Biodiversity Analysis in Los Angeles (BAILA)

NATURAL HISTORY MUSEUM
LOS ANGELES COUNTY

The Nature Conservancy

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Table of Contents

Executive Summary

This report provides a description of the Biodiversity Analysis in Los Angeles (BAILA) carried out by the Natural History Museum of Los Angeles County (hereafter "the Museum") and The Nature Conservancy (hereafter "the Conservancy"). It provides details on several aspects of BAILA, some of which are covered only briefly in the scientific journal article by the same authors (Li et al. 2019; available at https://www.scienceforconservation.org/products/BAILA). In particular, this report provides more information on why we conducted this analysis, how the partnership between the Museum and the Conservancy was formed, how the Core Team that conducted the analysis was organized and functioned, how a volunteer Scientific Advisory Group and a broad and numerous group of other stakeholders provided input and guidance that helped shape the analysis, and how the framework we used to conduct the analysis was developed. This report also briefly summarizes the results of the analysis and discusses how the framework used for BAILA may be used for biodiversity analyses of other metropolitan areas around North America and across the globe. Further details and additional discussion on the results and their implications, and on the applicability of the framework to other cities, can be found in Li et al. (2019), and in the data and other supplementary material posted online at https://www.frontiersin.org/articles/10.3389/fevo.2019.00277/full#supplementary-material and https://www.scienceforconservation.org/products/BAILA-data.

The Greater Los Angeles area is located within the California Floristic Province, one of just 36 biodiversity hotspots recognized worldwide (Myers et al. 2000). The area supports a surprising diversity of plants, animals, and other organisms, but the abundance and diversity of native species within the region have been sharply reduced by urban development and collateral habitat destruction and fragmentation. Studies of small sites indicate many of its parks, open spaces, and hillsides contain native plants and a variety of animals and that its street trees, front/backyard gardens, vacant lots, restored school yards, flood control channels and rivers provide important habitat for plants, insects, reptiles, mammals, and birds (Hogue 1993, Eversham et al. 1996, Rudd et al. 2002, Del Tredici 2010, Cooper 2011, Kowarik 2011, Sahagun 2012, Clarke et al. 2013, Clarke and Jenerette 2015, Rupprecht et al. 2015, The Nature Conservancy et al. 2016). Broadly speaking, a mosaic of novel, rehabilitated, restored, and remnant habitats are found across the urbanized Greater Los Angeles area today. It has been difficult, however, to gain a better understanding of which plants, animals, and other organisms were present, and how they were distributed across the region. This was especially true for the most urbanized residential, commercial, and industrial areas and the zones dominated by highways and other infrastructure, areas that are commonly thought to harbor few if any native species, but which scattered studies suggested might hold more wildlife than had been suspected.

Fortunately, within the past few years, key conditions became ripe for conducting an analysis that could reveal more about the region's biodiversity. The Museum had begun building a focus on urban biological diversity in 2007 and the Conservancy independently started a Los Angeles urban biodiversity conservation program in 2012. Soon after that, it became clear to staff from the Museum and the Conservancy that their organizational strengths were complimentary and a strong working relationship between scientists from both organizations was forged through a series of three jointly organized workshops on biodiversity in Greater Los Angeles held in 2015 (Sloniowski 20155a, 2015b). Those three workshops focused, respectively, on enhancing the understanding of Greater Los Angeles' biodiversity, enhancing conservation of the region's biodiversity, and enhancing people's appreciation of the region's biodiversity. The participants at the first workshop, stakeholders from a variety of disciplines and from across the region, enthusiastically endorsed the launch of a regional analysis of biodiversity. In the meantime, community science (also known as "citizen science") programs, many of them led by the Museum, and newly created social networks and mobile applications like iNaturalist and eBird, were enabling the collection of data on plant and animal occurrences at a pace and scale unimaginable just a decade before. These data were freely available for use. Inspired by the call of the participants at that first workshop in 2015, and the availability of occurrence data collected by community scientists across the region, the authors of this paper formed a Core Team in 2016 to conduct the Biodiversity Analysis in Los Angeles, which we abbreviate as "BAILA." We were also given valuable guidance from a volunteer Scientific Advisory Group, and from a broader and more numerous Stakeholder Group from across the region, who we invited to several workshops, and later to presentations on preliminary results (see Figure 4, Structure of BAILA Team).

To carry out BAILA, we first defined our study area (Figure 1) as the urbanized portion of Los Angeles County south of the San Gabriel Mountains. This area covers 3,208 km^2, includes 80 incorporated cities and 69 unincorporated neighborhoods, and is home to more than 9 million people. After investigating available frameworks for biodiversity analyses and realizing that none were appropriate for assessing the entirety of a large metropolitan area, we decided to create our own framework in a way that would be relatively simple to undertake, use data from public sources and community science efforts, and be broadly applicable to other urban areas throughout the world. Our aim was to provide planners and conservationists with information they can use to quickly evaluate the structural and biological variation within Greater Los Angeles and also a methodology that could be efficiently implemented in other urban areas. We would also like to better understand the patterns of plant and animal distribution across the region in relation to important physical, climatic, built environment, and social variables that shape the urban landscape.

We selected the U.S. Census Block Group as our basic geographic unit for analysis. A Block Group is intermediate in size between the U.S. Census Tract and the U.S. Census Block. It represents a cluster of Census Blocks, which are often the same as city blocks. A Block Group is generally bounded by roads, natural features, or political boundaries and often approximates neighborhood boundaries recognized by local residents.

The urban biodiversity assessment framework we then developed combines a customized hierarchical urban habitat classification scheme with community science-generated species occurrence data, such as those available from iNaturalist and eBird. The hierarchical urban habitat classification is based on publicly available data on the physical and anthropogenic environment. For BAILA, we used 18 physical and anthropogenic variables which included: (1) climatic variables such as average and maximum temperature and precipitation, (2) physical variables such as elevation and slope, (3) land cover values such as forest and grassland cover, (4) built environment variables such as percentage of impervious area (buildings and pavement), and (5) social variables such as human population density and traffic density (see Table 1). Using cluster analysis, we were able to classify our study area into nine urban habitat types (see Figure 5). We then assessed relationships between these urban habitat types and species occurrences using research-grade data on all types of living organisms (plants, animals, fungi and others) that had been reported to iNaturalist between January 1, 2010 and September 15, 2017. As an aside, community scientists are working so diligently in our region that by the time we finished writing this report in July 2019, the number of research-grade occurrences reported to iNaturalist had tripled.

We gave a name to each of the nine urban habitat types that reflects its geographic location and an additional distinctive feature of the type:

Type 1: Low development with natural vegetation
Type 2: Dams, reservoirs, and wetlands
Type 3: Foothill areas
Type 4: Urban parks and open space
Type 5: Valley arterial areas
Type 6: Valley less-developed areas
Type 7: Basin less-developed areas
Type 8: Most-developed areas
Type 9: Furthest from regional parks with natural vegetation

We assessed the distribution of the iNaturalist occurrence data across the entire study area and between the different urban habitat types. We found that there were large numbers of native species even in the most urbanized types. For example, more than 200 native species were observed in Type 5, even though this type covered one of the smallest total areas among the nine types. We also found significant differences in distributions of some species between the nine types. Greater numbers of total occurrences and larger numbers of species were found in the less urbanized types (Types 1, 2, 3, and 4). Some species were found across all nine types, while some were restricted to a subset of types or even to a single type. This information can be used to generate hypotheses and guide new research in understanding the mechanisms responsible for driving species distributions in Greater Los Angeles. It also provides insights for on-the-ground conservation management and planning regarding what environments are needed for species to survive in urban areas, where to implement conservation projects, and where additional community science surveys are needed.

We carried out BAILA with the aim of both increasing the understanding of biological diversity and its distribution across Greater Los Angeles and informing efforts to enhance biodiversity conservation in the region. The Conservancy is already using the results of BAILA to conduct spatially explicit analyses of how biodiversity of native species might be enhanced by the use of “green” stormwater infrastructure at sites across the region where new and upgraded facilities and projects have been proposed (Wise 2008, Chau 2009, Jayasooriya and Ng 2014, Chini et al. 2017, Porse et al. 2017). We hope that you, our readers, will also use our results to inform the conservation, infrastructure and land use planning, and implementation projects that you plan and carry out. Section 3 of this report provides further discussion of some other uses for BAILA.

In addition, we hope that others in the region use the framework we have developed to carry out new analyses. The methods for doing so are more fully described in Li et al. (2019). This framework can also be used to assess biodiversity in other cities where data exist. Urban areas around the globe are rapidly acquiring geospatial data layers and biodiversity occurrence data gathered and reported by community scientists, making these analyses more feasible over time.

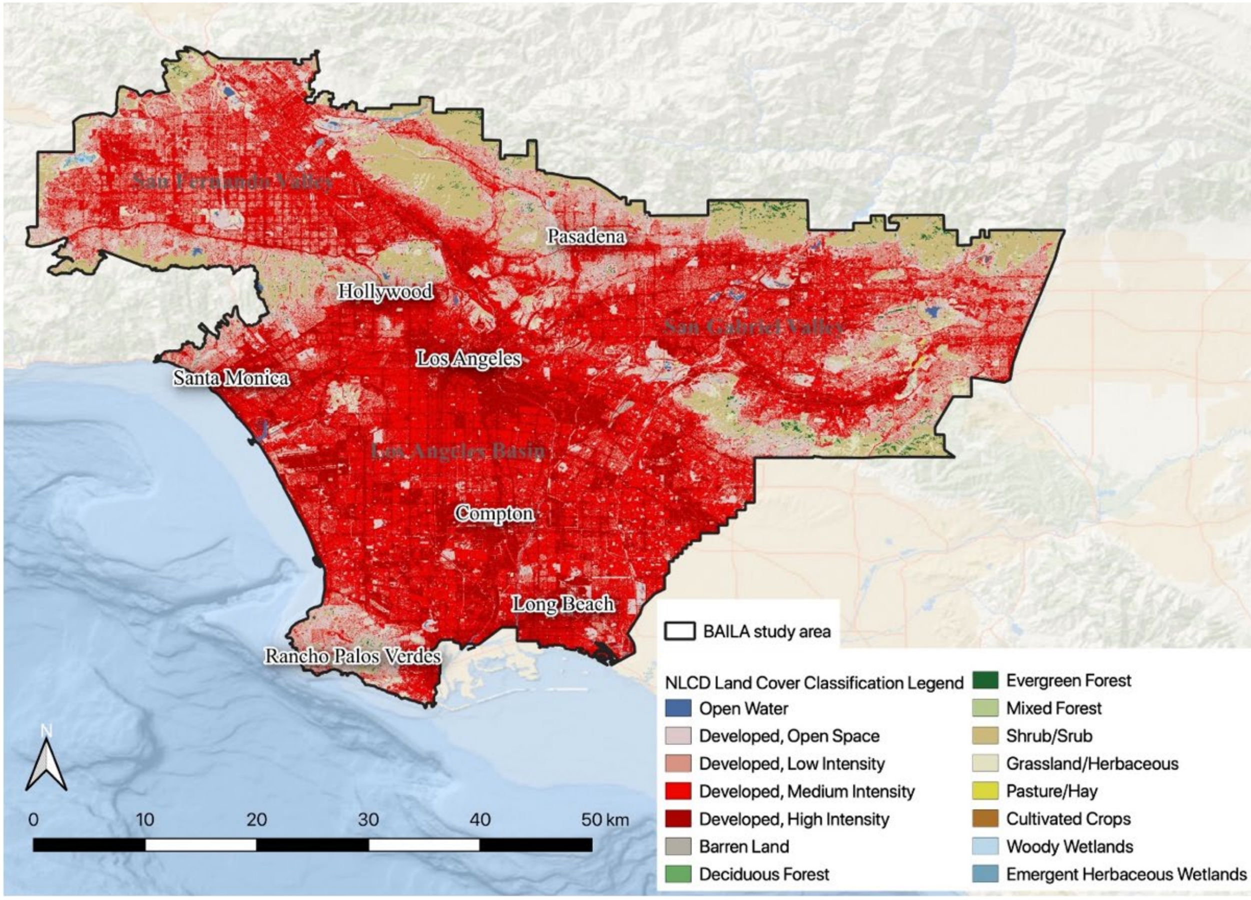


Figure 1. Map of the BAILA Study Area, depicting National Land Cover Database land cover types, which highlights that traditional land classifications often lump urban areas into only a few types, even though there is likely habitat variation across urban regions.

1. Introduction

1.1 Urban Areas and Biodiversity

Urbanization poses a significant threat to biodiversity worldwide (Grimm 2008), as urban development increases local extinction rates (Hahs et al. 2009) and decreases richness and evenness of species (Marzluff 2001, McKinney 2006). Land use changes associated with urbanization will continue to pose a challenge for biodiversity conservation well into the future, as the percentage of people living in urban areas continues to grow (Cohen 2006, United Nations 2018), and the percentage of the Earth's total land area covered by urban areas continues to expand (Seto et al. 2012).

Despite these challenges, urban areas do harbor wide varieties of organisms and ecological communities, undergo ecological processes, and benefit from ecosystem services. Improving our understanding of biodiversity in cities and learning how it can be protected and enhanced (Dearborn and Kark 2010) can yield ecosystem benefits and provide large numbers of urban residents and visitors with greater chances for regular contact with, and appreciation for, biodiversity (Miller 2005, Dunn et al. 2006, Cosquer et al. 2012, Shwartz et al. 2014). Greater appreciation for biodiversity by urban residents may, in turn, lead to better outcomes for biodiversity conservation (Miller and Hobbs 2002). In addition, urban areas have come to be recognized as important habitat for some species (Kühn et al. 2004, Luniak 2004); even rare and endangered species may be found in urban areas (Kowarik 2011).

Given the pace and scale of urbanization globally, and the recognition that urban areas do contain a variety of living organisms, our need for urban biodiversity research is at an all-time high. Despite this need, urban areas are understudied and poorly understood; urban-focused studies represent only 0.4% to 6.0% of the ecological literature (Collins et al. 2000; Miller and Hobbs 2002). The lack of information on plants and animals in urban areas is due to a variety of factors, including biases that exist within the funding, policy, research, and publication realms that impact the geographical distribution of field sites (Martin et al. 2012). There are also significant logistical challenges to conducting field research in urban areas (Hilty and Merenlender 2003), where researchers find themselves on a new parcel of private property every 10 to 15 steps, and fences and walls render lands inaccessible to survey teams.

In recent years, the rise in citizen or community science projects (Bonney et al. 2014, Eitzel et al. 2017) focused on recording species occurrence data in cities (Cooper et al. 2007, Dickinson et al. 2010, Spear et al. 2017), and the development of GPS-enabled smartphone apps such as iNaturalist and eBird, have allowed ever-larger numbers of people to easily collect and share species occurrence data (Sullivan et al. 2014, Pimm et al. 2015, Ballard et al. 2017). Local residents have greater access than scientists to the backyards, schoolyards, and other habitats in their neighborhoods, and they also have local knowledge of habitats and the species found there (Ballard et al. 2017, Spear et al. 2017). By partnering with community scientists, urban biodiversity scientists can rapidly generate a large amount of species occurrence data in urban areas.

The rise of community science has been accompanied by an emergence of interest among government agencies in biodiversity-related topics (LA Sanitation and Environment 2018) and a growing awareness of the importance of urban ecosystems on the part of conservation practitioners more broadly (McDonald 2008). All of these factors have helped researchers to begin to overcome some of the hurdles related to studying biodiversity in the urban realm.

1.2 Origins of This Los Angeles-Focused Analysis

Located in the California Floristic Province, one of only a few dozen internationally recognized and geographically distinct global biodiversity hotspots (Myers et al. 2000), the Greater Los Angeles area contains a diversity of plant and animal species (Lewis 2016). While the landscape has been heavily modified through the development of residential, commercial, industrial, and transportation infrastructure, many patches of remnant natural habitat remain, some places have been ecologically restored, and a variety of both native and non-native plants have been cultivated across the landscape.

The Greater Los Angeles area contains a variety of urban habitats. Community gardens, where residents cultivate edible, medicinal, and ornamental species have been found to contribute to a biologically diverse urban ecosystem (Clark and Jenerrette 2015). Studies of small sites within the region indicate many of its parks, open spaces, and hillsides contain native plants (Cooper 2011) and support broad communities of organisms, from insects to large mammals. Street trees (Clarke et al. 2013) and front/backyard gardens provide important habitat for insects and birds (Clarke and Jenerette 2015, Hogue 1993, Rudd et al. 2002), as do vacant lots (Eversham et al. 1996, Del Tredici 2010, Kowarik 2011, Rupprecht et al. 2015) and restored school yards (Sahagun 2012. Recent studies of backyard insects have even revealed over 40 species of flies new to science (Hartop et al. 2015, Hartop et al. 2016). The region's flood control channels and rivers provide habitat and corridors for wildlife movement, as well as serving as important wetlands in this Mediterranean Climate region (The Nature Conservancy et al. 2016). Taken together, the mosaic of novel, restored, and remnant habitats found across the urbanized Greater Los Angeles area support a rich diversity of species.

Gaining an understanding of the biogeography of Greater Los Angeles—patterns in the distribution and abundance of the region's organisms—is challenging. While a variety of studies focused on particular taxa (i.e., Tigas et al. 2002, Cooper and Muchlinski 2015) or broader suites of organisms (i.e., Delaney et al. 2010, Cooper 2015, Longcore 2016), regional assessments of biodiversity within the urbanized landscape are lacking. The vastness of Greater Los Angeles, combined with lack of access to private property, and lack of awareness, understanding, and appreciation of urban biodiversity, have contributed to this challenge.

Key ingredients for completing an urban biodiversity assessment for Greater Los Angeles, including its residential, commercial, and industrial areas, in addition to its parks and other open spaces, have recently coalesced. Among those key ingredients was a developing interest within the conservation community as a whole, the success of community science initiatives led by the Museum in generating urban species occurrence records, and the Conservancy better understanding and valuing biodiversity within cities (Goddard et al. 2010).

Typically, the Conservancy has conducted biodiversity assessments at the regional scale with the use of occurrence data from state Natural Heritage Programs (Groves 2003) such as the California Natural Diversity Database (CNDDB). Natural Heritage Programs follow a uniform set of standards in occurrence data collection, species identification, and data reporting that help ensure their reliability and that data from across jurisdictional lines can be combined and compared for analyses (NatureServe 2002, Jennings et al. 2009, McEachern and Niessen 2009). However, these programs have typically focused on gathering and providing data on species occurrences outside of urban areas and major agricultural areas. Previous work by the Conservancy (Figure 2) shows that CNDDB data for Greater Los Angeles is sparse, and the majority of records are collected outside of the most densely developed parts of the region.

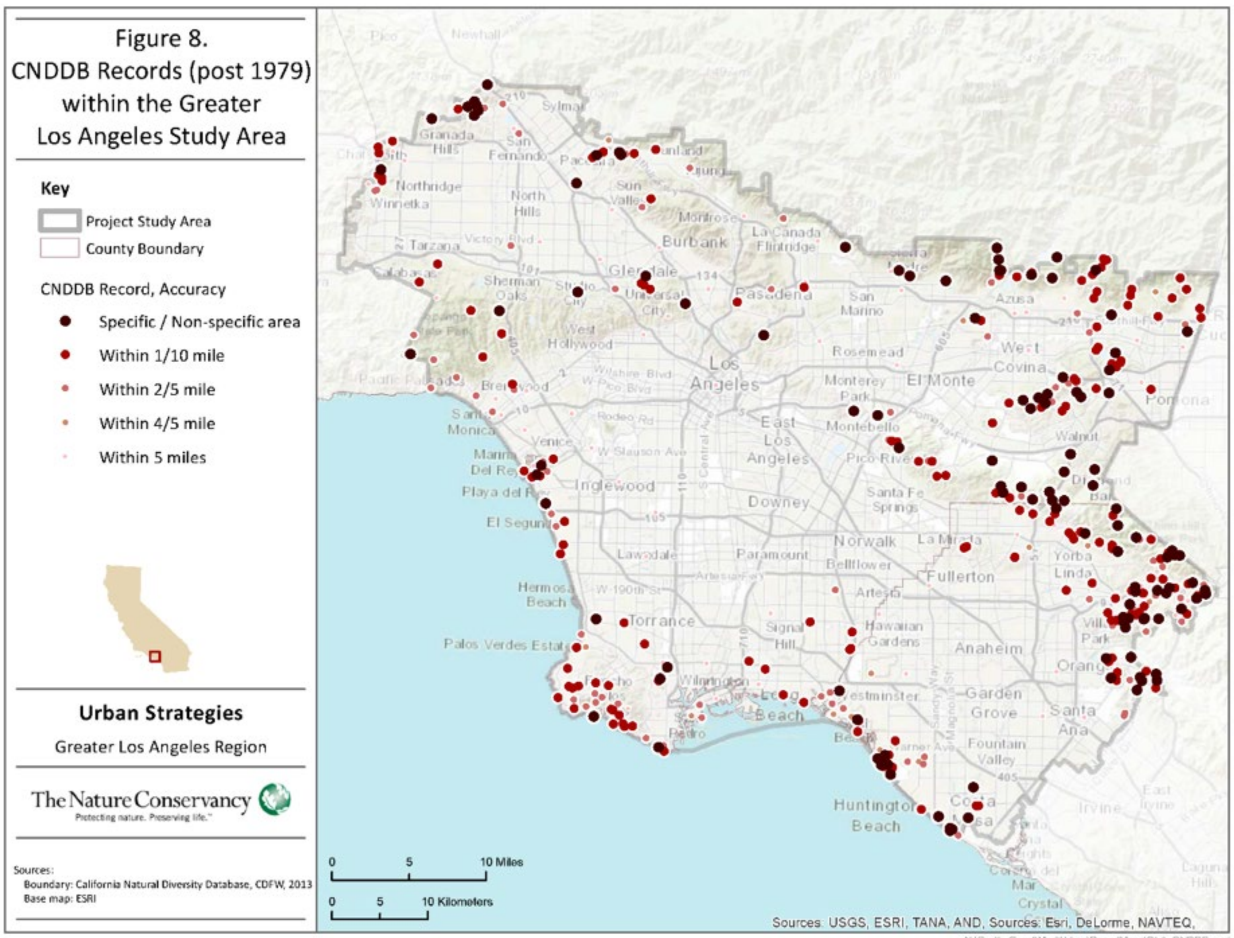


Figure 2. Map produced by The Nature Conservancy in 2013 displaying the generalized location and distribution of CNDDB records from 1980 through 2012 (n = 476) in Greater Los Angeles.

Fortunately, we do not need to rely on CNDDB records to conduct a biodiversity assessment in Greater Los Angeles. Urban species occurrence records are especially plentiful in this region due to efforts in the past decade on the part of the Museum to recruit and train community scientists. Researchers and educators in the Museum's Urban Nature Research Center and Community Science Office specifically encourage users to make observations in urban areas, including through targeted efforts such as bioblitzes, the Community Science SuperProject, and the City Nature Challenge. Therefore, we have an exceptionally large and diverse dataset of species occurrence data for the urbanized Greater Los Angeles region.

A recognition among Museum and Conservancy scientists of our complementary strengths and interests led to a desire to work collaboratively on an assessment of biodiversity in Greater Los Angeles. In 2016, the co-authors of this document formed a Core Team and named our project Biodiversity Analysis in Los Angeles, or BAILA (pronounced “bye-lah”; this is the Spanish word for “dance”). This project is a joint endeavor undertaken as a partnership between the Conservancy and the Museum.

1.3 Goals and Scope of BAILA

The goal of BAILA is to generate an urban biodiversity assessment framework that is relatively simple to undertake, uses data from public sources and community science efforts, and is broadly applicable to other urban areas throughout the world. The novelty of this framework is that it combines urban landscape heterogeneity with biodiversity and offers an improved understanding of urban biodiversity patterns that neither an urban typology nor species occurrence information alone could reveal. The purpose of this framework is not to produce a predictive species distribution model. Instead, it serves as a tool for planners and conservationists to quickly evaluate the structural and biological variation within an urban area and the general biodiversity patterns in relation to the complex urban landscape. By utilizing publicly available environmental and biodiversity data, our framework allows for other cities, municipalities, states, and non-governmental entities to carry out easy, fast, low-cost, and comprehensive urban biodiversity assessments.

One aspiration of the BAILA Core Team is that our project will contribute to a change that has been in the making over recent years in the mindset of the people of Los Angeles, particularly planners, decision-makers, land managers, and educators, about urban landscapes and biodiversity. By involving these parties in the BAILA Stakeholder Group throughout the process of developing and refining our analyses, we have sought to engage those with authority to influence the built environment in ways that could enhance biodiversity. Our aim has been to enable important stakeholders to appreciate and consider that numerous plants and animals inhabit the city, that the distribution patterns of organisms living in the built environment are quantifiable, and that the distribution and abundance of urban wildlife can be influenced through human actions that alter the landscape. BAILA demonstrates that quantitative assessments of urban patterns are possible. While the maps and data produced through BAILA may not be appropriate for every application in urban planning, design, maintenance, or management, the sharing of the BAILA methodology and approach provides several helpful lessons that can inspire planners, decision-makers, land managers, educators, and others to include urban biodiversity into their work, and to develop their own science-based assessment methods and metrics as needed.

1.4 BAILA in the Context of Conservation Planning

To further our general understanding of biodiversity and provide for its long-term maintenance, researchers and conservation practitioners have developed a suite of conservation planning approaches (Parker et al. 2018). These include increasingly sophisticated and effective analytical methods for identifying and describing the distribution of organisms, ecological processes, and places to protect and restore or rehabilitate (e.g. Margules and Pressey 2000, Groves 2003, Ball et al. 2009, Moilanen et al. 2009, The Nature Conservancy 2016). These analyses allow conservation agencies and organizations to target their funding and other resources on the highest priorities.

The conservation planning methods now available vary in the scale at which they are applied, from small, individual sites to entire regions, states, and nations (Parker et al. 2018). Conservation planning analyses can also vary in the values that they seek to maximize, with some focused on the protection of certain groups of species such as plants or birds, and others focused on vegetation communities, natural flow regimes of freshwater rivers, ecosystem services, or other conservation values (Margules et al. 1988, Vain-Wright et al. 1991, Poff et al. 1997, Mittermeier et al. 1998, The Nature Conservancy et al. 2016, Pollock et al. 2017). Increasingly, these analyses also seek to maximize other benefits, especially benefits to people such as access to open space, and ecosystem service benefits such as decreasing flood risk or improving air quality or groundwater storage (Ruliffson et al. 2003, Haight et al. 2005, Naidoo et al. 2008, Palmer et al. 2009, Smith et al. 2013, The Nature Conservancy et al. 2016).

Until recently, most regional conservation plans have prioritized relatively undeveloped portions of a region, sometimes using measures such as the Human Footprint (Woolmer 2008) to identify areas least affected by human activities. Regional conservation plans that include urban areas within their scope often classify these areas as a single category not worthy of further consideration (Figure 3; Parker 2015).

There are many possible methodologies that may be used to assess biodiversity and features across a landscape. Because enumerating all the individuals of all species found even within a very small area is difficult to impossible, planners must use surrogate or partial measures of biodiversity in order to assess similarities and differences in biota within or between planning areas (Margules and Pressey 2000). Regional-scale biodiversity assessments typically use some proxy of biodiversity, such as vegetation types. In the case of BAILA, we did not use natural vegetation types as the basic unit of analysis, as urban areas contain vegetation that is highly modified through clearing, cultivation, and the introduction of non-native species. However, we did use plant communities such as grassland and chaparral as variables in the cluster analysis that was used to derive our urban typologies.

In places where incomplete occurrence data exist, planners may use species distribution modeling (Guisan and Thuiller 2005) to provide spatially explicit predictions of where species are likely to occur across a landscape. Species distribution models were included as part of the target species habitat mapping conducted by the Conservation Biology Institute as part of the Green Visions Plan (Rubin et al. 2006). For most of the species included in the analysis, the California Wildlife Habitat Relationship System (California Interagency Wildlife Task Group 2002) was used to form the basis of the habitat map.

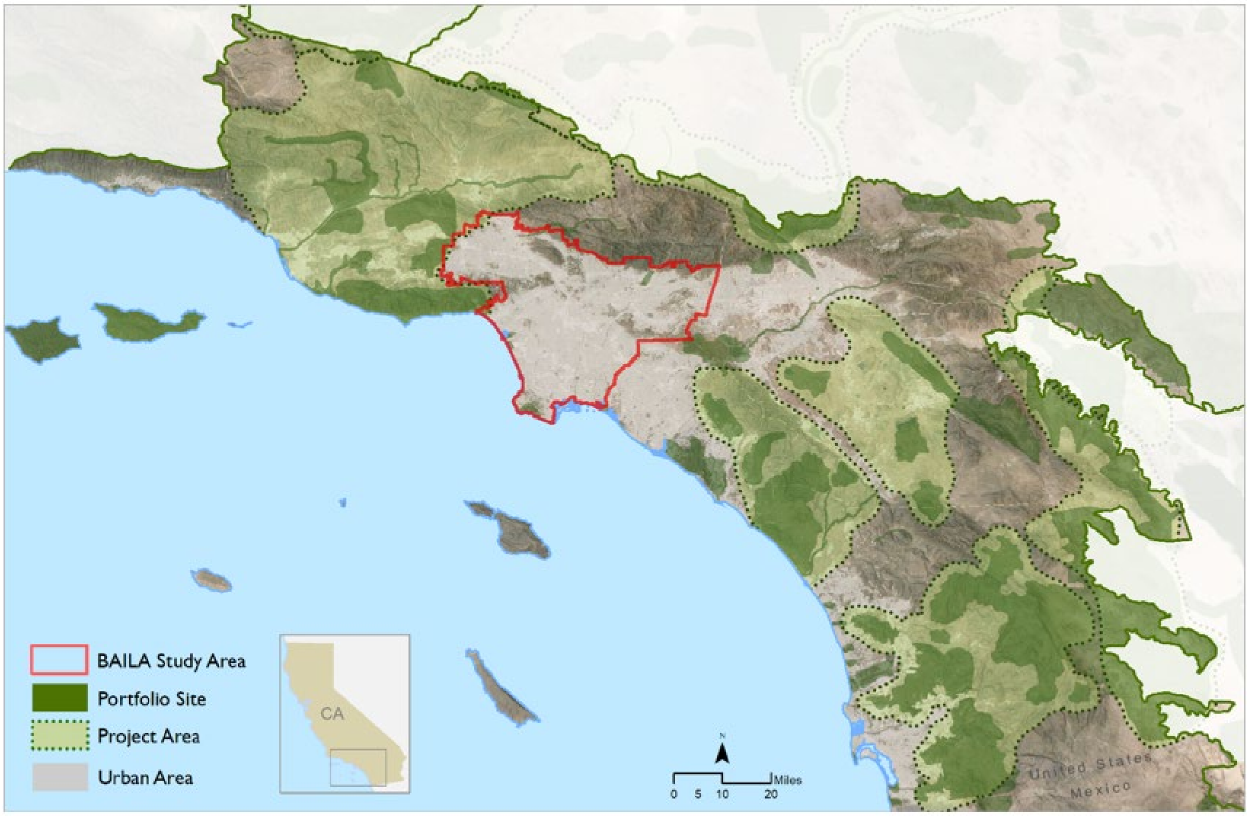


Figure 3. Map showing a preliminary ecoregional conservation plan for the California South Coast Ecoregion by The Nature Conservancy in the early 2000s. This map classifies the entire Greater Los Angeles region and the coastal cities of San Diego and Ventura Counties as a single "Urban Area" type, depicted here in gray.

A self-assessment tool that users can employ to set a baseline understanding of biodiversity in the city and then monitor changes over time, the City Biodiversity Index, also known to as the "Singapore Index," includes background information known as the "Profile of the City," and metrics for 23 indicators that measure native biodiversity, ecosystem services provided by biodiversity, and governance and management of biodiversity. A City Biodiversity Index report was recently completed by the City of Los Angeles (LASAN 2018). None of the other cities or unincorporated areas in the Greater Los Angeles area have completed the City Biodiversity Index. Future efforts by other cities or unincorporated areas within Greater Los Angeles to complete the Index—or efforts by the City of Los Angeles to modify the City Biodiversity Index indicators to better tailor the index to more meaningfully track the city's biodiversity, ecosystem services, and governance and management—may be guided by studies completed at UCLA (Alvarez et al. 2016), and by the analyses completed by BAILA.

A greenprint can be a strategic conservation plan and/or a mapping tool that explores how human communities benefit both economically and socially from parks, open space, and working lands. Some of the benefits included in a greenprint include recreation opportunities involving parks and trails, habitat protection and connectivity, clean water, agricultural land preservation, and increased resilience to climate change. A greenprint can be used to help the public understand the tradeoffs of different land use decisions. Greenprints often focus on the lands and waters around the periphery of urban areas, where development is ongoing or expected. The aim, in this case, is to identify both the most important sites to protect from that development and show where linkages between core habitat areas could be protected or restored (Thorne et al. 2009). The Conservancy's Greenprint Resource Hub (The Nature Conservancy 2017) is an excellent resource for learning about greenprints and how they can be used.

Smaller scale analyses of specific portions of large metropolitan areas have become increasingly common (e.g. U.S. Army Corps of Engineers 2013, Amigos de Los Rios 2014, The Nature Conservancy et al. 2016), but these generally cover existing open spaces or proposed restoration sites and cannot provide insights into the region-wide distribution and abundance of biodiversity. Even analyses that cover larger urban regions, such as those produced by the Green Visions Plan, often suffer from a lack of available data on organisms other than those observed in existing parks, waterways, and peripheral wildlands (e.g. National and State Parks, Wildlife Refuges, and National Forests).

BAILA followed steps common to many conservation planning exercises designed to identify sites of conservation value for protection, restoration, or rehabilitation. The basic steps included:

- Identifying the boundaries of the study area
- Identifying factors likely to be responsible for, or at least correlated with, the distribution of different species, vegetation types, and ecological processes across the study area
- Identifying suitable reliable and accurate data on occurrences of target species and vegetation types, and
- Creating and using data layers to map the distribution of biota and to better understand how these distribution patterns are correlated with environmental and other factors.

These are steps common to methods used for ecoregional planning by the Conservancy and the World Wildlife Fund, and by many other conservation, land, and water management agencies and organizations around the world (Olson et al. 2001, Groves et al. 2002, Groves 2003, Leslie 2005, Morrison et al. 2009, The Nature Conservancy et al. 2016).

While the stakeholder process used to guide BAILA is similar to that used in developing other types of assessments such as greenprints, and BAILA can be used to help decision-makers and planners with land use decisions, BAILA differs from most greenprint efforts in that BAILA explicitly values and categorizes elements of the built urban environment (i.e., neighborhoods, industrial and commercial areas, major arteries) as habitat, and doesn't just focus on the benefits of parks, open space, and areas outside of the urban realm. In addition, BAILA is focused on categorizing urban lands and exploring patterns in urban biodiversity, rather than mapping ecosystem goods and services for human communities.

2. Project Overview

2.1 Project Formation and Information Gathering

2.1.1 THE NATURAL HISTORY MUSEUM'S URBAN NATURE RESEARCH CENTER

Beginning in 2007, the Museum began planning a physical and conceptual renovation leading up to its centennial celebration in 2013,. This effort included developing new exhibits and an outdoor space usable for programming. The Museum planned to reclaim a large portion of the surrounding grounds; land that was previously two parking lots and adjacent concrete hardscape was turned into a 3.5-acre teaching and research garden that eventually was named the "Nature Gardens." Inside, 65% of the exhibit space was developed into new exhibits, including the "Nature Lab" to accompany the Nature Gardens. The "Nature Lab," which opened in June 2013, is a permanent exhibit that focuses on urban nature and the stories of species surviving and thriving in and around Los Angeles. For both the Nature Gardens and Nature Lab, a central goal was to get local residents "to put their nature eyes on," that is, to start observing the incredibly diverse biota that can be found all around us, all the time.

At the same time, a similar review and revision of Museum programming and branding was taking place with the goal of having research and programming be more relevant to the local community. With an estimated 35 million historical objects and specimens, the Museum's collections provide a snapshot into the growth of the Greater Los Angeles area. The past distribution of species is recorded by the specimens and their associated locality data. However, many more recent species occurrence records were needed to compare to the historical records, which would allow researchers to assess how species are impacted by urbanization. Such knowledge can then be used to assess what factors structure distributions in urban areas. This realization inspired the early development of several community science projects and the development of a new position at the Museum, the Manager of Citizen Science (now known as the Manager of Community Science). In 2010, the Lost Lizards of Los Angeles (LLOLA) project was launched to try to understand why there were no lizards present in and around the Museum grounds and asked for public help in doing a survey around the Museum. Photo vouchers submitted to LLOLA resulted in the discovery of several non-native geckos not previously known in Los Angeles County (Bernstein and Bernstein, 2013, Pauly et al. 2015). Later, with the hiring of Dr. Greg Pauly as Curator of Herpetology, this project was expanded to include all reptiles and amphibians throughout Southern California and transitioned to the iNaturalist platform. Similar projects were then developed for squirrels and terrestrial gastropods (Southern California Squirrel Survey and SLIME: Snails [and slugs] Living in Metropolitan Environments). In 2011, increasing interest in backyard sampling of insects led to the establishment of the BioSCAN project (Biodiversity Science: City and Nature) by Entomology Curator Dr. Brian Brown and other staff. BioSCAN was a survey of a north-south transect through Central Los Angeles of 27 private backyards, one school, a community garden, and the newly finished Nature Garden. This project was accepted for funding by the Museum and began its first year of sampling in 2012. From the first year of sampling, 30 new species of phorid flies were discovered in backyards and other habitats across Los Angeles (Hartop et al. 2015, 2016).

The early success of these community science efforts in documenting urban biodiversity and in leading to published studies in the peer-reviewed scientific literature resulted in expanding the Museum's staff and focus on community science. In 2013, the Museum created a Citizen Science Office (now the Community Science Office) with three staff and multiple volunteers and students. Simultaneously, curators conducting urban biodiversity research realized that many of their research questions and methodologies were overlapping. This prompted the formal development of the Urban Nature Research Center in 2015, with Dr. Brown and Dr. Pauly as co-directors and a growing group of researchers and staff scientists. Success in rapidly acquiring urban biodiversity data and in developing conservation-relevant community science projects was a critical factor leading to the Museum-Conservancy partnership that resulted in BAILA.

2.1.2 THE NATURE CONSERVANCY'S ENGAGEMENT IN LOS ANGELES

The Conservancy began exploring the role it could best play in Greater Los Angeles in 2012. In 2013, the Conservancy conducted both a needs assessment and a biodiversity assessment to better understand the opportunities available to the Conservancy for engagement in the region. These early assessments were critical to setting the stage for the Conservancy-Museum partnership that resulted in BAILA.

For the needs assessment, the Conservancy conducted in-person interviews with 14 environmental leaders in the Los Angeles area. The interviewees identified the Conservancy as an expert in land conservation, public policy advocacy, and science-based planning. Leaders who have worked with the Conservancy on complex public policy issues also consider the Conservancy expert facilitators. They urged the Conservancy to provide leadership in the environmental community through capacity building, facilitation, science support, and advocacy.

For the biodiversity assessment, the Conservancy used information on the modeled distributions of 48 species that had been collected by the Conservation Biology Institute as part of the USC Green Visions Plan (Rubin et al. 2006). The species distribution maps were generated using information about wildlife-habitat relationships, using assumptions about the likelihood of species occurrence based on the presence of naturally occurring vegetation communities. We generated maps of "biodiversity potential" based on the overlap of species maps from this study—where more species had been mapped to occur, we considered the biodiversity potential to be higher. The resulting map showed high biodiversity potential in wildlands, open space and other portions of the Greater Los Angeles area that were not developed. However, most of the Greater Los Angeles area was mapped as having no habitat value at all. Thus, this early analysis generated a finer-scale map depicting the "green vs. gray" dichotomy (Figure 3; Parker 2015) that is so prevalently depicted in regions that contain cities. This initial analysis did not give us information about the plants and animals living in the built environment, and we realized that we wanted to develop a new method of conservation planning that would allow us to have a more accurate and complete understanding of urban biodiversity.

2.2 Partnership and Institutional Relationship Development

A strong working relationship between scientists from the Museum and the Conservancy was largely initiated through a series of workshops focused on biodiversity in Greater Los Angeles (Sloniowski 2015a, 2015b). The Museum's scientists brought expertise and experience conducting research and leading community science projects that are providing new insights into the distribution and abundance of native and nonnative species across the metropolitan area (Grimaldi et al. 2015, Hartop et al. 2015, Pauly and Borthwick 2015, Pauly et al. 2015, Hartop et al. 2016, Ballard et al. 2017, Spear et al. 2017). The Conservancy's scientists brought experience and expertise in conservation planning and practice including geospatial analyses and on-the-ground conservation area management (e.g., Groves 2003, Randall et al. 2010, The Nature Conservancy 2016, Parker et al. 2018), along with a history of working with a variety of stakeholders to achieve conservation successes.

During meetings on September 4 and November 19, 2013, staff members from the Conservancy and the Museum decided that a mutually beneficial collaborative project for the two entities would be to jointly sponsor and convene two to three workshops for stakeholders involved in the conservation and restoration of nature in Greater Los Angeles. By jointly convening these workshops, the Museum and the Conservancy intended to identify and articulate a clear and compelling vision for a network of conservation areas, raise the profile of conservation across the region in general, and increase the ability of all participating stakeholders to build support and obtain funding for their work.

On January 10, 2014, the Conservancy and the Museum further refined the specific goals that workshops would intend to achieve. These goals were to: (1) enhance the body of knowledge on biodiversity in Greater Los Angeles, (2) enhance the biodiversity values (i.e., habitat quality) of Greater Los Angeles, and (3) inspire appreciation of Greater Los Angeles' biodiversity now and in the future. By working to achieve these shared goals, Conservancy and Museum staff were aspiring to raise the profile of the biodiversity potential of the Los Angeles region and explain why it matters, to coalesce local organizations around restoring and conserving biodiversity in Los Angeles, and to inspire other Los Angeles-area research and educational institutions to conduct and showcase scientific research into the biodiversity of Los Angeles and the variety of life already present in the region.

To create a biodiversity vision for Los Angeles, the Conservancy-Museum collaboration focused on involving and engaging key stakeholders early on. Because there were (and still are) many individuals, agencies, institutions, and organizations in the region with varying degrees of understanding, it was thought critical to invite participation of those who could identify the most important questions to gain a better understanding of urban biodiversity, those with the greatest expertise and vision for protecting the region's biodiversity, and those with the greatest ability and innovative ideas for educating the public about it.

Over several months in 2014, we discussed the structure and sequence of the workshop series and decided to hold three separate workshops. The first, focused on enhancing our knowledge and understanding of biodiversity, was held at the Museum on January 23, 2015. A list of the 36 researchers who participated in this workshop can be found in Appendix B. This workshop involved a group of scientists focused on research topics related to urban nature in Los Angeles. The second, focused on enhancing biodiversity itself, was held at the Conservancy's Los Angeles office on March 11, 2015, and involved conservation practitioners and members of agency groups. The third workshop was held at the Museum on June 26, 2015. It involved communicators and educators and focused on enhancing our appreciation for biodiversity in the urban realm.

From our first workshop, which was focused on enhancing our knowledge and understanding of biodiversity, came five major ideas for follow-up projects. These included expanding the scope of Museum projects focused on studying urban biodiversity, digitizing existing collections at the Museum relevant to regional urban biodiversity, endowing a taxonomist laureate for Los Angeles (i.e., a taxonomic expert also focused on urban biodiversity), organizing an annual science day or bioblitz, and producing a biodiversity inventory and map of the Greater Los Angeles area. The last of these became the inspiration for BAILA.

2.3 Formation of BAILA Team Structure

The BAILA initiative brought together the Museum's taxonomic expertise and community science experience with the Conservancy's conservation planning expertise and stakeholder engagement experience. However, the key missing piece was a Geographic Information System (GIS) specialist who could focus on the necessary analyses on a full-time basis. The Museum and the Conservancy each secured funding for this position, and a global search was conducted for a GIS specialist. This search resulted in hiring Dr. Enjie (Jane) Li, who holds a PhD in Environment and Society from Utah State University. Specializing in spatial analyses and GIS, Dr. Li's dissertation research examined how water and land use patterns could be integrated to inform sustainable urban planning in the western United States. She began work on BAILA in 2017.

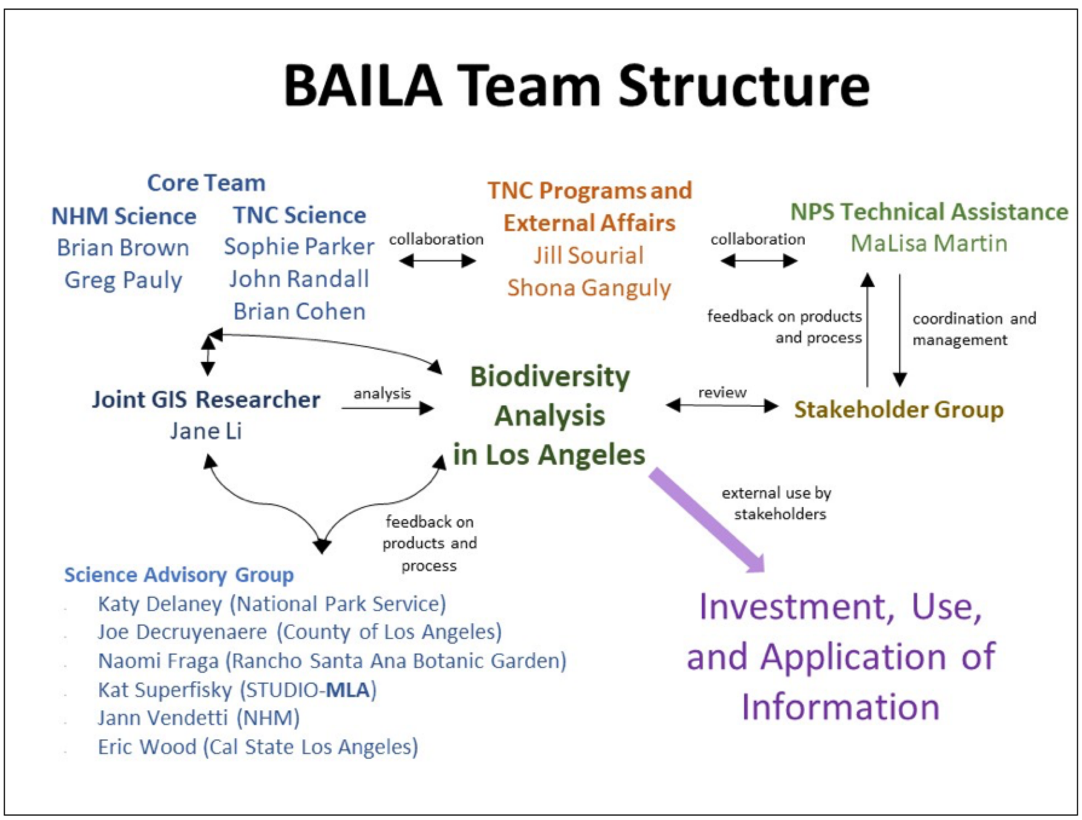


Figure 4. Structure of BAILA Team.

We also worked with colleagues from our own institutions and the National Park Service to host a series of stakeholder meetings in 2017 and 2018 to gather input on how our biodiversity analysis could be most useful in their work. The structure of the BAILA Team is shown here in diagrammatic form (Figure 4). The Museum and the Conservancy are each represented by scientists on the BAILA Core Team. Together, the members of the BAILA Core Team work with our joint GIS Researcher Jane Li to develop the plans for the analyses related to BAILA. Jane is responsible for completing the analyses and sharing them with the Core Team. Feedback is sought by the Core Team from a Science Advisory Group and from a Stakeholder Group. The ultimate goal is the investment, use, and application of BAILA by the Core Team and by those external to either the Museum or the Conservancy.

2.4 Approach to Data

Assessing biodiversity in urban areas is challenging. Such difficulty is attributed to two factors. First, urban areas are extremely diverse and complex. Many factors such as climate, land use, land cover, and human activity interact with each other and affect wildlife distributions. Second, traditional survey-based assessment approaches for collecting species occurrence data prove to be impractical in vast urban areas due to limited access to private lands, high financial cost, and intensive demand of technical expertise.

To address these issues, we developed a widely adoptable framework for city-level urban biodiversity assessments. First, we developed a new urban habitat classification to differentiate various urban habitat types in Greater Los Angeles while accounting for both ecological and anthropogenic characteristics. Then we adopted community scientist-generated species occurrence records to map species distributions in relation to the various urban habitat types (see Appendix A for detailed discussion of the development of community science and its application in biodiversity research and conservation practices). By combining an urban habitat classification with community scientist-generated species occurrence data, our framework sheds light on how various urban factors structure biodiversity. This information can then be used for urban planning and conservation management aimed at maintaining and enhancing desirable species and ecosystem services.

For the urban habitat classification, we used both ecological and anthropogenic factors that have direct influence on urban biodiversity. In general, these factors fall into three categories: the biophysical environment, the built environment, and the social environment. In total, 18 variables were selected for creating this typology based on their effects on urban biodiversity and data availability and accessibility (see detailed data selection process in Appendix A). We developed our framework with the intention that it could be easily applied in most urban areas across the United States and in many other places throughout the world. Therefore the 18 variables selected are generally available for other regions around the globe.

For community science-generated species occurrence data, we used species-level, research-grade iNaturalist occurrence data to assess biodiversity patterns across our urban study area. The iNaturalist platform, launched in 2008, allows users anywhere in the world to record observations of organisms from diverse taxonomic groups. We downloaded iNaturalist data reported between January 1, 2010 and September 30, 2017 from the Global Biodiversity Information Facility (GBIF). Research-grade observations are defined as observations with a photo voucher, locality, date, and a community-supported identification. In addition, research-grade observations cannot be cultivated or captive organisms. In total, 59,842 observations of 2,281 species met these requirements within our study area.

2.5 Generation of Typologies and Analysis of the Distribution of Biodiversity

For an in-depth description of the methods, results, and conclusions of BAILA, please see our peer-reviewed journal article, which is attached to this report as Appendix A. For an overview of our approach and main findings, please see below.

We selected a study area that captures most of the urbanized portions of Los Angeles County that lie south of the San Gabriel Mountains. We followed county and municipal boundaries rather than watershed or other natural boundaries for our study area so that we would be able to conduct post hoc analyses of sociodemographic factors using the results of BAILA. Our basic unit of analysis was the Census Block Group.

In many conservation planning efforts, wild (uncultivated) vegetation types and an array of environmental factors such as elevation, climate, soils, and geologic substrates are used to classify the study area into different habitat or land use types (Anderson et al. 1999, Groves et al. 2002, Groves 2003, Morrison et al. 2009, Sayre et al. 2014). For BAILA, we used many of these same environmental variables, but we did not use natural vegetation types. Instead, we identified other factors related to the built environment and human population that have been identified by previous research as being important drivers of species distributions in urban areas (Grimm et al. 2000, Shapiro 2002, Luck and Smallbone 2010, Aronson et al. 2014, Nielsen et al. 2014, Parker 2015). We started with more than 40 variables. We eliminated over half because they provided little or no extra ability to distinguish different urban habitat types. This was often because these factors were strongly correlated with another variable we were using, or because their values were uniformly or nearly randomly distributed across the study area. We eventually settled upon 18 variables that we used to identify the nine urban habitat types that constitute the typology we developed for Greater Los Angeles (Table 1).

TABLE 1: The variables and data sources used to develop a typology for Greater Los Angeles

VARIABLE	DESCRIPTION & DEFINITION	SOURCE
Biophysical Landscape		
Average annual temperature	Mean temperature per block group	The Basin Characterization Model (BCM) Dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution: 270m)
Maximum temperature	Mean maximum temperature of June, July, and August per block group	The BCM Dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution: 270m)
Average annual precipitation	Mean precipitation per block group	The BCM Dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution: 270m)

TABLE 1: (Continued)

VARIABLE	DESCRIPTION & DEFINITION	SOURCE
Elevation	Mean elevation per block group	2006 U.S. Geological Survey (USGS) National Elevation Dataset (NED): https://egis3.lacounty.gov/dataportal/2011/01/26/2006-10-foot-digital-elevation-model-dem-public-domain/ (resolution: 10ft)
Slope	Mean maximum temperature of June, July, and August per block group	The BCM dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution: 270m)
Average annual precipitation	Mean slope degree per block group	2006 USGS NED: https://egis3.lacounty.gov/dataportal/2011/01/26/2006-10-foot-digital-elevation-model-dem-public-domain/ (resolution: 10ft)
Percentage of forest	Percentage forest per block group	National Land Cover Database (NLCD) 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution: 30m)
Percentage of grassland	Percentage of grassland per block group	NLCD 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution: 30m)
Percentage of water and wetlands	Percentage water bodies per block group	USGS National Hydrography Dataset: http://prd-tnm.s3-website-us-west-2.amazonaws.com/?prefix=StagedProducts/Hydrography/NHD/State/HighResolution/Shape/ (resolution: 30m)
Built Landscape		
Tree canopy	Average percentage of tree canopy cover per block group	NLCD 2011 U.S. Forest Service Tree Canopy Analytical Layer: https://www.mrlc.gov/data/nlcd-2011-usfs-tree-canopy-cartographic-conus-0 (resolution:30 m)
Greenness (EVI)	Mean Enhanced Vegetation Index per block group	2016-2017 USGS Landsat 7 surface reflectance: http://clim-engine.appspot.com (resolution: 30m)
Imperviousness	Average percentage of impervious surface per block group	NLCD 2011 Percent Developed Imperviousness Layer: https://www.mrlc.gov/data/nlcd-2011-percent-developed-imperviousness-conus-0 (resolution:30 m)
Percentage of urban open space	Percentage of urban open space per block group	NLCD 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution: 30m)

TABLE 1: (Continued)

VARIABLE	DESCRIPTION & DEFINITION	SOURCE
Percentage of urban areas	Percentage of urban areas per block group	NLCD 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution: 30m)
Distance to the nearest natural areas	Average distance to the nearest natural areas per block group	LA County Land Types Dataset Wildlife Sanctuary Layer: https://egis3.lacounty.gov/dataportal/2015/01/08/la-county-land-types/ (resolution: parcel)
Social Structure		
Population	Total population per block group	U.S. Census 2010 Dataset: https://www.census.gov/geo/maps-data/data/tiger-line.html (resolution: U.S. Census Block)
Population density	Person/km² per block group	U.S. Census 2010 Dataset: https://www.census.gov/geo/maps-data/data/tiger-line.html (resolution: U.S. Census Block)
Traffic density	Average traffic density per block group	CalEnviroScreen 3.0 Dataset: https://oehha.ca.gov/calenviroscreen/indicator/traffic-density (resolution: U.S. Census Track)
Traffic noise	Average traffic noise per block group	U.S. Bureau of Transportation National Transportation Noise Map: http://osav-usdot.opendata.arcgis.com/datasets/07fd1054018249 5db6261317a154443e (resolution: 30m)

We used hierarchical cluster analysis (Wilks 2011) to categorize all 6,040 Census Block Groups found in our study area into a manageable number of urban habitat types based on their variation in the 18 input variables. We then used a combination of the dendrogram and the gap statistic to identify the optimal number of clusters.

We used iNaturalist occurrence data to assess biodiversity patterns across our urban study area. We did this by overlaying the 59,842 iNaturalist observations obtained from GBIF atop the nine urban habitat types (see below). Then we analyzed the number of observations and species observed within each urban habitat type. We also compared the numbers of native species and introduced species across taxa and urban habitat type. Furthermore, we examined the shared and the unique suites of species among and within each of the nine urban habitat types.

2.6 Results

Cluster analysis indicates that our study area can be differentiated into nine different urban habitat types (Figure 5). We gave a name to each urban habitat type that reflects its geographic location and/or an additional distinctive feature to improve communication about the urban habitat types, which are as follows:

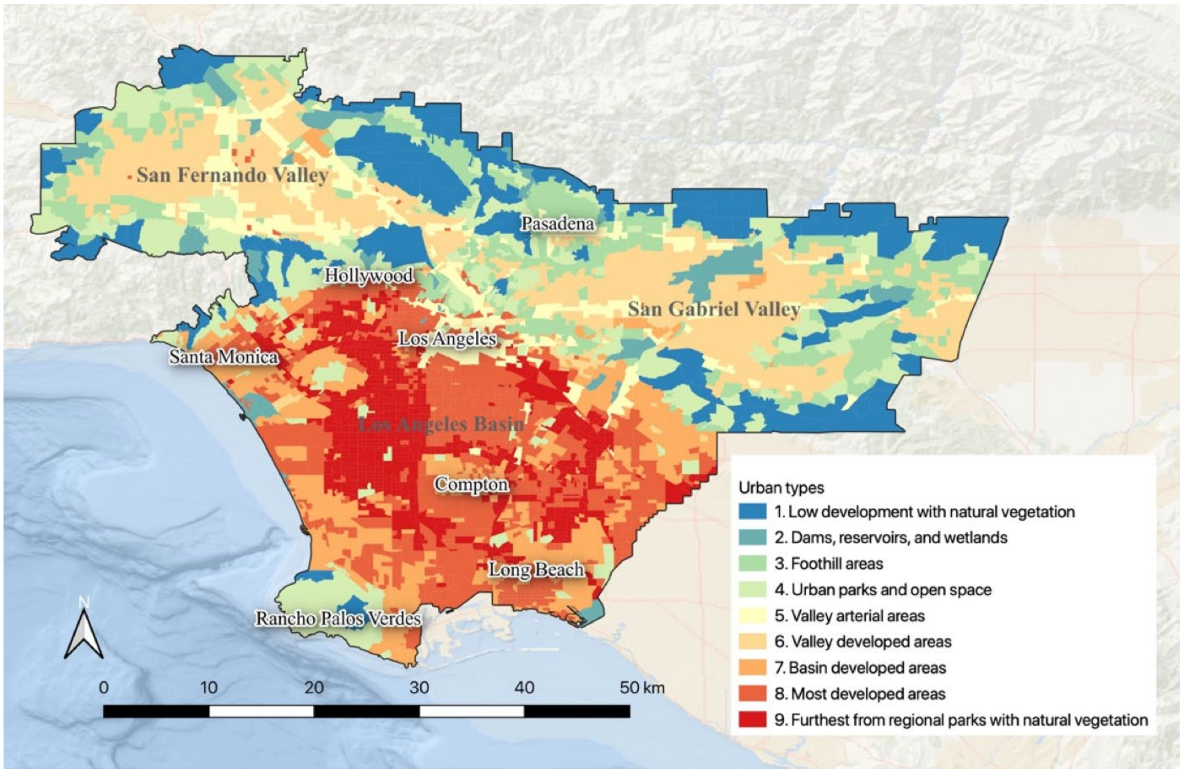


Figure 5. Map of the nine different urban habitat types.

Type 1: Low development with natural vegetation

- Very high natural vegetation, primarily grassland and forest
- Very steep terrain
- Very low urban development and low population density
- Relatively high precipitation for the Los Angeles area

Type 2: Dams, reservoirs, and wetlands

- Low vegetation cover
- Level terrain
- Very low urban development

Type 3: Foothill areas

- Affluent and well-vegetated neighborhoods
- Primarily residential uses
- Moderate terrain
- Moderate building site coverage and population density

Type 4: Urban parks and open space

- High tree canopy coverage and green open space
- Low urban development
- Primarily parks, cemeteries, and golf courses

Type 5: Valley arterial areas

- Highest traffic density and traffic noise
- High percentage of impervious surface
- Low in vegetation
- Primarily highways and surrounding neighborhoods

Type 6: Valley less-developed areas

- Moderate terrain, mostly in the San Fernando and San Gabriel Valleys
- Relatively hotter and wetter weather
- Low tree canopy coverage and greenness
- High urban development and population
- Primarily residential uses

Type 7: Basin less-developed areas

- Flat terrain, mostly in the Los Angeles Basin
- Milder and dryer weather
- Low tree canopy coverage and greenness
- High urban development and population
- Primarily residential uses

Type 8: Most-developed areas

- Very high urban development and population
- Far from regional parks with natural vegetation
- Very low tree canopy coverage and greenness
- Mixed land use

Type 9: Furthest from regional parks with natural vegetation

- High urban development and population
- Very high traffic density and noise
- Low tree canopy coverage and greenness
- Furthest from regional parks with natural vegetation
- Mixed land use

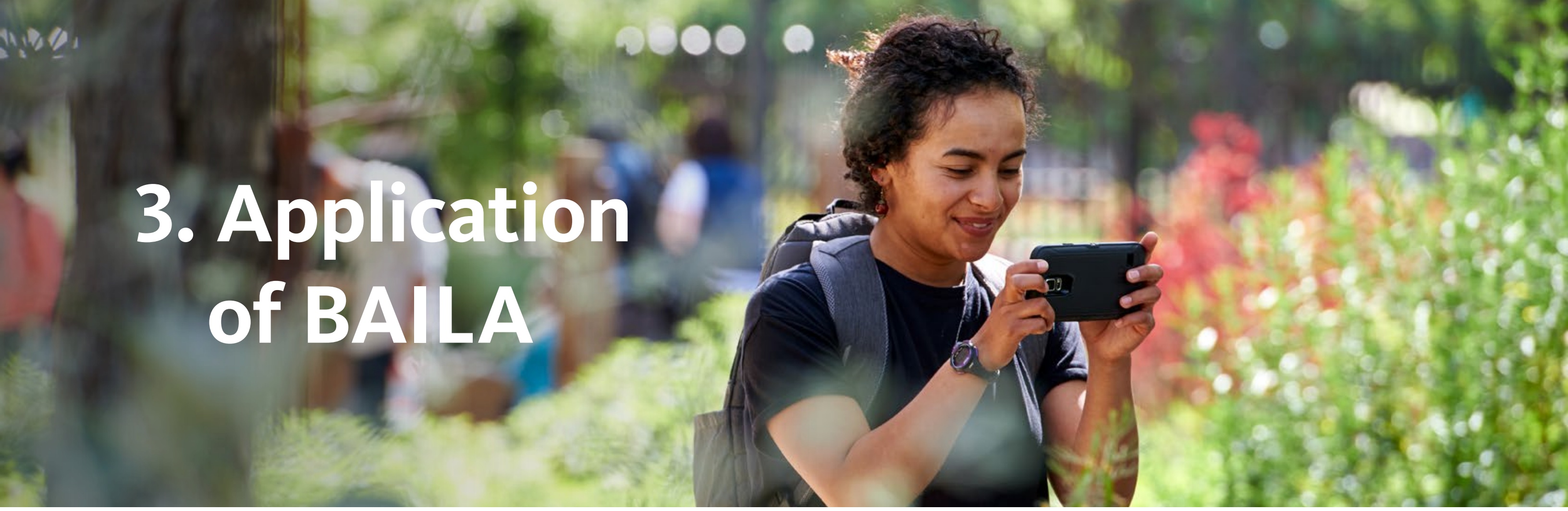
Combined with community scientist-generated species occurrence data, we found that there is great variation in species distributions, with some species being found across all nine urban habitat types while some were more restricted to a subset of the types. This finding indicates that urban heterogeneity affects species distributions (Stein et al. 2014, Norton et al. 2016). It also indicates that each of the nine urban habitat types, despite their different levels of observed species richness, support various organisms, and each should be recognized for its contribution to the biodiversity of the urban area. Additionally, we found that although community scientists-generated species occurrences are plentiful, they are also unevenly distributed; we found that parks, wetlands, and open space have more observations than more urbanized portions of our study area. To promote a better understanding of urban biodiversity patterns, documentation of organisms in the more urbanized neighborhoods should be encouraged.

Our results indicate that there is great variation in species distributions across the BAILA study area. Some species are found across all nine urban habitat types, while some were more restricted to a subset of types. This helps generate hypotheses and guide new research in understanding the mechanisms driving species distributions in complex, urbanized landscapes. It also provides insights for on-the-ground conservation management and planning regarding what environments are needed for species to survive in urban areas and where to implement conservation projects.

Our analyses found that wetlands (Type 2) and urban parks (Type 4) had the most bird species observations. Therefore, increasing acreage of urban wetlands and parklands (e.g., by investing in green stormwater infrastructure) could be a strategy for increasing habitat and opportunities for residents to observe wildlife.

Our analyses also found that while introduced species occurred in all nine of the urban habitat types, introduced mammals and spiders were observed more frequently in the more urbanized types. Not surprisingly, these results suggest that efforts to detect and track introduced species should be concentrated in urban areas, where community science approaches can be especially effective at overcoming the challenges of private property access for detecting introductions (e.g., Pauly et al. 2015).

Each of the nine urban types, despite their different levels of observed species richness, support a variety of organisms. For example, more than 200 native species were observed in Type 5, one of the more urbanized types, and one of the urban habitat types covering the smallest total area. This indicates that native species habitat can be found not only in large urban green spaces but also within commercial, industrial, and residential districts (Rudd et al. 2002, Blair 2004, Acar et al. 2007). Thus, all urban areas have the potential to benefit from strategic interventions.



3. Application of BAILA

3.1 Application of BAILA Results within Los Angeles

We developed BAILA to provide more detailed information on the distribution of biological diversity across the Greater Los Angeles region and to inform a variety of conservation, infrastructure and land use planning and implementation projects. Such projects may include stormwater drainage and treatment, major restoration projects such as those that have been proposed for portions of the Los Angeles River, implementation of the City of Los Angeles Biodiversity Initiative, transportation infrastructure upgrades and repairs, projects to bolster environmental justice, and setting regional priorities for biodiversity surveys and research. In each case, spatially explicit data ("layers") from BAILA would be used along with data on other physical, social, economic, and land use variables of interest.

The Conservancy is already using the results of BAILA to conduct spatially explicit analyses of how biodiversity of native species might be enhanced by the use of "green" stormwater infrastructure at sites across the region where new and upgraded facilities and projects have been proposed (Wise 2008, Chau 2009, Jayasooriya and Ng 2014, Chini et al. 2017, Porse et al. 2017). Green stormwater infrastructure may include the construction or restoration of waterways, floodplains, and retention and infiltration basins; installation of rain gardens, green roofs, tree plantings, and permeable pavement; and removal of impermeable pavement and built environments. The goal with these efforts is to increase and extend the ability of a region's natural waterways, wetlands, aquifers, parks, green spaces and other areas of native and wild vegetation to reduce flood risks, capture surface water and its pollutants, and improve the quality of water that continues to flow through the region (Wise 2008, Jayasooriya and Ng 2014, Rupprecht et al. 2015, Chini et al. 2017). ARCADIS, a prominent design and consulting firm with expertise in stormwater engineering and hydrology, is working with the Conservancy and contributing to this analysis pro bono. The analysis will address three primary questions:

1. What are the water quality and water quantity benefits that a project could yield? (To be addressed by ARCADIS)

2. What are the social benefits that a project could yield (e.g., environmental justice, recreation, human health, jobs, etc.)? (To be addressed by ARCADIS, based on feasibility)

3. What are the biodiversity/nature benefits that a project could yield? (To be addressed by the Conservancy)

4. What are the human wellbeing benefits that a project could yield?
(To be addressed by the Conservancy)

BAILA may also be useful in informing major restoration projects, such as those proposed for some stretches of the Los Angeles River (City of Los Angeles 2007, U.S. Army Corps of Engineers 2013, LLARRP 2016, Porse et al. 2017). For this work, more detailed studies of the proposed restoration sites have been and will be undertaken, and BAILA's utility is likely to be in providing insights into nearby or more distant sites which support native plants and animals that may be able to move to and from the proposed restoration site. For example, one goal of Los Angeles River restoration efforts is increasing habitat for a number of bird species of special concern, such as the sharp-shinned hawk, Vaux's swift, loggerhead shrike, yellow warbler, yellow-breasted chat, burrowing owl, horned lark and summer tanager as well as indicator species such as the acorn woodpecker and California quail (City of Los Angeles 2007). BAILA has information on locations where these species occur elsewhere in the region that might serve as stepping stones for movement of these species to and from the river restoration sites.

Similarly, BAILA might help inform transportation planning, mitigation, and construction (e.g. CalTrans and City of El Segundo 2018) by identifying high biodiversity value areas and opportunities to create or rehabilitate habitats. The patterns of biodiversity revealed by BAILA might be used to identify sites of high conservation value or restoration potential immediately adjacent to the transportation route in question, or at more distant sites that might serve to best mitigate any habitat losses likely to be caused by proposed construction. BAILA may likewise be used to inform the development of a biodiversity index tailored to Los Angeles which the City of Los Angeles Bureau of Sanitation is leading (LASAN 2018). Data from BAILA may also prove useful in analyses aimed at directing resources to build greater environmental justice (for example, by providing more equitable access to parks, open spaces, and other healing environments and addressing the needs of underserved neighborhoods and individuals) (e.g., Garcia and Sivasubramanian 2013, California Environmental Justice Alliance 2017 and 2018, Rigolon et al. 2018).

Finally, new community science efforts may be guided by BAILA, as both taxonomic and geographic data gaps have been identified by the analysis. The collection of field data to fill these gaps may occur through direct calls to the community, such as neighborhood-focused bioblitz events, and through the targeted efforts of experts.

3.2 Application of BAILA Method to Other Cities

The methods we developed through the planning and execution of BAILA can be adapted and used to assess biodiversity in other cities where data exist. We developed BAILA in part to demonstrate the increasing feasibility of conducting urban biodiversity analyses. Urban areas around the globe are rapidly acquiring geospatial data layers and biodiversity data, making these analyses more feasible over time.

We developed the BAILA methodology so that it can be replicated in most areas across the United States by using geospatial data whose spatial extent covers the entire country and extracting out the specific portion of our study area. We substituted higher resolution local data when available; however, that is not a requirement to conduct the analyses. The GIS and analytic tasks require a range of technical skills. The data gathering and GIS processing require standard GIS skills and can be achieved under supervision by early-career GIS staff or by self-managed intermediate GIS staff. We conducted our analyses using both the Esri suite of GIS software and QGIS, an open-source GIS software package. The analytic processes require a higher level of technical and analytic expertise with a solid working knowledge of spatial statistics and appropriate software packages, such as R.

In an effort to share the method and the results of BAILA, the Conservancy has shared our approach internally with our North American Cities Consortium (which includes 24 cities) and our Global Urban Conservation Planning Community of Practice, and at our Nature Conservancy Global Science Meeting. In all instances, we provided information to interested parties on how BAILA was initiated, what methods we used, and how our methods could be adopted for use in other cities.

4. Conclusion

The BAILA project is an innovative collaboration whose results were unlikely to emerge from work by the Museum or the Conservancy alone. Its results and methods are being used as the basis for further studies on biodiversity in Los Angeles and potentially other cities. The combination of the outreach and application expertise within the Conservancy and the organism-level expertise at the Museum is a model that deserves to be emulated as closely as the BAILA protocol. Additionally, the BAILA collaboration has built connections within the City of Los Angeles between scientists and stakeholders that allow progress to be made on many projects that require a diverse array of abilities and resources. Such projects range from investigations on yard use (effectiveness of drought-tolerant plantings) and the utility of wildlife corridors to the detection of invasive species hotspots, and the importance of different water usage regimes. Applications based on the BAILA results will help city planning and redevelopment efforts to make cities more livable and healthier for humans and wildlife alike.

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1. Appendix A: Peer-reviewed Journal Article

Please visit https://www.scienceforconservation.org/products/BAILA to gain access to the peer-reviewed publication about the BAILA methodology.

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METHODS
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An Urban Biodiversity Assessment Framework That Combines an Urban Habitat Classification Scheme and Citizen Science Data

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A lack of information about urban habitats, and a lack of professionally-collected species occurrence data are often cited as major impediments to completing bioassessments in urban landscapes. We developed an urban biodiversity assessment framework that addresses these challenges. The proposed framework combines a customized hierarchical urban habitat classification scheme with citizen science-generated species occurrence data, such as iNaturalist and eBird. It integrates publicly available data on the physical and anthropogenic environment with species occurrence information and serves as a novel method for conducting urban biodiversity assessments. This framework provides insights into how species occurrences within an urban landscape are associated with spatial variation in the physical and anthropogenic environment. It can also yield information useful for planning and conservation management aimed at maintaining and enhancing the abundance and diversity of native and other desirable species in urban areas. This framework requires minimal taxonomic expertise on the part of those who employ it, and it can be implemented in urban areas worldwide, wherever adequate data exist. We demonstrate the application of this framework in the highly urbanized portion of Los Angeles County, California, USA. Our demonstration used 18 physical and anthropogenic variables to classify our study area into nine urban habitat types. We then assessed relationships between these urban habitat types with species occurrences using research-grade data from iNaturalist. This analysis detected significant differences in distributions of some species between these nine urban habitat types and demonstrated that the proposed framework can be used to conduct urban biodiversity assessments. With increasing availability of remote sensing data and publicly-generated biodiversity data, this framework may be used for analysis of urban areas around the globe.

Keywords: urban biodiversity assessment, citizen science, urban habitat classification, landscape planning, conservation management, iNaturalist, Los Angeles

INTRODUCTION

As the percentage of people living in urban areas continues to grow, and the extent of urbanized lands continues to expand (United Nations Department of Economic Social Affairs Population Division, 2014), understanding and protecting biodiversity in cities where large numbers of people live is of global conservation relevance (Kaplan et al., 1998). Importantly, making cities more welcoming to nature can provide large portions of the populace with greater chances for regular contact with, and appreciation for, biodiversity (Parker, 2015). However, developing a widely adoptable methodology to assess, plan for, and conserve urban biodiversity remains a challenge (Margules and Pressey, 2000; Ferrier, 2002). This is largely attributable to the lack of information about wildlife habitat and species occurrence data in urban areas and a lack of understanding about the role that spatial variation in anthropogenic factors (i.e., factors related to human social structure or the built environment) may play in species distributions across urban areas. These information gaps often stem from limited access to private property to collect such data, as well as the tendency among those conducting regional biodiversity assessments to classify urbanized areas using a small number of general, "developed" land cover types (e.g., **Figure 1**), and to assume that all of these land cover types have little or no biodiversity value (Pickett et al., 2001).

Species' abundances and distributions are highly dependent on fine-scale environmental variation (Blair and Launer, 1997; Williams et al., 2009). Thus, conducting biodiversity assessments in large urban areas requires spatially explicit characterizations of their heterogeneity (Pickett and Cadenasso, 1995; Stein et al., 2014). However, existing methods to quantify urban heterogeneity differ in how they combine biophysical and anthropogenic components (Grimm et al., 2000) and in the spatial scales at which they are applied (Wu and Loucks, 1995). Coarse-scale ecosystem classifications based on physical, climatic, and biological conditions, such as the Anderson or Anderson-derived classification systems (Anderson et al., 1976) or the Multi-Resolution Land Characteristics classification system (Wickham et al., 2014) often fail to capture the dynamic social processes and varied built environments that typify urban areas and that may greatly influence species distributions (Pickett and Cadenasso, 1995). Fine-scale approaches like HERCULES (Cadenasso et al., 2007) and "ecotopes" (Ellis et al., 2000; Chan and Paelinckx, 2008), while highly detailed, combine social use and biophysical parameters within a single patch, but each of the resulting urban types/ecotopes are independent of each other, thereby obscuring how they are related in terms of physical features and ecological functions (Wiens et al., 1993; Steenberg et al., 2015). Although a growing number of studies have conducted site-specific analyses to elucidate how urban heterogeneity structures biodiversity (e.g., Kinzig et al., 2005; Hand et al., 2016), the methods used are often too complex and costly to scale up to the level of entire cities or metropolitan regions (Goddard et al., 2010).

Heterogeneity in both natural and urban ecosystems is relative and scale-dependent (Klijn and de Haes, 1994; Grimm et al., 2000); for example, patches at a particular scale (e.g., blocks) can be aggregated into larger patches (e.g., neighborhoods) and are often themselves composed of smaller patches (e.g., home lots). Thus, an urban ecosystem classification is best structured as a nested hierarchy. A hierarchical approach to urban ecosystem classification captures the scale-dependent nature of ecosystems and facilitates understanding (Wu, 1999). This approach has rapidly gained ground in urban ecology, due to its ability to incorporate biophysical and anthropogenic components (Wu and Loucks, 1995). Hierarchical approaches have been adopted for a variety of research and management purposes (e.g., Nielsen-Pincus et al., 2015; Steenberg et al., 2015; Jackson-Smith et al., 2016). However, to our knowledge, no hierarchical classification has been developed with a focus on understanding how the distribution of urban biodiversity is related to urban habitat heterogeneity, and specifically on how species' distributions in urban areas are structured by variation in the biophysical landscape, the built environment, and the social structure of the region.

Urban biodiversity assessments have also been hampered by a lack of species occurrence data (Ferrier, 2002). However, the explosive growth in citizen science projects, and the use of platforms such as eBird and iNaturalist, have greatly enhanced the amount and availability of species occurrence data from urban areas (Silvertown, 2009; Spear et al., 2017). Although citizen science data have been critiqued for being gathered with non-standardized survey methods, similar biases and errors often exist in surveys conducted by professional biologists, even in some of the most commonly used species occurrence datasets (Devictor et al., 2010). Occurrence data gathered by citizen scientists in urban areas are proving to be particularly valuable because these same urban landscapes are typically under-surveyed by traditional, professional survey methods (Ballard et al., 2017). Citizen science has become an established method for advancing scientific knowledge in urban areas, including tracking population trends and distributions of species (e.g., Gardiner et al., 2012; Border et al., 2017; Spear et al., 2017), researching animal behaviors (e.g., Bonier et al., 2007; Boydston et al., 2018; Pesendorfer et al., 2018), and identifying and prioritizing urban conservation and management actions (e.g., Gregory et al., 2005; Crall et al., 2010). Likewise, data gathered by citizen science programs have served as the basis for thousands of peer-reviewed publications (Sullivan et al., 2009).

We developed an urban biodiversity assessment framework to address the challenges associated with the lack of information about urban habitats and the lack of professionally-collected species occurrence data available for urban areas. Our urban biodiversity assessment framework has two main components (**Figure 2**): a customized hierarchical urban habitat classification scheme that uses physical and anthropogenic factors to systematically differentiate habitat types within an urban landscape; and the use of citizen science-generated species occurrence data to examine species distributions across these habitat types. Serving as a novel and broadly applicable approach for conducting urban biodiversity assessments, this framework aims to integrate and make the best possible use of available environmental, and species information. This framework allows

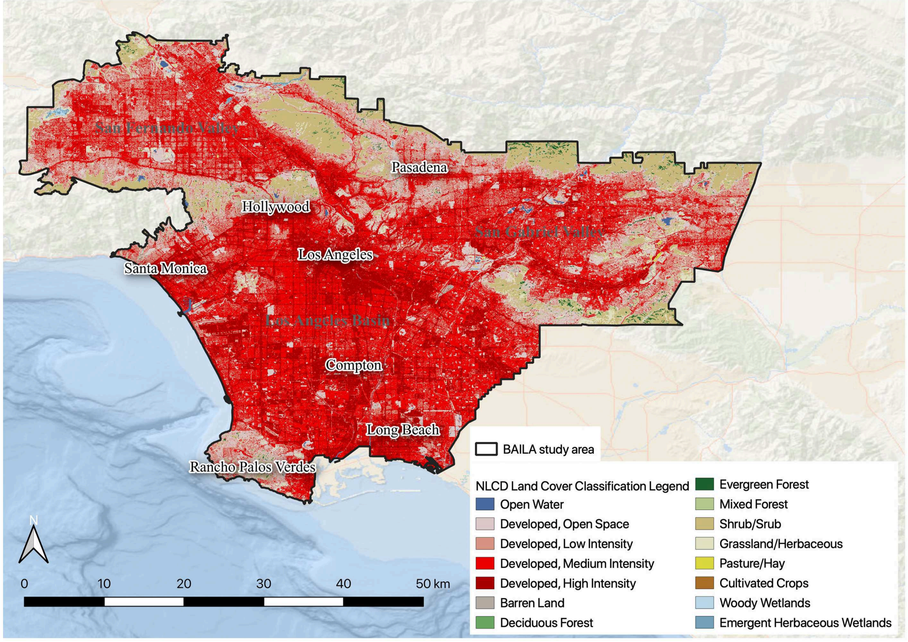

FIGURE 1 | Study area with National Land Cover Data (NLCD) classification demonstrating that much of the study area is developed with only a few NLCD classes.

users to investigate: (1) how different species use different types of urban habitats, (2) which species have been observed only in certain types of urban habitats, and (3) community compostion differences across different urban habitat types. Additionally, such pattern exploration can help users generate hypotheses to further investigate the underlying drivers of urban biodiversity patterns. These analyses may also reveal particular areas or urban habitat types that have been undersampled and where new citizen science projects might be targeted. We demonstrate this framework in the highly urbanized portion of Los Angeles County, California, USA, and we term this demonstration Biodiversity Analysis in Los Angeles (BAILA). With increasing availability of remote sensing data and publicly-generated biodiversity data, the proposed framework can be adopted globally, and provide information useful for urban planning and conservation management aimed at maintaining and enhancing the abundance and diversity of native and desirable species in urban areas.

METHODS

Study Area

The first step in developing an urban classification scheme is to specify the boundaries of the study area (**Figure 2**). To demonstrate our framework, we selected the urbanized portion of Los Angeles County, California, USA as our study area (**Figure 1**). The study area is situated in the California Floristic Province, one of the world's 36 recognized biodiversity hotspots (Myers et al., 2000). It covers 3,208 km^2, including 80 incorporated cities and 69 unincorporated neighborhoods, and is home to more than 9 million people. It contains several different biophysical environments, and three major landscapes: the Los Angeles Basin, the San Fernando Valley, and the San Gabriel Valley. Bordered to the west and south by the Pacific Ocean and to the north and east by mountains and hills, the coastal Los Angeles Basin is generally cooler in the summer and milder in the winter but receives less rainfall than the inland San Fernando and San Gabriel Valleys. Daytime temperatures can vary as much as 20°C (36°F) between the coastal Los Angeles Basin and the San Fernando Valley or San Gabriel Valley. Although 86% of our study area has been heavily modified through the development of residential, commercial, industrial, and transportation infrastructure (**Figure 1**), recent studies and iNaturalist data demonstrate that it nonetheless contains a broad array of species (e.g., Clarke et al., 2013; Hartop et al., 2015; Allen et al., 2016). However, there is little understanding of how different taxa are distributed across the study area and of the factors that drive those distributions.

Identifying the Geographic Unit for the Urban Classification Scheme

The second step in developing an urban classification scheme is to select a basic geographic unit for analysis (**Figure 2**). The geographic unit should be selected based on the scale at which users wish to apply the resulting classification scheme, as well as the scale at which relevant data are available within the study area. The geographic unit may be based on ecosystem-based boundaries (e.g., subwatersheds or climate zones), jurisdictional boundaries (e.g., cities or neighborhoods), demographic boundaries (e.g., U.S. Census Tracts or U.S. Census Block Groups), or artificial grids that divide a study area into equally-sized cells. The decision about the geographic unit should

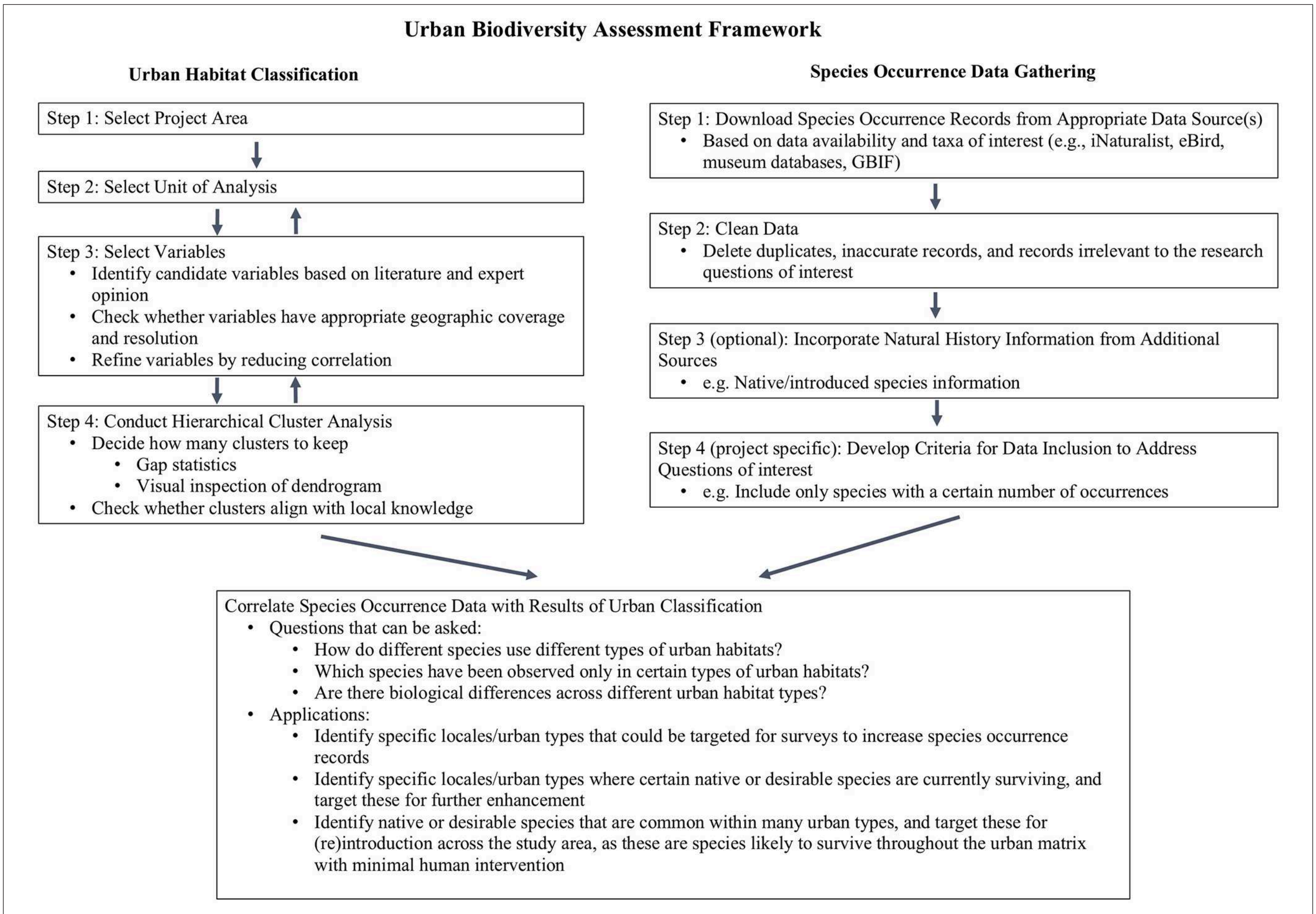

FIGURE 2 | Diagram of the urban biodiversity assessment framework.

take into consideration the future applicability and usability of the classification. For example, an artificial grid might be less useful for those focused on urban conservation planning and management, whereas jurisdictional and/or demographic boundaries may be more familiar and more easily used by decision-makers.

In the case of BAILA, to balance the trade-offs between the resolution of the available datasets, the need to ensure our results would be useful for city and county-level planning processes and conservation management programs, and to address computational limitations, we chose the U.S. Census Block Group (hereafter referred to as "BG") as our basic unit of classification. A BG is a geographic unit that is intermediate in size between the Census Tract and the Census Block. It represents a cluster of Census Blocks (often the same as or similar to city blocks). BGs are generally bounded by roads, natural features, or political boundaries, and often approximate neighborhood boundaries recognized by local residents. Generally, within a BG, biophysical factors (such as microclimate and elevation), socioeconomic status, housing development type, and landscaping are relatively homogenous (Geronimus and Bound, 1998). BGs are available in Geographic Information System (GIS) format across the entire U.S. (and can be downloaded at: http://www.census.gov/cgi-bin/geo/shapefiles/index.php). Many other countries have similar census units. BGs have been widely used in U.S. urban landscape classification studies as an appropriate unit to quantify heterogeneity across large urban areas (Grove et al., 2006). Within the BAILA study area, there were 6,040 BGs ranging in size from 0.03 km^2 to 23.65 km^2, with an average size of 0.53 km^2.

Variable Selection for the Urban Classification Scheme

To effectively understand how fine-scale environmental variation shapes urban biodiversity, an urban habitat classification scheme must include variables that represent three key elements of an urban region: the biophysical landscape, the built environment, and the human social structure. However, the inclusion of variables can vary based on data availability within the study area and data resolution compatibility. We suggest that users who adopt our framework first identify variables that have demonstrated or suspected direct effects on shaping biodiversity. This can be achieved through literature review or by consulting with local experts who have on-the-ground knowledge of the factors that shape local biodiversity. The next step is to inventory whether the proposed variables have suitable spatial datasets. Generally, local county GIS portals, Natural Earth Data (https://www.naturalearthdata.com/), USGS Earth Explorer (https://earthexplorer.usgs.gov/), US Census Bureau (https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml), NASA's Socioeconomic Data and Applications Center (https://sedac.ciesin.columbia.edu/), and Esri Open Data (https://hub.arcgis.com/pages/open-data) are reputable places to search for free, remotely sensed and GIS-based data. We also encourage potential users to contact local biodiversity experts, researchers, and conservation agencies for input on sources of available and suitable data. Fortunately, remotely sensed and GIS-based environmental data are becoming increasingly available worldwide. Finally, users must refine the list of candidate variables and develop a final set to be used in the analysis. In this step, users first should ensure that the data are of similar resolution and fully cover the study area. Users may also address collinearity between variables, either by extracting features using Principle Component Analysis (PCA) (Wold et al., 1987; Jackson-Smith et al., 2016), or by running correlation analyses among variables, and removing highly correlated variables based on knowledge about which variable has a weaker mechanistic relationship with urban biodiversity. The advantage of using correlation analyses is that they are easier to interpret than PCA.

In BAILA, through discussions with experts and literature review, we first identified 48 candidate variables relevant to the distribution of biodiversity in our study area. Those variables represent the biophysical, built environmental, and social aspects of the urban landscape. After data screening, 31 variables were kept whose data resolution was suitable for BG level classification and had full coverage of the study area. We further narrowed down those 31 variables to 18 based on reducing collinearity between variables. Specifically, when variables were highly correlated ($r > 0.6$), we kept variables that had the most direct impact on biodiversity. For example, we excluded land use (e.g., commercial, residential, industrial, etc.) and housing type (e.g., single-family housing, multi-family housing) from the framework because these attributes are highly correlated with percentage of imperviousness and greenness, population density, and traffic density (Appendix S1 in **Supplementary Material**); further, it is these latter factors, and not land use and housing type, that are the more direct drivers of urban biodiversity (Luck and Wu, 2002). Notably, we did not include a variety of socio-economic variables, such as education, income, property value, and ethnicity. Although some studies have identified correlations between socio-economic factors and urban vegetation (Luck and Wu, 2002), the relationship between socioeconomic factors and urban biodiversity, independent of other biophysical and built environment attributes, is not well-understood. In addition, we performed a sensitivity analysis by removing those highly-correlated variables (e.g., number of housing units, BG size, and nighttime light) one at a time to evaluate whether the final classification outcome changed dramatically and meaningfully in a way that was consistent with local knowledge of the region. We kept 18 variables for which there are strong empirical or theoretical grounds for presuming that they affect urban biodiversity and for which there are appropriate datasets for the analysis (**Table 1**). They include temperature, precipitation, terrain, landcover, greenness, distance to natural areas, population, and traffic noise and density. As it happens, these 18 variables are all well studied and known to have effects on biodiversity in urban areas around the world. These 18 variables may serve as examples for variable selection globally.

All 18 variables were calculated for each of the 6,040 BGs based on the definitions provided in **Table 1**. Given that the 18 variables have different units of measurement, we standardized each variable to range from 0 to 1. Data extraction and consolidation were performed in R 3.4.2 utilizing *sf* and *tidyverse* packages.

Conducting the Hierarchical Cluster Analysis

A hierarchical clustering algorithm is recommended for users to develop a customized urban habitat classification. Hierarchical clustering starts by treating each unit (in our BAILA case study, the units are the BGs) as a separate cluster, then repeatedly merges the two most similar clusters (Wilks, 2011). This continues until all the clusters are merged together, resulting in a nested hierarchical structure of the clusters (Wilks, 2011). Thus, it is an ideal method to reveal the hierarchical structure of complex urban environments. Hierarchical clustering can be performed with either a distance matrix or raw data. When raw data are provided, the algorithm requires a specified distance method to convert it to a distance matrix. Another feature of a hierarchical clustering algorithm is that the user decides how many final types the classification will identify (e.g., 5 types, 9 types, or 40 types). This grants users the flexibility to classify urban areas into a few, generally distinctive types, or numerous types that have more subtle differences. There is no definitive method for determining the optimal number of clusters in an analysis. A simple and frequently used solution consists of visually inspecting the dendrogram produced by hierarchical cluster analysis to see if it suggests a particular number of clusters (Bridges, 1966; Köhn and Hubert, 2006). Gap statistic is another method to estimate the optimal number of clusters by identifying at which point the rate of increase of the gap statistic begins to slow (Tibshirani et al., 2002). Whatever approach is used, we suggest that users check the final classification results to ensure that they are consistent with local knowledge. Decisions about the final number of clusters should also take into consideration the potential application and usability of the final urban habitat classification.

In BAILA, we used hierarchical cluster analysis to categorize the 6,040 BGs based on variation in the 18 input variables. We used Euclidean distance to measure dissimilarity between

TABLE 1 | List of variables used in the BAILA urban typology classification framework.

Variables	Description and definition	Source
BIOPHYSICAL LANDSCAPE		
Average annual temperature	Mean temperature per block group	The basin characterization model (BCM) dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution:270 m)
Maximum temperature	Mean maximum temperature of June, July, and August per block group	The BCM dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution:270 m)
Average annual precipitation	Mean precipitation per block group	The BCM dataset: http://climate.calcommons.org/dataset/2014-CA-BCM (resolution:270 m)
Elevation	Mean elevation per block group	2006 U.S. Geological Survey (USGS) National Elevation Dataset (NED): https://egis3.lacounty.gov/dataportal/2011/01/26/2006-10-foot-digital-elevation-model-dem-public-domain/ (resolution:10 ft.)
Slope	Mean slope degree per block group	2006 USGS NED: https://egis3.lacounty.gov/dataportal/2011/01/26/2006-10-foot-digital-elevation-model-dem-public-domain/ (resolution:10 ft.)
Percentage of forest	Percentage of forest per block group	National Land Cover Database (NLCD) 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution:30 m)
Percentage of grassland	Percentage of grassland per block group	NLCD 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution:30 m)
Percentage of water and wetlands	Percentage of water bodies per block group	USGS National Hydrography Dataset: http://prd-tnm.s3-website-us-west-2.amazonaws.com/?prefix=StagedProducts/Hydrography/NHD/State/HighResolution/Shape/ (resolution:30 m)
BUILT ENVIRONMENT		
Tree canopy	Average percentage of tree canopy cover per block group	NLCD 2011 U.S. Forest Service Tree Canopy Analytical Layer: https://www.mrlc.gov/data/nlcd-2011-usfs-tree-canopy-cartographic-conus-0 (resolution:30 m)
Greenness (EVI)	Mean Enhanced Vegetation Index per block group	2016–2017 USGS Landsat 7 surface reflectance: http://clim-engine.appspot.com (resolution:30 m)
Imperviousness	Average percentage of impervious surface per block group	NLCD 2011 Percent Developed Imperviousness Layer: https://www.mrlc.gov/data/nlcd-2011-percent-developed-imperviousness-conus-0 (resolution:30 m)
Percentage of urban open space	Percentage of urban open space per block group	NLCD 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution:30 m)
Percentage of urban areas	Percentage of urban areas per block group	NLCD 2011 Land Cover Layer: https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0 (resolution:30 m)
Distance to the nearest natural areas	Average distance to the nearest natural areas per block group	L.A. County Land Types Dataset Wildlife Sanctuary Layer: https://egis3.lacounty.gov/dataportal/2015/01/08/la-county-land-types/ (resolution: parcel)
SOCIAL STRUCTURE		
Population	Total population per block group	U.S. Census 2010 Dataset: https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t (resolution: U.S. Census Block)
Population density	People/km^2 per block group	U.S. Census 2010 Dataset: https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t (resolution: U.S. Census Block)
Traffic density	Average traffic density per block group	CalEnviroScreen 3.0 Dataset: https://oehha.ca.gov/calenviroscreen/indicator/traffic-density (resolution: U.S. Census Tract)
Traffic noise	Average traffic noise per block group	U.S. Bureau of Transportation the National Transportation Noise Map: http://osav-usdot.opendata.arcgis.com/datasets/aa9154e1eab44ccf8fab309052799ba0 (resolution:30 m)

each pair of BGs and Ward's minimum variance method to measure dissimilarity between clusters of BGs. All analyses were performed in R 3.4.2 using *fastcluster*, *dendextend*, and *tidyverse* packages. We used visual inspection of the dendrogram and the gap statistic to estimate the optimal number of clusters. The gap statistic was performed with 30 bootstraps and a maximum of 15 clusters. The R script used to perform the hierarchical cluster analysis and gap statistic can be found at: https://github.com/enjieli/BAILA. Last, we inspected the final results of the classfication to verify that each of those urban habitat types were consistent with our local knowledge of the study area.

Citizen Scientist-Generated Species Occurrence Data

Owing to growth in citizen science efforts, there is an increasing availability of species occurrence data for urban areas (Spear et al., 2017). Some citizen science platforms/programs are focused on a single taxon (e.g., eBird; https://ebird.org/home), while others are focused on diverse groups of organisms (e.g., iNaturalist; https://www.inaturalist.org). Generally, citizen scientist-generated species occurrence data are free and publicly accessible, and many programs/platforms also provide easy online access to download and use data. In addition, the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/en/) is a global data repository where, through a single portal, users can access biodiversity data from diverse sources including museum specimen records and citizen science observations.

For BAILA, we used iNaturalist observations as our source of species occurrence data. iNaturalist has gained great popularity in Los Angeles County due to a series of ongoing citizen science projects managed by the Natural History Museum of Los Angeles County (Ballard et al., 2017). Also, the iNaturalist database contains species occurrence records for a broad suite of taxa, making it ideal for biodiversity assessments. We used 59,842 observations (2,281 species) of species-level, research-grade iNaturalist observations spanning a variety of taxa (e.g., birds, plants, insects, reptiles, mammals, gastropods, arachnids, fungi, etc.) reported between 1 January 2010 and 15 September 2017 (GBIF.org, 2017) to assess biodiversity patterns across our study area. iNaturalist data can be downloaded through a data export tool (https://www.inaturalist.org/observations/export) or through GBIF. Research-grade observations are defined by iNaturalist as observations with a photo voucher, locality, date, and community-supported identification, and they cannot be cultivated or captive organisms. Importantly, depending on the research questions, users might want to include cultivated or captive organisms as these may be important components of the flora and fauna in some urban areas. Such information is also downloadable on iNaturalist. Our case study focuses on wild biodiversity; therefore, we did not include cultivated or captive organisms. Additionally, we gathered information on the provenance (native/introduced status) of these species from the California Department Fish and Wildlife, Calflora, the California Bird Records Committee, and iNaturalist. We were able to categorize 857 species as native to California and 434 as introduced. An additional 990 species (mostly insects) lacked provenance information.

Coupling Species Occurrences With the Urban Habitat Classification

Using species occurrences in parallel with an urban habtiat classification, our framwork can offer insights on the distribution of local urban biodiversity, facilitating the exploration of a variety of ecological questions. Using BAILA as an example, our framework can be used to explore the number of observations and species observed within each urban habitat type, the numbers of native and introduced species across taxa and urban habitat types, as well as aspects of the urban habitat that could be modified to make the area more welcoming to certain species. Further, our framework can investigate the shared species among urban habitat types, and the suites of species unique to specific urban habitat types. Lastly, our framework can be used to examine community dissimilarity across the urban habitat types. Due to the non-standardized survey method of citizen science-generated biodiversity data, we suggest that users develop criteria for data inclusion to address questions of interest. For example, when analyzing species found only in certain types of urban environments, a minimum number of observations can be set to ensure that those species have been commonly observed and therefore, that the observations are unique to that urban habitat type(s). However, such a cutoff is subjective, will depend on the total number of occurrences and the desired accuracy of the assesment, and may sharply limit the number of species and occurrences available for analysis. We suggest users set a cutoff based on inspection of the histogram or percentile rank of the numbers of observations per species.

In the case of BAILA, when analyzing the shared species among urban habitat types, and the suites of species unique to each urban habitat type, many species were observed only a few times within our entire study area, making it difficult to distinguish whether they were unique to a certain urban habitat type, or whether they were simply difficult to observe or under-sampled. Therefore, we only included species with at least 5 observations (945 out of 2,281 species) in our analysis. In the BAILA dataset, there are 59,842 observations of 2,281 species. The median number of observations per species is 3, the 60th percentile is 5, and the 75th percentile is 13. While using the 75th percentile cutoff (species with at least 13 observations) would surely increase the confidence of finding unique species in each urban habitat type, it would significantly reduce the number of species to be included in the analysis. In this case, only 587 out of 2,281 (about 26%) species would be kept for further analysis, which would dramatically reduce the representation of the biodiversity of the region. Therefore, to ensure we have some representation of the diverse species in the region, we choose the 60th percentile as the cutoff, which is five observations per species.

We used Non-metric Multidimensional Scaling (NMDS; Kruskal, 1964) to examine community dissimilarity across the urban habitat types. For ordination analyses, we treated each BG containing iNaturalist observations as a sample. Within each sample, the iNaturalist observations were treated as sampling units. Because it is mathematically difficult to calculate community dissimilarity with 2,281 species, especially when sites share few species, we analyzed only the 100 most frequently observed species using BGs that contained at least 30 observations. As a result, 160 BGs with 24,571 observations of the 100 most observed species were retained for ordination analyses. All 9 of our urban habitat types were included within the 160 BGs. We used the Jaccard coefficient, treating species with observations as "present" and those without observations as "absent," to construct similarity matrices of those 160 BGs. This reduces the noise caused by uneven and biased sampling efforts in the iNaturalist dataset and heightens the signal of species distribution patterns. The fit (or stress) of an NMDS ordination was evaluated at both 2- and 3-dimensions with 1,000 iterations. We also performed a Permutational Multivariate Analysis of Variance (PerMANOVA) to test whether the community compositions among the various urban habitat types were significantly different based on 1,000 permutations of the data. Both NMDS analysis and PerMANOVA were performed using the *vegan* package in R 3.4.2.

RESULTS

A Typology for Urban Biodiversity

The gap statistic (**Figure 3**) indicated the study area could be optimally divided into three ($gap_3 = 1.5211$; **Figure 3**) distinct categories which are the less urbanized habitat types (Types 1–4),

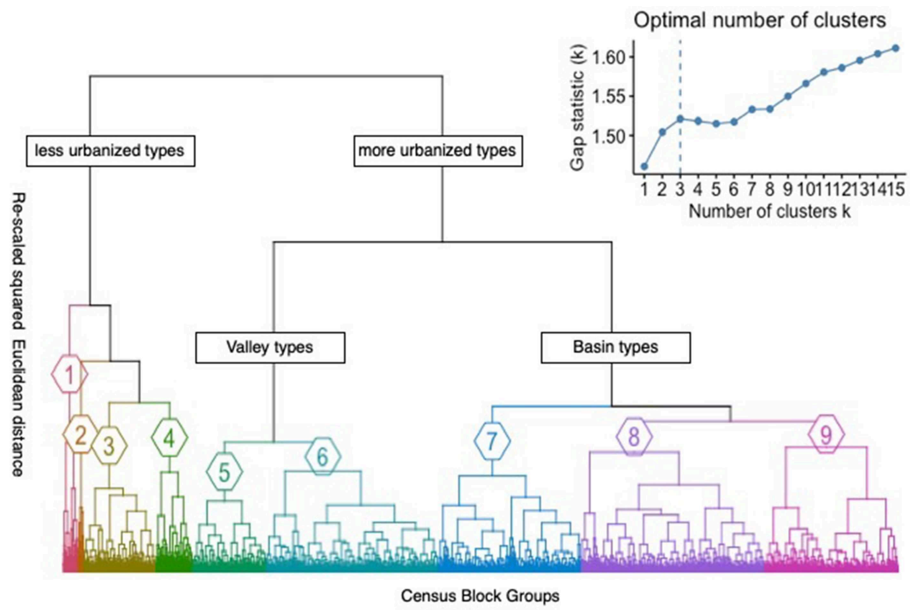

FIGURE 3 | Dendrogram showing the hierarchical clustering of Census Block Groups and the distance among clusters in multivariate data space. The gap statistic (upper right) showing the total within-cluster variation for different values of k; the number of optimal clusters was determined by identifying at which point the rate of increase of the gap statistic began to slow down. Refer to **Figure 4** for definitions of the nine urban habitat types.

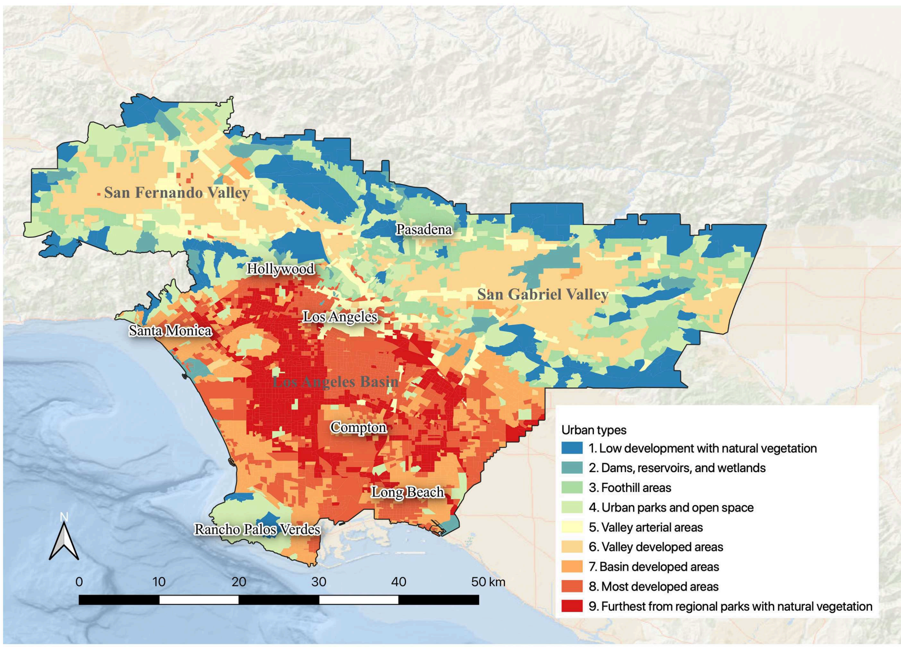

FIGURE 4 | Spatial layout of the nine urban habitat types in the study area. These nine urban habitat types were identified from hierarchical clustering of 18 variables.

and two categories of more urbanized types: Valley urban habitat types (Types 5–6), and Basin urban habitat types (Types 7–9; **Figures 3**, **4**). We also identified 9 distinct urban habitat types nested within these three different categories based on visual inspection of the dendrogram (**Figures 3**, **4**). Each of these nine urban habitat types was given a name that reflects its geographic location and/or an additional distinctive feature to improve communication (Appendix S2 in **Supplementary Materials**). It should be noted however, that each of these nine urban habitat types was delineated by a cluster analysis of 18 variables, and the names that we assigned these urban habitat types are at best a shorthand that allows us to more readily communicate about them, but which in no way fully describes how they differ from one another.

Overall, there were significant differences between the less urbanized and the more urbanized habitat types in percentage of impervious surface ($M = 32.78$, $SD = 13.46$ vs. $M = 64.78$, $SD = 11.04$; $t_{(6038)} = 2.89$, $p < 0.001$), percentage of tree canopy cover ($M = 4.78$, $SD = 4.51$ vs. $M = 64.78$, $SD = 1.76$; $t_{(6038)} = 62.46$, $p < 0.001$), and greenness ($M = 0.22$, $SD = 0.05$ vs. $M = 0.14$, $SD = 0.04$; $t_{(6038)} = 52.90$, $p < 0.001$). The dendrogram (**Figure 3**) also indicated that there was great variation among the four less urbanized habitat types, while variation among the 5 more urbanized habitat types was not quite as strong.

Differences among the more urbanized habitat types in climatic factors, such as temperature and precipitation, were largely explained by geography, with Types 7 (Basin developed areas), 8 (Most developed areas), and 9 (Furthest from regional parks with natural vegetation) occurring largely in the more coastal Los Angeles Basin, and Types 5 (Valley arterial areas), and 6 (Valley developed areas) occurring largely in the San Gabriel and San Fernando Valleys to the north. The Basin urban habitat types had significantly cooler mean annual temperatures ($M = 23.05°C$, $SD = 1.05$ vs. $M = 25.68°C$, $SD = 0.58$; $t_{(5104)} = 52.90$, $p < 0.001$), and less rainfall ($M = 347.94$ mm, $SD = 25.95$ vs. $M = 421.27$ mm, $SD = 32.77$; $t_{(5104)} = 62.46$, $p < 0.001$) than the Valley urban habitat types.

Patterns of iNaturalist Observations

The iNaturalist observations were unevenly distributed across the study area (See **Table 2** and Appendix S3 in **Supplementary Materials** for species accumulation curves for each urban habitat type). There were more observations in the less urbanized habitat types (Types 1–4; $n = 40,122$) than in the more urbanized habitat types (Types 5–9; $n = 19,720$) (**Table 2**). For BGs that have iNaturalist observations, the average number of observations, number of species observed, and the density of observations were higher in the less urbanized habitat types (**Table 2**). Types 1 (Low development with natural vegetation), 2 (Dams, reservoirs, and wetlands), and 4 (Urban parks and open space), where the majority of the public lands are located, had the most observations per BG (139, 164, and 53 respectively), highest species richness per BG (51, 64, 23, respectively), and highest species richness per unit area (35/km^2, 102/km^2, and 28/km^2, respectively), while Type 5 (Valley arterial areas), which contains busy and loud traffic areas, had the fewest number of observations (2,421) and the fewest species (523) observed.

Insects, birds, and flowering plants (Magnoliophyta) constituted the majority of observations across all 9 urban habitat types (**Figure 5**). Type 1 (Low development with natural vegetation) had the greatest diversity of observed native flowering plant species (207). However, even in the highly urbanized areas, such as Types 5 (Valley arterial areas), and 9 (Furthest from regional parks with natural vegetation), more than 50 native flowering plant species were observed. Overall, we found 26,824 observations of 772 of California native species in the less urbanized habitat types (Types 1 through 4) and 9,679 observations of 539 native species in the more urbanized habitat types (Types 5 through 9). Native species accounted for

TABLE 2 | Summary of iNaturalist observations by urban habitat type.

Urban habitat type	Total area (km^2)	Total BGs	Avg. BG size (km^2)	No. of BGs with more than 1 ob (of total BGs)	No. of obs	No. of Sp.	Avg. No. of obs per BG	Avg. No. of Sp. per BG	Avg. No. of Sp. per km^2	No. of obs of native species (No. of native Sp.)	No. of obs of introduced species (No. of introduced Sp.)
1. Low development with natural vegetation	466.83	109	4.28	105 (0.96)	14,576	1,084	139	51	35	9,915 (495)	3,151 (208)
2. Dams, reservoirs, and wetlands	96.13	39	2.46	37 (0.95)	6,069	833	164	64	102	4,511 (451)	960 (168)
3. Foothill areas	340.32	524	0.65	398 (0.76)	6,806	779	17	8	26	3,664 (323)	2,069 (216)
4. Urban parks and open space	411.43	262	1.57	239 (0.91)	12,671	1,184	53	23	28	8,734 (559)	2,351 (247)
5. Valley arterial areas	216.75	536	0.40	352 (0.66)	2,421	523	7	5	15	1,261 (215)	735 (150)
6. Valley less developed areas	536.54	1245	0.43	687 (0.55)	4,282	724	6	4	13	2,313 (270)	1,113 (189)
7. Basin less developed areas	376.50	1033	0.36	616 (0.60)	5,346	884	9	6	23	2,907 (375)	1,228 (190)
8. Most developed areas	460.12	1328	0.35	763 (0.57)	3,516	675	5	4	19	1,515 (269)	1,130 (164)
9. Furthest from regional parks with natural vegetation	303.82	964	0.32	598 (0.62)	4,155	626	7	4	16	1,683 (227)	1,434 (141)

Ob(s) Stands for observation(s).

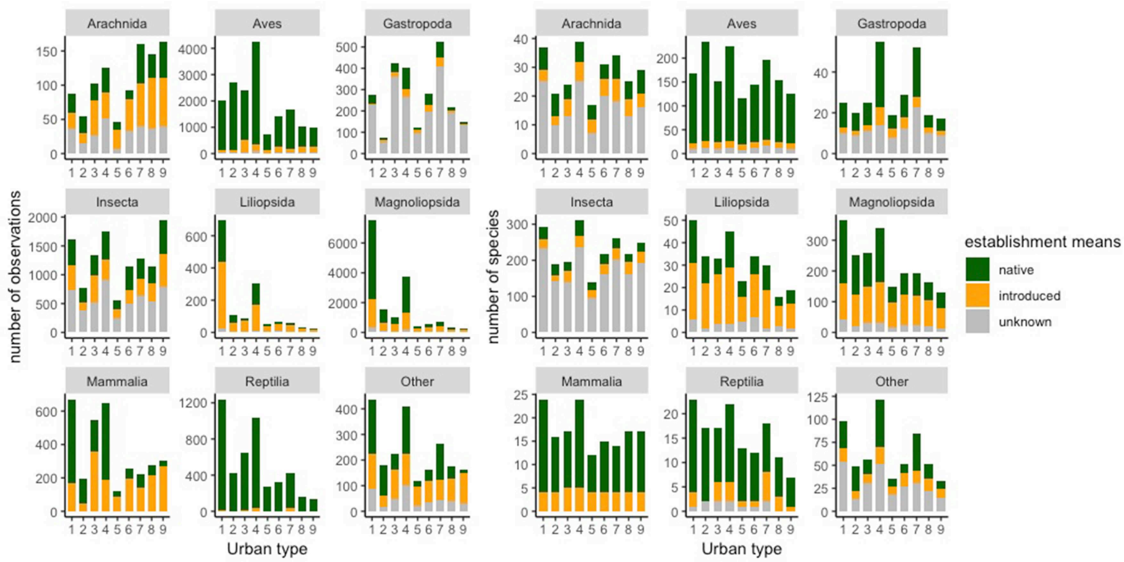

FIGURE 5 | Summary of iNaturalist data by select taxa in each urban habitat type.

the majority of occurrences (67%) in the less urbanized habitat types. Type 4 (Urban parks and open space) had the highest number of both native species (559 species) and introduced species (247 species).

The observed abundance and richness of introduced species varied depending on taxon and urban habitat type, and they were not dominant in any of the 9 urban habitat types (**Table 2** and **Figure 5**). Across all types, 83% (Type 5; Valley arterial areas) to 89% (Type 2; Dams, reservoirs, and wetlands) of the bird species occurrences reported were native to California; fewer than 10% (12–14 species) were introduced species (**Figure 5**). For mammals, we found that there were more occurrences of native species than introduced species in areas with lower human population densities and less human activity, such as Types 1 (Low development with natural vegetation), 2 (Dams, reservoirs, and wetlands), and 4 (Urban parks and open space), whereas in areas with higher human populations and more activity, such as Types 3 (Foothill areas), and 5 (Valley arterial areas) through 9 (Furthest from regional parks with natural vegetation), introduced mammal occurrences were reported twice as often as native mammals (**Figure 5**). This result was largely driven by observations of a single species, the Eastern Fox Squirrel (*Sciurus niger*), which is the focus of a museum-led citizen science project.

The distribution of species (with at least 5 observations) varied across the 9 urban habitat types. A total of 185 species (20%) were found in all nine urban habitat types, including the Western Fence Lizard (*Sceloporus occidentalis*), Eastern Fox Squirrel, European Honey Bee (*Apis mellifera*), Brown Garden Snail (*Cornu aspersum*), Monarch Butterfly (*Danaus plexippus*), House Sparrow (*Passer domesticus*), and House Finch (*Haemorhous mexicanus*). Those 185 commonly observed species included 61 bird species, 50 of which were native, and 45 flowering plant species, of which only one third (15 species) were native, and 28 were introduced. Seventeen species were exclusively observed in only one of the 9 urban habitat types. Most of these were native plants in Type 1 (Low development with natural vegetation) and shorebirds and freshwater birds in Types 2 (Dams, reservoirs, and wetlands), and 4 (Urban parks and open space). In addition, 120 species were unique to the less urbanized habitat types (Types 1 through 4), the most common of which were California Broomsage (*Lepidospartum squamatum*), California bordered plant bug (*Largus californicus*), Phainopepla (*Phainopepla nitens*), Rock Wren (*Salpinctes obsoletus*), and White-breasted Nuthatch (*Sitta carolinensis*). 20 species were found exclusively in the more urbanized habitat types (Types 5 through 9), with 7 being introduced, 4 native, and 9 of unknown provenance, including: the slug *Deroceras invadens*, Spotted Lady Beetle (*Adalia bipunctata*), and Common House Spider (*Parasteatoda tepidariorum*).

Ordination Analysis Using the 100 Most Commonly Observed Species

For the 160 BGs included in the ordination analysis, Types 1–9 had 40, 16, 22, 33, 8, 13, 10, 13, and 5 BGs, respectively. Thus, we had samples in each of the nine urban habitat types. There were more than 4 times more observations from the less urbanized habitat types (19,748) than from the more habitat urbanized types (4,823). We used a 3-dimensional solution for the NMDS (Appendix S4 in **Supplementary Materials**), because we could not find a 2-dimensional solution for convergence. Overall goodness-of-fit was good (stress = 0.161). Results of PerMANOVA suggested that observed species composition differed between the urban habitat types (r^2 = 0.15743, $p = 0.001$).

TABLE 3 | Results of PerMANOVA pairwise comparisons of community composition among the nine urban habitat types. Refer to **Figure 4** for definitions of the nine urban habitat types.

Pairs	*F*	r^2	*p*-value	p_{adjust}
1vs. 2	6.542	0.108	0.001	0.036
1 vs. 3	7.874	0.116	0.001	0.036
1 vs. 4	4.505	0.060	0.001	0.036
1 vs. 5	6.186	0.119	0.001	0.036
1 vs. 6	10.333	0.168	0.001	0.036
1 vs. 7	6.033	0.112	0.001	0.036
1 vs. 8	12.663	0.199	0.001	0.036
1 vs. 9	6.147	0.125	0.001	0.036
2 vs. 3	3.329	0.085	0.001	0.036
2 vs. 6	2.839	0.095	0.001	0.036
2 vs. 8	5.297	0.164	0.001	0.036
3 vs. 4	2.677	0.048	0.001	0.036
3 vs. 8	2.098	0.060	0.001	0.036
4 vs. 5	2.773	0.066	0.001	0.036
4 vs. 8	5.592	0.113	0.001	0.036
5 vs. 8	2.284	0.107	0.001	0.036

The F is a Pseudo F test score to compare among-group variances and within-group variances with no assumption of multivariate normality. p-values obtained by comparing the actual F test result to that gained from 1,000 random permutations of the objects between the groups. Bonferroni correction reported as p_{adjust}. Only significant comparisons were reported.

Pairwise comparisons showed that Type 1 (Low development with natural vegetation) and Type 2 (Dams, reservoirs, and wetlands) had significantly different species compositions from the remaining 7 urban habitat types (**Table 3**). The 4 less urbanized habitat types had very distinct community compositions from each other, with the exception of Types 4 (Dams, reservoirs, and wetlands) and 2 (Urban parks and open space), which were relatively similar to one another ($F = 2.434$, $r^2 = 0.049$, $p = 0.004$, and $p_{\text{adjust}} = 0.144$). This is not surprising, considering some urban parks contain lakes and ponds. However, with the exception of the pair of Type 5 (Valley arterial areas) and Type 8 (Most developed areas), we did not find statistically significant differences in species composition amongst the 5 most urbanized habitat types (Types 5 through 9) (**Table 3**).

DISCUSSION

BAILA Case Study

We found quantifiable environmental and biological differences within the BAILA study area. Instead of treating the urban area as one mass region with low biodiversity potential, our hierarchical clustering analyses distinguished nine urban habitat types that differed in extent of urbanization (i.e., percentage of impervious surface cover, human population density, percentage of urban area cover), climate, and other variables including traffic density and traffic noise. Species were distributed across these types in various ways, with some species being found across all types and others that were more restricted to one or a subset of types. Each of the 9 urban habitat types, support a variety of organisms, albeit with different levels of observed species richness and overall abundance (**Table 2** and **Figure 5**). For example, more than 200 native species were observed in Type 5, one of the more urbanized habitat types, and one of the types covering the smallest total area. This also indicates that native species can be found not only in large urban green spaces but also within commercial, industrial, and residential districts (Rudd et al., 2002; Blair, 2004; Acar et al., 2007). This in turn indicates there is potential to enhance biodiversity in all of the urban habitat types with strategic interventions.

The variables used for this classification span the biophysical, built, and social landscapes, and urbanization was found to be the main factor driving the basal divergence in the hierarchical classification (less urbanized types vs. more urbanized types; **Figure 4**). Ordination analysis also showed that there were significant differences in community composition associated with differences between the urban habitat types (**Table 3**). This finding corroborates other studies that have shown that urban heterogeneity affects species distributions (Stein et al., 2014; Norton et al., 2016). Although we did not find significant differences in observed species distributions among the 5 most urbanized habitat types (Types 5 through 9) (**Table 3**), this might have resulted from our use of only the 100 most commonly observed species in the ordination analysis. While analyzing commonly observed species increased the statistical confidence of the community composition analysis, it might have caused us to overlook species that are truly unique to just one or a few of the more urbanized types. On the other hand, this finding might be indicative of "biotic homogenization" within the more urbanized types across our study area. Many studies indicate that urban areas can be biotically homogenous, containing a suite of "cosmopolitan," generalist species (Blair, 2004; McKinney, 2006; McDonald et al., 2013; Leong and Trautwein, 2019). Collection of additional occurrence data in the 5 more urbanized types would help answer questions about whether they support distinctive suites of species or are "biotically homogenized."

Our study demonstrates that the iNaturalist platform provides taxonomically diverse biodiversity data that can be used for spatially explicit urban biodiversity studies (see also Cooper et al., 2007; Bonney et al., 2009; Spear et al., 2017). About 60% of the land within our study area is privately owned, making it difficult to access and survey using traditional approaches. Datasets of professionally gathered species occurrence data, such as the California Natural Diversity Database (CNDDB), and other state Natural Heritage Program and national Conservation Data Center databases, contain few records for urban areas. For example, CNDDB had 956 occurrence records for only 154 species within our study area, and most of those species are rare and/or of special conservation concern, with little information about common and/or introduced species and with even less information from the more urbanized areas. Further, the number of records in such databases is growing only slowly, especially for heavily urbanized areas. In contrast, iNaturalist contained more than 59,842 observations of a diverse assortment of 2,281 species, including birds, plants, insects, reptiles, mammals, gastropods, arachnids, and fungi across all 9 urban habitat types, and those numbers are growing rapidly as more and more people participate in citizen science projects and as more and more people use iNaturalist.

Our case study could also provide insights for on-the-ground conservation management and planning in the Los Angeles area. There is increasing interest in enhancing native plant biodiversity within our study area, and other urban areas, through urban habitat restoration. Our analysis has generated a list of native plants that naturally occur and are commonly found across all 9 urban types [e.g., Eastern Mojave buckwheat (*Eriogonum fasciculatum* var. *foliolosum*), laurel sumac (*Malosma laurina*), toyon (*Heteromeles arbutifolia*), willow baccharis (*Baccharis salicina*), black sage (*Salvia mellifera*), California brittlebush (*Encelia californica*), western sycamore (*Platanus racemosa*), Southern California black walnut (*Juglans californica*), California poppy (*Eschscholzia californica*), and Coulter's Matilija poppy (*Romneya coulteri*)], even in areas with high percentages of impermeable cover (i.e., buildings and pavement). This offers practical suggestions for the implementation of urban habitat enhancement projects that intend to incorporate plants. In addition, our analyses found that while introduced species occurred in all urban habitat types, introduced mammals and spiders were observed more frequently in the more urbanized habitat types (**Figure 5**). These results suggest that efforts to detect and track introduced species should be concentrated in more urbanized areas, where citizen science approaches can be especially effective at overcoming the challenges of private property access for detecting the arrival and spread of introduced species.

Merits and Shortcomings of This Framework

Biodiversity assessments require information on both environmental variation and spatial distributions of the organisms within a study area. On the one hand, habitat classification derived from remotely sensed environmental data (such as climate, terrain, soil, landcover, etc.) have been widely used as surrogate information in assessing biodiversity. However, mapped habitat types may or may not correspond with actual biological differences. The potential for mismatches between assumed vs. real species-habitat relationships is high. On the other hand, species occurrence data are often sparse or unevenly sampled. Despite the abundant amount of citizen science-generated species occurrence data, it is still challenging to detect the geographical patterns, particularly in relation to environmental variation. By using an urban habitat classification in tandem with species distribution data, our framework serves as a useful tool to better evaluate whether mapped habitat types are meaningful in predicting biodiversity, as well as to detect species distribution patterns in relation to environmental variation. The combination of an urban habitat classification and species distribution data allows users to generate hypotheses to futher investigate the underlying drivers of the observed biodiversity patterns.

Remote sensing and GIS have progressed over the past decade with inexpensive, fine-resolution, and easily available data, as well as advanced analytical techniques that allow for the development of urban habitat classification systems tailored to urban biodiversity. An urban habitat classification generated using our framework will differ depending on the urban area evaluated, the variables used, the scale at which the classification is done, and the number of clusters chosen. In the future, data for many of our 18 variables are likely to exist at a finer resolution across our study area than those available today. Data on other variables may also become available, allowing further improvements to our analyses. We identified several other variables that may have been particularly useful for our study but for which data were unavailable or were not available at a fine enough scale across our study area to warrant inclusion. Examples include GIS data of soil types, street tree species, vegetation types, and irrigation system presence and use. When adopting this framework for other regions, we encourage users to carefully select variables based on availability of data, socio-ecological context of the locale, species of interest, and specific objectives of the analysis. While we developed this framework to study broad patterns in biodiversity, it could be easily modified to address other questions, such as how certain taxa use particular urban environments. In that case, the variables used for the urban classification should be key drivers that affect the distribution of the taxa of interest.

Citizen science-generated biodiversity data provide taxonomically diverse information in urban areas that are historically under-sampled by professionals. Our framework has several advantages, especially in urban areas where the lack of professionally-collected species occurrence data have historically limited opportunities for such analyses. Among these benefits are the incorporation of more data gathered on privately-owned lands, educational and other societal benefits related to involving volunteer citizen scientists in the gathering of data (Ballard et al., 2017), and avoiding the expense involved in employing professional biologists for field or lab work. Biodiversity assessments typically require taxonomic experts to carry out surveys or identify specimens in existing collections; however, this taxonomic expertise can now be crowdsourced to the online iNaturalist community (which includes taxonomic experts), such that the input dataset can be made up of high-quality occurrence records for which the species identity has a high level of confidence.

Our framework may also serve as a useful tool for identifying gaps in citizen science-generated species occurrence data. An analysis of the locations of the iNaturalist observations across the entire study area reveals specific areas (i.e., specific BGs) and specific urban habitat types that apparently have not been sampled by community scientists or where surveys for specific taxa have not yet been undertaken, thus revealing specific locales that could be targeted for future surveys. More observations from unsampled and under-sampled areas will improve our understanding of how different species utilize different urban habitats. In particular, such information will be useful to guide future citizen science projects to fill in such data gaps, and to improve the appreciation of and engagement with nature in communities located in currently under-sampled BGs. Furthermore, there are BGs that have no iNaturalist records at all. Using our framework, we can predict which species might occur in an under-sampled BG based on those that have been observed in other BGs of the same urban habitat type. Citizen science projects that focus on data collection in these BGs can be used to test these predictions.

In order to generate a meaningful urban habitat classification and be able to detect geographic patterns of local urban biodiversity, our framework requires a large amount of environmental and species occurrence data. Although the hierarchical classification could be performed with a minimum of one input variable, the outcome would be less comprehensive in terms of representing the full spectrum of the biophysical, built environmental, and social aspects of the urban environment. For example, for areas with a lack of social data, one could generate an urban habitat classification with only biophysical and built environment data. However, such an urban habitat classification might be weak in interpreting the effects of social variables on urban biodiversity. One can also generate an urban classification solely using social factors, but the resulting classification might not provide direct insights into how physical features shape local biodiversity. In general, we recommend that users select a suite of variables spanning the biophysical, built environmental, and social aspects of urban environments to achieve a more comprehensive urban habitat classification. However, it is not necessary to overload the classification model with variables, as many of the variables are correlated. On the other hand, the more species occurrence data incorporated, the more rigorous the biodiversity assessment can be. For areas lacking in species occurrence data, we encourage users to promote citizen science projects that gather occurrence records for use in future urban biodiversity studies. In addition, where citizen science-generated species occurrences data are growing rapidly, we encourage users to take advantage of the increasing availability of data to continuously improve their understanding of biodiversity. For example, in BAILA, we used 59,842 iNaturalist observations collected between 1 January 2010 and 15 September 2017. As of 28 June 2019, an additional 114,295 research grade (twice as many) observations were added in our study area. We are confident that with such significant growth in species occurrence data, some intricate and complex patterns of urban biodiversity could be revealed in our study area. To sum up, with continuous growth and development in GIS, remote sensing, and citizen science projects, many urban areas around the globe now have, or will soon have, both the environmental data and the species occurrence records needed to conduct robust urban biodiversity assessments.

CONCLUSION

The goal of this study was to generate an urban biodiversity assessment framework that is relatively simple to undertake, uses data from public sources and citizen science efforts, and is broadly applicable to other urban areas around the world. The novelty of this framework is that it combines urban habitat information with citizen science-generated species occurrence data and offers an improved understanding of urban biodiversity patterns that neither an urban habitat classification nor species occurrence information alone could reveal. With continuing advancement in GIS and remote-sensing, and the exponential growth of citizen science-generated species occurrence records, we believe that our framework will provide even more robust knowledge of urban biodiversity over time as the data used in the analyses improve. We hope our pioneering case demonstrates the importance of citizen science-generated species occurrence records such as those available from iNaturalist, and inspires and encourages other urban areas to promote citizen science projects that gather occurrence records for use in future urban biodiversity studies.

DATA AVAILABILITY

Publicly available datasets were analyzed in this study. iNaturalsit species occurrence data can be found here: https://doi.org/10.15468/dl.vnpfxd. Data and R script used for generating the urban habitat classification can be found here: https://github.com/enjieli/BAILA.

AUTHOR CONTRIBUTIONS

SP, JR, GP, and BB developed the long-term collaboration that led to this manuscript, including securing funding for this project. All authors helped design and revise this methodology. EL acquired the appropriate data layers, with assistance from BC. EL performed the analyses and drafted the manuscript, with significant input from SP, JR, and GP. All authors edited and revised the manuscript and gave final approval for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2019.00277/full#supplementary-material

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2. Appendix B: Workshop Participants

	First Name	Last Name	Specialization/Position	Affiliation
1	Ruben	Alarcon	Pollination	EcologyCalifornia State University Channel Islands
2	Carol	Bornstein	Horticulture/Botany	Natural History Museum
3	Erin	Boydston	Urban Carnivore Research	U.S. Geological Survey
4	Christy	Brigham	Planning, Science, Resources Management	Santa Monica Mountains National & Recreation Area
5	Brian	Brown	Entomology (Dipterology)	Natural History Museum
6	Brian	Cohen	Geography/GIS	The Nature Conservancy
7	Jeffrey	Cole	Entomology	Pasadena City College
8	Dan	Cooper	Ornithology/Biology	Cooper Ecological Monitoring
9	Katy	Delaney	Conservation Biology	U.S. National Park Service
10	Sabrina	Drill	Ichthyology	UC Cooperative Extension
11	Emile	Fiesler	Arthropod & Gastropod Inventories	Bioveyda Biodiversity Inventories
12	Robert	Fisher	Herpetology	U.S. Geological Survey
13	Jim	Folsom	Trees	Huntington Botanical Gardens
14	Naomi	Fraga	Botany	Rancho Santa Ana Botanic Garden
15	Kimball	Garrett	Ornithology	Natural History Museum
16	Margot	Griswold	Restoration Ecology	Land IQ
17	Jim	Hogue	Entomology	California State University Northridge
18	Darrel	Jenerette	Botany & Plant Sciences	UC Riverside
19	Jamie	King	Environmental Science	California State Parks
20	Chuck	Kopczak	Marine Ecology	California Science Center

	First Name	Last Name	Specialization/Position	Affiliation
21	Elizabeth	Long	Lepidopterology	UCLA La Kretz Center/ Natural History Museum
22	Travis	Longcore	Ornithology/Urban Ecology	University of Southern California
23	Sophie	Parker	Soil/Ecosystem Ecology & Conservation	The Nature Conservancy
24	Greg	Pauly	Herpetology	Natural History Museum
25	John	Randall	Botany/Invasive Species Ecology & Conservation	The Nature Conservancy
26	Seth	Riley	Large Predator Ecology	U.S. National Park Service
27	Phil	Rundel	Ecology/Conservation	UCLA
28	Polly	Schiffman	Grassland Ecology/Conservation	California State University Northridge
29	Brad	Shaffer	Herpetology	UCLA
30	Chris	Solek	Aquatic Ecology	Council for Watershed Health
31	Eric	Stein	Freshwater Bioassessments	Southern CA Coastal Water Research Project
32	Eric	Strauss	Urban Ecology	Loyola Marymount University
33	Jann	Vendetti	Terrestrial Malacology	Natural History Museum
34	Jannet	Vu	GIS	UCLA
35	Tom	Wake	Archaeology	UCLA
36	Gary	Wallace	Botany	Rancho Santa Ana Botanic Garden

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