, it is important that UIs 1) are robust and repeatable, 2) can be applied across areas with different levels of urbanization, and 3) are effective in identifying the impacts of urbanization to inform the specific ecological objectives for which they were developed. The ability of UIs to deliver on these three goals may depend on the number and type of factors used in their development.

This review will provide a comprehensive assessment of the range of UIs that have been created for and applied to coastal marine systems. For the purposes of this review, we define coastal marine systems as areas up to 50 km inland along coastal regions. We will identify what systems UIs have been created for, the factors used to determine urban impacts, methods used to develop the UI, and how UIs have been applied in various studies. We then use this information to identify coastal areas where UIs are lacking and to identify common factors used across indices that provide best practices for UI development. We also provide guidance for standardizing UIs moving forward, an effort that will enhance the effectiveness of this tool in assessing ecological impacts of urbanization.

Methods

We conducted literature searches for UIs developed for and utilized in coastal ecosystems. Studies describing how UIs were developed, created, and/or utilized in ecological studies were searched for in the Web of Science database and in Scopus using the search terms “marine OR intertidal OR coast* OR beach” to identify appropriate ecosystems, combined with “urbani*ation index OR UI” to identify the inclusion of urban indices, and combined with “Ecology OR Zoology” as Web of Science Categories to ensure resulting articles were associated with ecological studies. Searches were carried out from January to November 2024, with additional searches conducted in May 2025, returning 1,946 scientific papers. These papers were then filtered to include only those that met the following criteria: 1) they used a UI, 2) they were conducted in coastal regions, defined here as within 50 km of the coast, 3) they explicitly described how they formulated their UI, and 4) the study had an ecological focus as opposed to using UIs to inform urban development or some other purpose. We identified a total of 56 papers that met these criteria and that were therefore included in this review.

From each of these 56 papers, we extracted information on where the UIs were utilized, countries and environments, factors used in the UI, purpose of the UI, and how the UI applied to the study. This information was then assessed across studies to identify similarities and differences between UIs. These assessments were done across studies utilizing similar factors, study habitats, and purpose.

Currently, there is a large base of UIs focused on aiding urban development. Out of the literature search conducted in this study, which highlighted an ecological focus toward urbanization development, several papers returned by the initial search had a primarily anthropocentric focus rather than an ecological focus, and so were not included in this review. The aims of these studies are often to identify how urban growth is impacting coastal cities, via coastline changes, to identify risks to coastal populations, or to examine human-mediated disturbances, such as litter. Much like the ecological studies, each of these studies uses different UIs and implements them in different ways. This is often done by either examining changes through time or across locations. For example, Wu et al. (2022) assessed how the shape of the coastline changed through time, largely through the development of artificial structures. While Rehman et al. (2022) examined the site-specific vulnerability to changes in coastal morphology and loss of coastal habitat, and Cevik Degerli and Cetin (2023) identified urban growth through time via the increase in artificial structures and land use changes. Kim et al. (2020) used the hemeroby index, which measures the distance between existing and anticipated natural vegetation in the absence of humans, to assess the level of urbanization. Overall, these types of studies highlight research that aims to address impacts by humans on humans as urban growth increases. While this is an effective use of UIs, they leave out the more interconnected ecological impacts found alongside urbanization, which is the focus of our review.

Results/discussion

Ecological uses of urbanization indices

Urbanization indices have been used to assess impacts of urbanization in coastal habitats in numerous areas around the globe (Figure 1). Below we highlight two broad ecological categories (habitat assessment and impacts on species) into which studies that employ UIs can be divided. We have categorized these based on similar intentions of the individual studies – if the primary

FIGURE 1
Global map of dots representing the location of each study included in the review. The dot color represents the habitat utilized in each specific study. Approximately 1/3 of existing studies come from sandy shores (yellow dots). The next most common, shown by green dots, are nearshore habitats (i.e., non-habitat-specific “coastal areas”). Estuary (light blue); reef (purple); stream (pink); mangrove (dark green); rocky shores (dark blue); salt marsh (red); coastal water (blue); dune (orange).

focus was on habitat, they were categorized into habitat assessment, and if the main focus was on effects of urbanization on a specific species, they were categorized into impacts on species. However, methods used to achieve the intent are typically different across studies within the same categories. We have grouped similar methodologies together within categories, but even so, each study primarily uniquely characterizes urbanization. As detailed below, methods used to quantify urbanization range from a distinct separation of urban vs. non-urban on a yes-no scale to an integration of a large number of factors, obtained from government databases, satellite imagery, and on-the-ground observations in order to quantify specific levels of urbanization.

Habitat assessment

Papers described in this category (listed in Table 1) use UIs to determine changes in specific study habitats, either through time or between sites as urbanization progresses in the defined habitat region. Several papers in this category had a conservation focus, using UIs in conservation planning, including studies on several Hawaiian Islands (Tsang et al., 2019) or across beach-dune systems on the Catalan coastline (Garcia-Lozano et al., 2020) and in Korea (Liang et al., 2024). Other studies used UIs to examine how urbanization changed specific habitat types, including mangrove forests (Nwobi and Williams, 2021), salt marshes (Li and Liu, 2022), and coral reefs (Mwadzombo et al., 2023).

As noted above, UIs varied in their level of complexity. The simplest form of a UI is to describe specific sites as either being urbanized or not urbanized. This yes-no approach was utilized by Nwobi and Williams (2021) and Mwadzombo et al. (2023) to identify their study sites. This distinction between sites was then used to analyze the study habitat's (mangrove and coral reefs, respectively) health as impacted by urbanization influences.

A somewhat similar approach was taken by Garcia-Lozano et al. (2020); however, they identified urbanization via percentages rather than simply yes/no. Areas near a city were identified as at least 60% urbanized, those near residential areas as at most 50% urbanized, and those on natural beaches as up to 30% urbanized. Several others have used analogous approaches to assess percentage increase in urbanized areas and associated decrease in natural areas (Hu et al., 2021; Alphan et al., 2022; Bao and Yang, 2022; Cinar et al., 2024). This categorization of sites to urbanization level is more specific than the yes-no approach, but the factors to quantify the percentage of urban influence were not well described and left room for interpretation. In addition, the categorization of urbanization here is still somewhat broad and does not account for the nuances of urbanization factors or the gradient of influences that urbanization can have.

A seemingly alternative approach to measuring urbanization itself was used by Li and Liu (2022). They instead measured the area of the desired habitat itself (marsh area at the mouth of two estuaries), assuming that loss of marsh area was due to an increase in urbanized area. Their study therefore used changes in the area of marsh habitat to understand how urbanization over time influenced habitat quality. While this approach has the benefit of directly measuring changes in the habitat of interest, it is possible that habitat changes through time may result from factors that are not directly tied to urbanization. For instance, in the particular case of salt marshes, in addition to the impacts of urbanization, marsh loss can also result from sea level rise (Crosby et al., 2016), changes in consumer pressure (Holdredge et al., 2009), disasters such as oil spills (Silliman et al., 2012), land subsidence (Cahoon et al., 1995), and increased storm activity associated with climate change (Miller et al., 2021). Attributing all marsh losses to urbanization may therefore misrepresent the impacts of urbanization. One approach to addressing this uncertainty is to conduct studies along a gradient of urban to more rural areas, where it is expected that there will be higher confidence that areas closer to urban centers will have more distinguishable impacts that can be attributed to urbanization itself.

Other studies have quantified the UI directly; however, the complexity of UIs varied greatly. A well-established sandy shore index that uses seven factors to define urban impacts has been developed by González et al. (2014). Several authors have used this index in different contexts. For instance, it was used by Liang et al. (2024) to test the impacts of urbanization on benthic quality by examining the correlation between the UI and seven different indices of benthic quality within their study region. They found that the correlations differed across each benthic index and also differed with time that sampling was conducted. The authors highlight the need to use control sites without human interference and similar morphodynamics as the study beaches. Other UIs are much more complex, incorporating a wide range of factors. For instance, Tsang et al. (2019) integrated 22 different factors covering a range of categories (urban land features, agricultural features, pollution sources, degree of fragmentation, etc.), mostly taken from online databases, to identify areas with high value for conservation.

Impacts on species

Overall, studies within this section (listed in Table 1) use a UI to gauge how urban influences impact species diversity and/or the abundance of focal species. These studies examine the influence of urbanization on species across a range of spatial scales, and in turn tend to differ across spatial scales in the complexity of the UI that is used. Studies that focus on a larger, more regional scale typically use a UI that subjectively decides if sites are urban or non-urban or alternatively uses one or three factors to characterize urbanization on a continuous scale. As with habitat assessment UIs, some studies that use UIs to examine impacts on species have also used a dichotomous yes/no scale. These studies have based this determination on one of several factors, such as the presence of only native vegetation with no evidence of urban modification, versus the presence of urban development (Yanes, 2012; Wedge et al., 2015; Selvam et al., 2025), or based on whether sampled areas were found within protected areas or at developed sites (Montefalcone et al., 2017; Abbate et al., 2019; Araujo-Lima et al., 2023). Alternatively, studies characterized regions as urbanized or

TABLE 1 Studies reviewed here that use urbanization indices to address ecological questions.

Habitat	Category	UI Factors	Reference
Coastal-Terrestrial	Habitat Assessment	Satellite land temperature imagery converted to land use types	Cinar et al., 2024
Shores	Habitat Assessment	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Liang et al., 2024
Shores	Habitat Assessment	Human modification (spatial extent of human impacts; roads, croplands, livestock, built up areas, human population density, mining, oil wells, wind turbines, night-time lights) and Anthropogenic litter density	dos Reis Cavalcante et al., 2024
Marine	Habitat Assessment	Level of Water Pollutant (High = Wet season, Low = Dry Season)	Mwadzombo et al., 2023
Coastal - Terrestrial	Habitat Assessment	Land cover (built up, agriculture, shrubland, bare, water) and SHAPE metrics	Alphan et al., 2022
Coastal - Terrestrial	Habitat Assessment	Landscape pattern index and Shannon diversity index	Bao and Yang, 2022
Coastal-Aquatic	Habitat Assessment	Land Type: Bare, Farmland, Forest, Shoreline, Water, Salt Flat, Paddy, Pond, Marsh	Li and Liu, 2022
Coastal- Terrestrial	Habitat Assessment	Landsat images to determine habitat type and human-constructed areas	Hu et al., 2021
Shores	Habitat Assessment	Disturbed sites (logging or clearance for construction activities, passage for boats) and undisturbed sites	Nwobi and Williams, 2021
Coastal-Terrestrial	Habitat Assessment	Distance to nucleus of municipality Urban = (located within the main nucleus of the municipality with at least 60% of urbanized hinterland – a 500 m wide strip along the coast), urbanized beaches (those found in residential areas outside the main nucleus of the municipality with a maximum of 50% of urbanized hinterland), and natural beaches (up to a maximum of 30% of urbanized hinterland).	Garcia-Lozano et al., 2020
Coastal-Terrestrial	Habitat Assessment	Anthropogenic landscape disturbance (27 variables). urban- population density, density of utility pipelines, road density. high, med., low intensity of urban land uses. open urban land use and impervious surfaces	Tsang et al., 2019
Shore	Habitat Assessment	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	González and Holtmann-Ahumada, 2017
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Beach sanitation, 4) Solid Waste on the Sand, 5) Vehicles driving on Sand, 6) Visitor frequency	Huang et al., 2025
Coastal - Aquatic	Impacts on Species	Land use/cover change detection maps	Selvam et al., 2025
Coastal - Aquatic	Impacts on Species	Land cover/land use (area covered by buildings), contrasted with the area delineated for the catchment of each watershed. Watersheds were classified in 3 urbanization levels: high >15% urbanized area, medium 15-5%, low <5%	Lemes da Silva et al., 2024
Shores	Impacts on Species	Rural Sites = Environmental protection area, Urban sites = Areas in city municipality	Araujo-Lima et al., 2023
Shores	Impacts on Species	Amount of tourist buildings (hotels, restaurants, camping sites, etc.), level of sewage discharge	Ben-Haddad et al., 2023
Shores	Impacts on Species	(1) Proximity to urban centers, (2) building on the sand, (3) beach cleaning, (4) solid waste on the sand, (5) vehicle traffic on the sand, and (6) frequency of visitors. For each category, a value from "0" to "5" is attributed, representing a gradient from the absence to the highest level of the impact, respectively	Checon et al., 2023a
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Checon et al., 2023b
Shores	Impacts on Species	1) Distance to urban centers in km, 2) Buildings on the sand, 3) Beach cleaning, 4) Solid waste, 5) Vehicle traffic on sand, 6) Visitor frequency	Schlender et al., 2023
Coastal-Aquatic	Impacts on Species	Landscape pattern index (patch level index, patch type level index, landscape level index), landscape percentage, patch density, landscape shape index, split index, tag index, Shannon	Yang et al., 2023

(Continued)

TABLE 1 Continued

Habitat	Category	UI Factors	Reference
Coastal-Aquatic	Impacts on Species	Pollution source, poorly urbanized - Polycyclic aromatic hydrocarbons (PAHs) coming from burning of sugarcane straw, intermediate urbanization - untreated and industrial sewage, highly urbanized - site located in port	da Silva et al., 2022
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitor	Gül, 2022
Shores	Impacts on Species	Sites quantified as Urban or Non-Urban	Veiga et al., 2022
Shores	Impacts on Species	Human Stressors: 1) Human Settlement (population density), 2) agriculture (Cropland, Livestock), 3) Transportation (Major roads, minor roads, two tracks, railroads), 4) Mining and Energy Production (Mining, oil wells, wind turbines), 5) Electrical Infrastructure (Powerlines, Nighttime Lights)	Barboza et al., 2021
Coastal-Aquatic	Impacts on Species	Typology, Salinity, Bottom Substrate Types, Red Mullet Body Condition	Gücü et al., 2021
Shores	Impacts on Species	Dynamic processes (wave-related exposure, sea level, wave height), social factors (distance from the shoreline to the coastal urban settlement, population density, type of urban settlement), beach morphology (substrate classification, conservation status of dunes), and evidence of coastal erosion (shoreline displacement, occurrence of coastal erosion indicators)	Siqueira et al., 2021
Marine	Impacts on Species	Land Cover; Bare Lands, Artificial Land, Agricultural Land, Forest. Land Use; Artificial Surface, Bare Surface, Cultivated Lands, and Forest	Tu et al., 2021
Coastal-Aquatic	Impacts on Species	Impervious Surface Levels	Li et al., 2021
Coastal-Aquatic	Impacts on Species	Human-related pressure: increased sedimentation, pollution, invasive species, climate change	Schäfer et al., 2021
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Gül and Griffen, 2020
Shores	Impacts on Species	% Watershed imperviousness, % Marsh Instream, % Marsh Downstream, Culvert Presence, % Hardened Shoreline, Mean Creek Width and Depth	Rudershausen and Buckel, 2020
Shores	Impacts on Species	Human population density, vegetation cover, nighttime light intensity	Orlando et al., 2020
Coastal-Aquatic	Impacts on Species	Stream discharge, flow, and water quality	Serra et al., 2019
Coastal-Terrestrial	Impacts on Species	Developed Sites = Impermeable surfaces (parking lots, condominiums, hotels, etc. located within 200m buffer), Rural Sites = in protected lands	Abbate et al., 2019
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Gül, 2019
Coastal-Terrestrial	Impacts on Species	Land cover and impervious surfaces, 4 distinct land cover intensities. also measured “clumpiness index”, degree of aggregation of land cover classes around sites.	Majewska et al., 2019
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Laitano et al., 2019
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Costa and Zalmon, 2019
Coastal-Aquatic	Impacts on Species	Upland Use (Agriculture, Developed, Forested, or Mixed)	Seitz et al., 2018
Coastal-Terrestrial	Impacts on Species	Land use degree index, split between positive and negative ecological factors, positive are natural features (woodland, grassland, wetland) negative (arable land, garden land, traffic land, residential land, industrial land. and the least used is unused land.	Yi et al., 2018
Marine	Impacts on Species	Stress factors were related to water quality alteration (eutrophication, pollution, hydrological changes, acidification, and turbidity). Urbanization level was listed as either protected, marine protected areas, low urbanized, or high urbanized.	Montefalcone et al., 2017

(Continued)

TABLE 1 Continued

Habitat	Category	UI Factors	Reference
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	Cardoso et al., 2016
Marine	Impacts on Species	Percentage of urban area coverage (urban areas, number of beach kiosks and restaurants, jetties, fish markets, storm sewers, ports, and the number of fishing sheds)	Portugal et al., 2016
Marine	Impacts on Species	Urban land use (density of single family homes with frequent boat docks). divided between urban and reference sites. reference creeks were "relatively undeveloped along surrounding shorelines and watersheds, primarily forested land cover" IDed with aerial photographs and in-field assessments (500m buffer around study creek) urban - housing and road density	Wedge et al., 2015
Coastal - terrestrial	Impacts on Species	Land use change, and national land cover database. Impervious cover, cropland, grassland and pasture, forest and shrubland	Jha, 2015
Shores	Impacts on Species	Population Density, Size of Urban Area, % Urban Cover, % Vegetation Cover, Distance from nearest sewage discharge site	Martins et al., 2014
Coastal-Terrestrial	Impacts on Species	Green space gradient	Galbreath et al., 2014
Shores	Impacts on Species	1) Proximity to Urban Centers, 2) Buildings on the Sand, 3) Cleaning of the Beach, 4) Solid Waste on the Sand, 5) Vehicle traffic on Sand, 6) Quality of Night Sky, 7) Frequency of Visitors	González et al., 2014
Coastal-Terrestrial	Impacts on Species	Human population density, number of dwellings, and vegetation index	Scherner et al., 2013
Coastal-Terrestrial	Impacts on Species	Pristine- localities with abundant native vegetation and no evidence of current urbanization or landscape modification. Human-impacted - localities with ongoing urban development with noticeable human-induced habitat alteration. Classification does not consider historical anthropogenic impacts.	Yanes, 2012
Coastal-Aquatic	Impacts on Species	Impervious Land Cover	King and Baker, 2010
Coastal-Terrestrial	Impacts on Species	Basin Land cover, Human Demography, Basin Infrastructure (24 Variables)	Coles et al., 2010
Coastal-Terrestrial	Impacts on Species	Population density, road density, percent urban land use/land cover, combined by taking the average of the standardized values. additional urban stressor variables used (81 variables across 5 categories; chemistry, habitat, hydrology, demography, riparian land use/land cover)	Purcell et al., 2009
Coastal-Aquatic	Impacts on Species	"City sites" are divided into city, estuary, and reference sites.	Wilson et al., 2008
Coastal-Aquatic	Impacts on Species	% Land Cover	Morgan and Cushman, 2005

Studies are divided generally into those that use urbanization indices for habitat assessment and those that use indices to assess the impacts on species.

not based on ease of access, such as on islands vs. mainland areas (Jha, 2015), or based on the level of urbanization that had occurred using high vs. low human population densities of the area (Veiga et al., 2022).

Studies using one factor to characterize urbanization continuously have primarily looked at land use/cover type as a proxy for the level of urbanization. Studies have done this differently, including using the level of impervious surfaces (King and Baker, 2010; Li et al., 2021), land use type (Seitz et al., 2018), or amount of non-natural area within a catchment (Morgan and Cushman, 2005) to determine UI level and predicted urbanization impacts. For instance, Galbreath et al. (2014) use the percentage of foraging zone green space (i.e., area that could be used as animal habitat) to determine a gradient of urbanization across their study sites. Similarly, studies using three factors also include land use/cover metrics but additionally include a metric of human population density as well as a local factor in determining UI levels, such as number of dwellings (Scherner et al., 2013) or intensity of night lights (Orlando et al., 2020).

In contrast to the approach described above for studies at large spatial scale, studies that focus on a smaller spatial scale generally create UIs using seven or more factors and typically include more site-specific factors. The most notable being the sandy shore index created by González et al. (2014) mentioned above, which uses seven factors to describe urbanization along the sandy shore. Factors included direct disturbances seen on sandy beaches, such as solid waste, mechanical beach cleaning frequency, and buildings on the sand, as well as more diffuse disturbances from the surrounding area, such as proximity to urban centers and quality of the night sky. Other UIs using around seven factors also include more site-specific measures of urbanization such as sewage outfall locations, jetties, number of fishing sheds, ports, etc (Martins et al., 2014; Portugal et al., 2016; Rudershausen and Buckel, 2020). Finally, Siqueira et al. (2021) used 10 factors to create their UI, covering a wide variety of categories, some of which were directly related to urbanization (human population density, distance of structures to the shoreline) and others that are not directly, but may be indirectly related, to urbanization (wave action, beach morphology, and coastal erosion). Finally, Purcell et al. (2009) took the development of UI to the extreme by using 81 variables across 5 categories, including chemistry, habitat, hydrology, demography, and riparian land use/land cover to assess urbanization and how this influenced benthic macroinvertebrates.

Several studies have used UIs to examine the impacts of urbanization on bioindicator species that are themselves benchmarks of urban impacts. For instance, several studies have used a UI developed by González et al. (2014) to assess urbanization level and then have correlated this with the abundance of bioindicator ghost crabs (Costa and Zalmon, 2019; Gül and Griffen, 2020; Gül, 2022; Checon et al., 2023a; Schlender et al., 2023). Other studies have done the same with bivalves (Laitano et al., 2019), sand bubbler crabs (*Scopinera globosa*) (Huang et al., 2025), or other crustaceans (Cardoso et al., 2016). Other studies have done this same thing, but have developed their own UI rather than using the UI developed by González et al. (2014). For instance, Ben-Haddad et al. (2023) assessed urbanization using the amount of tourist infrastructure (hotels, restaurants, camping sites, etc.) combined with the level of sewage discharge and examined how these correlated with the abundance of the bivalve *Donax trunculus*. Similarly, Barboza et al. (2021) combined several metrics of human stressors, including population density, agriculture, the presence of roads, railways (and other transportation components), mining, oil wells, wind turbines, and electrical infrastructure to assess urbanization. They then used these to assess ghost crab abundance as a bioindicator.

Call for standardization

As noted in our summary of both categories discussed above, there is considerable variation in the level of detail used to quantify urbanization. Some studies simply use the presence/absence of urbanization as a descriptive label rather than as a quantitative metric. Others quantify the level of urbanization but do so using only a single metric, such as land use type. Other studies use an intermediate number of factors, usually land use type with the addition of a population metric and an idiosyncratic local factor. Still, others use a large range of factors (7–10 or more) that integrate site-specific factors together with larger-scale, more general, factors. This is often accomplished by drawing on a wide range of data types that include both social aspects of human presence in the area and physical or biological conditions of the habitat (e.g., González et al., 2014; Siqueira et al., 2021; dos Reis Cavalcante et al., 2024). These factors may be accessible via public databases (e.g., population size) or may require measurements made by researchers at each specific study site. Thus, UIs differ broadly in robustness, in spatial and temporal coverage or data that they incorporate, and in the diversity and quantity of factors used to assess the specific level of urbanization within the study system.

Overall, UIs have been useful in assessing habitat quality and human impacts across the desired study systems and habitats. However, the different degrees of details offered by different UIs leads to different information being gleaned by the studies. UIs that use a yes-no approach are likely more subjective and ignore that urbanization is experienced as a gradient. At the same time, this approach offers a concise distinction in assessments between urban and rural sites that often facilitates the ease of subsequent analyses. On the other end of the spectrum, studies with UIs that use a large number of factors are likely more robust, but as the number of factors building into a UI increases, the potential for redundancy in different metrics increases. Whether this is problematic depends on how the UI is created and how it is subsequently used. If UIs are created by averaging together different component factors, then correlation is likely a minor issue. But if UIs are created by treating component parts as independent predictor variables in statistical analyses, then multicollinearity becomes an important issue when correlations between predictors exist. A variety of nuanced statistical approaches have been used in UI development and there likely is not a single statistical approach that would fit all situations and data types. When large numbers of factors are included and multicollinearity is a concern, researchers may need to use exploratory factor analysis to understand underlying structure within their dataset and principle component analysis or other statistical techniques to reduce dimensionality of their data.

The summary of existing UI studies given above highlights that while previous studies implementing UIs in an ecological context have had a range of purposes, some of which are very similar across studies, each individual study commonly establishes their UI independently and differently. For instance, both Abbate et al. (2019) and Portugal et al. (2016) examined the influence of urbanization on species richness and diversity within their ecological community of interest. However, Abbate et al. (2019) categorized land as either protected or developed as their estimated UI, while the UI of Portugal et al. (2016) integrated the percentage of urban area together with the number of human structures, including beach kiosks, restaurants, jetties, fish markets, storm sewers, ports, and fishing sheds. This idiosyncrasy in the development of UI complicates the comparison of urbanization impacts across studies. Similarly, this approach makes it difficult to implement previously established urbanization levels through time, even at the same site, to understand how urbanization or its impacts in an area have changed over time. For example, many studies described above compare urbanized and nonurbanized areas, treating urbanization as a binary factor. In these cases, increasing urbanization impacts through time as urban centers grow and develop would not be detectable using this type of yes/no index. Having a standardized UI for different habitats that treats urbanization as a continuous variable rather than binary and that draws on the same factors would remove these issues and would allow for greater comparisons to be drawn across studies and through time.

Currently, sandy beach habitats are the only system in which a standardized UI has been used. As noted above, González et al. (2014) created a UI based on seven measured factors: proximity to urban centers, buildings on the sand, frequency with which a beach was cleaned mechanically, solid waste on the sand, vehicle traffic on the sand, quality of night sky taken from an online database, and frequency of visitors. Each of these metrics was given a value from 0–5 based on a pre-defined level of categorization. They then standardized each of these to values ranging from 0 (natural) to 1 (urbanized) and then averaged these seven factors to yield an overall level of urbanization. This index was then applied to different sites within their study area. The clarity/specificity of this index and its ease of implementation at individual replicate study sites has led to its use by several other researchers across a variety of studies.

Studies that use this UI to assess habitat quality have addressed a variety of specific questions. The simplest way this index was used is by assessing the level of urbanization across seven beaches in Chile (González and Holtmann-Ahumada, 2017). However, in a more complex usage of this index, Liang et al. (2024) assessed beach quality in Korea as compared to seven additional benthic indices. Similarly, Checon et al. (2023a) assessed urbanization impacts across 90 different beaches in Brazil and correlated the González et al. (2014) UI with other benthic indices.

This index has also been used in addressing urbanization impacts on species within the sandy beach environment across a large range of sites. For instance, Checon et al. (2023b) assessed urbanization across 90 Brazilian beaches and then correlated those samples with the abundance of ghost crabs and polychaetes at their sample sites to assess the quality of those species as bioindicators. Cardoso et al. (2016) used this UI to assess crustacean, mole crabs, and beach hoppers abundance across 22 beaches. Additionally, Costa and Zalmon (2019) used this index to address how urbanization across their sandy shore sites has impacted the abundance of ghost crabs. Laitano et al. (2019) assessed how the different levels of urbanization seen on Argentinian beaches correlate with bivalve recruitment to the beach, and Gül and Griffen (2020) examined how claw size changed in ghost crabs at different beaches across a range of urbanization levels. The level of urbanization, as provided by this index, has also been used in comparison to other potential impacting factors, seen in Gül (2022) in assessing if urbanization or beach morphology more heavily influence ghost crabs. The use of this standardized UI has enabled these studies to examine how species react to different levels of urbanization in a way that is comparable both across sites within a study, but also across studies.

Some studies have used the template of the seven original factors in González et al. (2014) within their index, but have modified it to include additional factors or to remove factors. The most common change is seen in the removal of the quality of night sky measurement (Checon et al., 2023a, b; Costa and Zalmon, 2019; Laitano et al., 2019). The quality of night sky is a more diffuse factor and may not be pertinent to comparing beaches in close proximity that differ in urbanization impacts but occur under the same night sky. This factor is also somewhat removed from specific dynamics addressed by individual research questions that focus on conditions at individual beaches.

The ability to compare across UIs can depend not only on standardization of the factors that are used in UI construction, but also on the quality of the data that are used. For instance, data used to construct UIs is often drawn from government sources, including census data, GIS database information, land use planning, etc. The quality and detail of these data sources can differ considerably both within and between countries. The quality and detail of these data will in turn influence the accuracy and utility of the UI that they inform. These differences should be recognized both while constructing UIs and when making comparisons across studies that seemingly use similar or standard UIs.

While standardization is important, we recognize that UIs also need to capture nuances of both local environments and study purposes. For instance, coastal urban areas often draw considerable tourism, and this tourism can influence nearby ecological systems, both positively (e.g., through responsible ecotourism) and negatively. The consequences of different levels of urbanization may therefore depend on the intended uses of that urban environment. For instance, a coastal urban development that includes primarily private residences may have very different impacts than the same area developed with high occupancy hotels that facilitate high levels of tourism. Incorporating such variation in the type of urbanization may increase the utility of UIs. While not included in this review, indices that are developed primarily to inform urban development often account for these differences in types of urbanization, as they attempt to effectively manage human use of developed areas through the incorporation of green spaces, etc. These non-ecological UIs may therefore provide methodological insights that can be gleaned for developing UIs that have a more ecological focus.

Recommendations for future UI development

While a UI has been developed for sandy shores as described above, every habitat type would benefit from having a similarly standardized UI to apply across studies, across sites, or through time (Figure 2). While there are numerous habitat types within coastal environments, we will focus on intertidal habitats, such as mangrove forests, salt marshes, and rocky intertidal shores. Below we provide guidance on approaches and factors that may be most useful for developing UI in these coastal habitats. We acknowledge that some studies have already used UI to assess these intertidal habitats. For instance, Veiga et al. (2022) used a UI on rocky shores habitats in Portugal; however, they simply assigned shores as either “urban” or “non-urban” and did not develop a quantitative metric to assess the degree of urbanization. Similar approaches have been used for other intertidal habitats (mangroves, salt marshes) other than sandy shores.

Urbanization may impact intertidal habitats in numerous ways. We have separated these into six main categories: water quality, proximity to urban areas related to water, proximity to urban areas related to land, beachgoers, on-site disturbances, and diffuse factors. Table 2 includes a variety of factors that reflect urbanization in each of these categories. These can either be measured directly or indirectly using proxies for the metric of interest. Table 2 does not give an exhaustive list and there may be other factors that fall

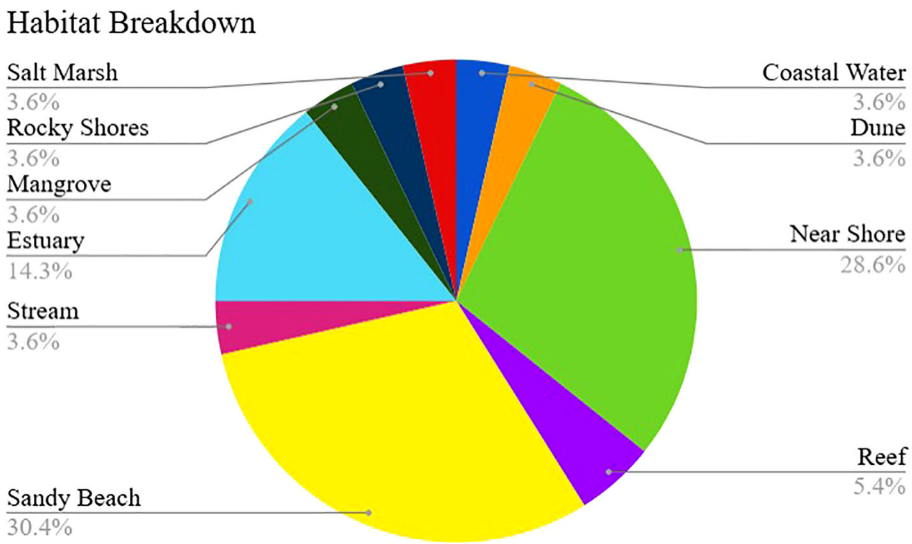

FIGURE 2
Pie chart with breakdown of habitats used in studies, colors that correspond to the map. Sandy shores (yellow) represent the majority of studies in the review. Near shore areas (light green) represent the second most abundant habitat type and include all studies that had a general study region incorporating coastal areas. Which includes a broader accumulation of habitat types; combinations of urban, agricultural, and other land types found in near shore regions.

under a category that may be more directly related to a specific study area or coastal habitat type.

González et al. (2014) utilizes factors across most of these main categories shown in Table 2 in their development of a sandy shore UI; however, they do not address any water quality metrics or proximity to urban factors from the water. The omission of these categories may be appropriate depending on the study area or species in mind. For example, González et al. (2014) were interested in analyzing the more terrestrial side (i.e., the upland area) of the shore. If instead, the study performed includes more interest in marine influence, such as species lower down in the intertidal on sandy shores, then component factors would need to include more water quality metrics. Thus, the recommendations below should be taken flexibly depending on the goals and purpose of the study.

We recommend, when creating a UI, to include at least one factor from each of these main categories in Table 2 because each of these categories addresses a different aspect of urbanization. However, there may be a need for balancing the diversity of factors included in a UI with redundancy in the factors that are included. For instance, while it may be desirable to include multiple factors from the same category (e.g., if the primary goal of a study is to understand the influence of urbanization on subtidal environments, then multiple metrics from the water quality and proximity to urban areas related to water may be desirable), we note that when adding multiple factors from the same category, the likelihood of multicollinearity increases. As an extreme example, the study previously mentioned by Purcell et al. (2009) included 81 variables in their UI, and the likelihood of correlations between this number of variables is high. As noted above, if each individual factor is averaged to generate the UI, as was done for the sandy shore UI by González et al. (2014), including large numbers of correlated factors may not be a statistical problem, but likely provides diminishing returns with each additional factor added. Additionally, the more factors that are included, the more likely that a single crucial factor included in the UI (i.e., the factor that drives the influence of urbanization on habitats or species) will be swamped by averaging across a large number of factors, and therefore will have less influence over the level urbanization indicated by the UI. Sampling effort and accuracy may also depend on how the information for these factors is collected. Some factors can be assessed using online databases, whereas others require on-site sampling. The frequency with which online databases are updated and the types of information available in each area may differ, and this should be considered to understand the quality and time scale available for the data found there. These considerations may influence which factors and how many factors from each category are best included in a UI, especially when the area examined is large enough that data must be pulled from multiple databases that may contain data collected using different methods.

The utility of including different factors in UI development will likely also depend on the level at which these factors are measured. For instance, trampling increases with the number of beachgoers and will be influenced not only by the number of beachgoers visiting an area, but by the amount of scientific research at the site, the number of restaurants in the area that harvest from the sites, etc. Simple counts of beachgoers (tourists) are likely to miss these more nuanced, but potentially more impactful, uses of a beach. Other factors that are non-point source disturbances may be important components of urban impacts. This may include factors such as air quality or sound disturbances. While these factors are important aspects of urbanization, their ecological impacts on the coast may be difficult to measure because they may be transient, or at least highly temporally variable, and may depend on factors such as wind

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TABLE 2 Potential factors that can be measured to assess urbanization impacts, either directly or as proxies, across six general categories of impacts.

1. Water Quality
Distance to Outfalls
Water samples (chemical and nutrient levels)
Shellfish closures, Beach closures (Proxy)
Waste treatment type (Proxy)
Proximity to agriculture (Proxy)
Proximity to river/estuary, sources of land runoff (Proxy)
Turbidity
Proximity to dredged area, time since dredging
2. Proximity to Urban (Water)
Distance to shipping lanes
Distance to canals and channels
Distance to marina, size of marina
Number of private boat docks
Fishing: number of fishing licenses, structures for fishing (<ns/>, distance to)
3. Proximity to Urban (Land)
Distance to buildings, type of buildings
Distance to roads and type of roads
Land cover/type, % impervious surfaces
Population size of nearest big city, distance to big city
Number of registered vehicles
On-site facilities
Number of hotels near site (Proxy)
Number of restaurants near site (Proxy)
Distance to conservation areas (inverse proxy)
4. Beachgoers
Annual number of people visiting
Number of residents in the area (Proxy)
Amount of parking near site (Proxy)
Dog-friendly (Proxy)
5. On-site Disturbance
Habitat modification
Trampling
Sample collection
Buildings on the beach
Cleaning of the beach
Solid waste or debris
6. Diffuse Factors
Air quality
Night sky quality
Sound

Urbanization indices may benefit by including factors from each of these categories, while the specific factor chosen may differ depending on habitat type (e.g., rocky shore vs. salt marsh vs. mangrove, etc.).

direction (for air quality) or on the presence of structures that serve as barriers (for sound). These factors may additionally depend not only on land-based urban impacts, but on marine activities, such as boating/shipping and water-based recreation.

Future studies may benefit from following a specific pattern in developing UIs. First, studies should clearly determine the purpose or goal of a UI within their study, the scale (e.g., individual beach or entire coastal region), the system that it will be applied to, and the data sources available to them to quantify aspects of urbanization, such as those shown in Table 2. Once these are clearly established, the next step is to select factors that will be used within the UI and to determine their relative importance, perhaps through preliminary study or drawing on information in the published literature. Based on these relative importances, factors could then be weighted differently within the UI.

A specific case-study may clarify how this pattern could be implemented. We will use an example that builds on the UI developed by González et al. (2014) for sandy shores that we highlight above. Many studies have used this UI to examine the utility of bioindicator species, including ghost crabs. In this context, the goal of these studies is often to assess the impacts of urbanization across different beaches on ghost crab population abundance. After measuring each of the 7 factors included in their UI on a scale of 1 to 5, González et al. (2014) then summed these and divided by the total possible (i.e., 35) to get a value from 0 to 1, where 0 is rural and 1 is highly urbanized. However, the seven factors used should not be equally relevant to ghost crabs. For instance, the quality of the night sky may have little impact on ghost crabs, while mechanical beach cleaning and physical disturbance from cars driving on the beach should both have large detrimental impacts by collapsing crab burrows. The remaining four factors may be intermediate in importance. In this case, we can use all of the original seven factors, while inserting an intermediate step of multiplying the initial field values of 1–5 by a weighting factor that ranges from 0 to 1. These weighted field values (now ranging from 0 to 5) would then be used to complete the UI by summing and divided by the total possible to get the level of urbanization that ranges from 0 to 1. A specific numerical example is given in Table 3, where two hypothetical beaches are compared using this approach.

The specific example given above could be replicated for other types of systems as well, such as mangroves, salt marshes, rocky shores, etc. However, this must be done on a case-by-case basis, depending on the goals of the study and the idiosyncrasies of the ecological system. Here we provide a specific hypothetical example

TABLE 3 Example calculations for weighted UI, using González et al., 2014 factors for a comparison of two hypothetical beaches.

Factor	Beach 1 In Field Scores[1]	Beach 2 In Field Scores[1]	Weighted Scale[2]	Beach 1 Adjusted Scores[3]	Beach 2 Adjusted Scores[3]
Mechanical beach cleaning	1	5	1	1	5
Vehicles on Beach	3	5	1	3	5
Frequency of Visitors	3	4	0.7	2.1	2.8
Buildings on Beach	4	4	0.3	1.2	1.2
Proximity to Urban Centers	4	3	0.3	1.2	0.9
Solid Waste on Beach	5	3	0.3	1.5	0.9
Quality of Night Sky	5	1	0	0	0
Total[4]	25	25		10	15.8
Final UI[5]				0.286	0.451

[1]Assumed hypothetical values; [2]Values assigned based on anticipated importance for ghost crabs; [3]Values calculated by multiplying field scores by weighted scores; [4]Calculated as sum of values for all factors; [5]Calculated by dividing the total sum of adjusted scores by 35, which is the total score possible for the seven factors.

of how this could be done in salt marsh habitats. We noted above that salt marsh habitats can be degraded through both the impacts of urbanization and through other non-urbanization impacts (sea level rise, invasive species, etc.). The majority of studies on UI in salt marshes examined here focused on nekton, since salt marshes are important nursery grounds for fish and other nekton (Minello et al., 2003). These organisms can be strongly influenced by pollution from urban industrial activities (Reichmuth et al., 2009). If we assume therefore that our goal was to develop a UI to examine chemical pollution in saltmarshes from urban activities, we could proceed by selecting a single factor from each category given in Table 2 that should be important in chemical pollution. For instance, we could select proximity to sources of land runoff from industrial processes (category 1), in-field observations of the numbers of anglers fishing in the marsh of interest (category 2), percent impervious surfaces that would facilitate pollution runoff (category 3), category 4 (number of beachgoers) is likely to be less important for the question examined here and is further already captured by quantifying anglers, the proportion of the marsh that has been drained, diked, or otherwise modified (category 5), and finally, category 6 (diffuse factors) are also likely to be less important for the question examined here and so could be skipped. Once each of the metrics is selected, a 1–5 scale should be determined *a priori* for each one. For each of the factors chosen, this can be easily done by selecting cutoffs (e.g., ≤ 20% impervious surface = 1; 21 ≤ 40% impervious surface = 2; etc.). The next step is to use this scale to determine the in-field score for the factor in each category. These in-field scores would then be modified by multiplying each by the weighted scale (also determined *a priori* based on the purpose of the study). Calculations would then proceed as shown in Table 3. In this way, researchers would be able to use their UI to assess the specific purpose of the study.

The recommendations given in the preceding paragraphs provide a standardized methodology for developing UIs that are quantitative and sufficiently uniform to enable comparison across sites and even across studies. At the same time, this framework allows for sufficient flexibility to meet study- and system-specific requirements by enabling researchers to include both the type and number of desired metrics that make sense for their study system and questions. And while the use of different metrics in individual UIs across studies would limit the ability to quantitatively compare urbanization across studies where UIs are not identical, the general structure and meaning of different UIs created using this approach would still be similar enough to enable general qualitative comparisons (i.e., all UIs would be continuous rather than categorical, each would use a common scale, etc.).

Conclusions

Coastal environments present unique challenges when assessing the impacts of urbanization for at least three reasons. First, human population growth is occurring more rapidly in coastal regions than anywhere else. Second, coastal regions are comprised of diverse ecological habitats, each with unique susceptibilities to human impacts, but each also with unique contributions to ecosystem stability, economic success, and human wellbeing. Third, urban impacts in coastal regions stem from both terrestrial and aquatic human activities. Given the complexity of this situation, UIs are extremely helpful tools that can help to reduce dimensionality and enable comparison across contexts and locations. The current use of UIs, however, is unstandardized. This inhibits the comparison of urban impacts across studies, across time, and within and between habitat types. Standardizing UIs across specific habitats would facilitate these comparisons and would therefore accelerate efforts to understand the impacts of urbanization on coastal and marine habitats. In addition, UIs are needed across a broader range of habitat types within coastal systems in order to aid in the overall understanding of how urbanization is affecting the diversity of coastal habitats around the world and to allow for a more succinct way to identify and quantify urban impacts. The suggestions and guidance that we provide for UI development, if followed, would result in UIs that are more useful, more standardized, and more comparable across studies and systems.

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