frontiers in Ecology and Evolution

ORIGINAL RESEARCH
published: 28 July 2017
doi: 10.3389/fevo.2017.00086

Citizen Science as a Tool for Augmenting Museum Collection Data from Urban Areas

Dakota M. Spear[1*†], Gregory B. Pauly[2,3] and Kristine Kaiser[1,3,4]

[1] Department of Biology, Pomona College, Claremont, CA, United States, [2] Urban Nature Research Center, Natural History Museum of Los Angeles County, Los Angeles, CA, United States, [3] Section of Herpetology, Natural History Museum of Los Angeles County, Los Angeles, CA, United States, [4] Department of Biology, California State University, Northridge, CA, United States

OPEN ACCESS

Edited by:
Thomas Henry Whitlow,
Cornell University, United States

Reviewed by:
Loren B. Byrne,
Roger Williams University,
United States
Andrea Olive,
University of Toronto, Canada

***Correspondence:**
Dakota M. Spear
dms12011@mymail.pomona.edu

†Present Address:
Dakota M. Spear, Department of Zoology, University of Cambridge, Cambridge, United Kingdom

Specialty section:
This article was submitted to Urban Ecology, a section of the journal Frontiers in Ecology and Evolution

Received: 21 April 2017
Accepted: 13 July 2017
Published: 28 July 2017

Citation:
Spear DM, Pauly GB and Kaiser K (2017) Citizen Science as a Tool for Augmenting Museum Collection Data from Urban Areas. Front. Ecol. Evol. 5:86. doi: 10.3389/fevo.2017.00086

Museum collections are critical to contemporary biological research, but museum acquisitions have declined in recent decades, hampering researchers' ability to use collections to assess species responses to habitat modification, urbanization, and global climate change. Citizen science may be a key method to bolster museum collections data, particularly from urban regions, where ongoing data collection is critical to our understanding of ecosystem dynamics in a highly modified and variable landscape. In this study, we compare data collected as part of the citizen-science project Reptiles and Amphibians of Southern California (RASCals), hosted on the platform iNaturalist (www.inaturalist.org), to data in the VertNet database (www.vertnet.org), which houses millions of museum collection records from over 250 natural-history collections, for four focal species, including a native lizard of conservation concern that has declined with urbanization, a native lizard that is widespread in urban areas, and two invasive aquatic species. We compared numbers of VertNet records over time to modern RASCals records, and the number of records collected from urban, suburban, and protected areas from both databases. For all species, citizen-science records were generated much more rapidly than museum records. For three of our four focal species, RASCals participants over 27 months documented from 70 to 750% more records than were added to the VertNet database after 1990. For the urban-tolerant southern alligator lizard, RASCals participants collected nearly 45 times more modern urban records than are contained in the VertNet database. For all other species, the majority of RASCals records were collected within suburban or other highly modified landscapes, demonstrating the value of citizen science for collecting data within urban and suburban ecosystems. As new museum acquisitions decline, citizen-science projects like RASCals may become critical to the maintenance of modern species-distribution data.

Keywords: American bullfrog, citizen science, coast horned lizard, museum collections, red-eared slider, southern alligator lizard, Southern California, urbanization

INTRODUCTION

Museum collections are critical to contemporary biological research, providing data that can be used to assess shifting species ranges, changing species assemblages, the history of infectious disease, historical and present levels of environmental contaminants, the effects of global climate change, patterns of biological invasion, and more (Barber et al., 1972; Davis, 1996; Parmesan, 1996; McCarthy, 1998; Fanning et al., 2002; Suarez and Tsutsui, 2004; Lister et al., 2011). However, in recent decades collections of new specimens have declined precipitously along with decreases in funding and in the popularity of scientific collecting (Dalton, 2003; Gropp, 2003; Suarez and Tsutsui, 2004; LaDuc and Bell, 2010).

This lack of data has hampered researchers' ability to use collections to assess species responses to habitat modification, urbanization, and global climate change, even as urbanization is on the rise, both locally and globally. Urban development is a primary threat to global biodiversity, causing increases in air and soil pollution, road density, population density, average ambient temperature, and the introduction of non-native species. Combined with habitat loss attributed to urban growth, anthropogenic habitat change can have drastic negative impacts on local ecosystems, and can lead to changing species assemblages and decreases in species diversity (Mackin-Rogalska et al., 1988; Kowarik, 1995; McIntyre, 2000; Blair, 2001; McKinney, 2002; Alvey, 2006; Ditchkoff et al., 2006; Zhao et al., 2006; Grimm et al., 2008a,b; Ren et al., 2008). Yet we still lack a thorough understanding of how human development impacts ecosystem functioning and biodiversity on a broad scale (Collins et al., 2000; McIntyre, 2000; McKinney, 2002; Grimm et al., 2008a), a problem that becomes more difficult to overcome as museum acquisitions decline.

Citizen science may be key to bolstering the crucial data historically housed in museum collections. Moreover, citizen science may be a particularly effective method for obtaining data in urban regions, where challenges to a full understanding of ecosystem dynamics are manifold. First, urban ecology often requires comprehensive data collected over extremely large geographic areas to answer questions about regional patterns and responses to urbanization: most cities and their surrounding suburbs are many dozens or even hundreds of square kilometers in area. Such widespread data collection is expensive and labor intensive, challenges that are increasingly insuperable as funding for specimen collecting declines (Dalton, 2003; Gropp, 2003; Suarez and Tsutsui, 2004; LaDuc and Bell, 2010). Second, much of the land in urban areas is private property making access difficult, which limits the ability to apply standard methods for biodiversity assessment. Third, quite often, city residents do not consider the fauna observed in cities worth documenting. Citizen science provides a potential solution to all of these logistical difficulties by incorporating the recruitment of volunteers from across study areas and allowing residents to learn the importance of the wildlife in their own neighborhoods. These benefits of citizen science are especially apparent in urban areas, where large, dense, and diverse populations make volunteer recruitment easier (McCaffrey, 2005; Cooper et al., 2007; Dickinson et al., 2010; Ballard et al., 2017).

The goal of this study was to assess whether citizen science can be a solution to the urban biodiversity data crisis for species with varying responses to urbanization. To address this goal, we examined citizen-science data collected by a single project on a single geographically and taxonomically widespread citizen-science platform. We chose to focus on the iNaturalist platform (www.inaturalist.org) because it is broad and can be applied to any photographable taxon anywhere in the world. We focused on four species with different responses to urbanization, including two native and two non-native species, giving us insight into the breadth of species for which citizen science can provide critical data. We compared modern citizen-science data to data from traditional museum collections across the past century to ask (1) how citizen-science data acquisition compares with traditional museum collection growth over time; (2) how the two methods of data collection compare for data acquisition from urban areas; and (3) the benefits and limitations of citizen-science data as a tool to augment museum data for evaluating distributions in an urban landscape.

METHODS

Data Sources

We acquired the citizen-science dataset from the Reptiles and Amphibians of Southern California (RASCals; http://www.inaturalist.org/projects/rascals), a citizen-science project, which was started in June of 2013 by GBP and the Natural History Museum of Los Angeles County. RASCals is hosted on the internet-based citizen-science platform iNaturalist (iNaturalist.org), maintained by the California Academy of Sciences. The RASCals project focuses on reptiles and amphibians within the 10 counties of Southern California: San Luis Obispo, Kern, Santa Barbara, Ventura, Los Angeles, San Bernardino, Orange, Riverside, San Diego, and Imperial Counties. We used only research-grade observations, which are defined as those having a voucher photograph, date, latitude and longitude coordinates, and a community-supported identification.

We compared data from iNaturalist to museum collection data from VertNet (www.vertnet.org), an NSF-funded database that contains millions of georeferenced records from over 250 natural-history collections globally. We used all georeferenced VertNet records of specimens collected from within the 10 counties of Southern California, regardless of the institution in which the specimen was housed (Supplementary Table 1). Records from VertNet and RASCals were accessed March 2015 and September 2015, respectively. Thus, we analyzed records from the RASCals project that had accumulated over the first 27 months of the project's existence.

Focal Region

Southern California is home to approximately 22.7 million people. Most of this region and its inhabitants reside in the California Floristic Province, one of the Earth's 36 biodiversity hotspots. Hotspot status is due in large part to the dramatic habitat loss and alteration resulting from the high human population of the region and associated urbanization. Most Southern Californians reside in the Greater Los Angeles Area (18.6 million) or the Greater San Diego Region (3.3 million), with the former being the nation's second largest metropolitan region and the world's fifth largest metropolitan region in a biodiversity hotspot. Given the high biodiversity, high threats to this biodiversity, and the relatively large number of natural history museums with collections relevant to this region, Southern California is well-suited for studies on the impacts of urbanization and the use of citizen science in documenting urban biodiversity.

Focal Species

Using data from both VertNet and RASCals, we evaluated current species distributions and changes in distribution over time of two native species and two invasive species. We chose these four species because they had at least 50 observations made by RASCals participants in the first 27 months of the RASCals project and because they vary greatly in their responses to urbanization (see below) and probability of detection. Further, they represent a diverse suite of species, varying in whether they are native or non-native, terrestrial or aquatic, and declining or common in urban areas.

The coast horned lizard, *Phrynosoma blainvillii,* ranges from the Sacramento Valley of Northern California to Baja California, Mexico (Stebbins and McGinnis, 2012; Thomson et al., 2016). However, populations have rapidly declined in much of this region, especially in Southern California, due to habitat destruction and the decline of native ants, their primary food source, with the arrival and spread of non-native Argentine ants (Jennings, 1987; Fisher and Case, 2000; Suarez et al., 2000; Fisher et al., 2002; Lemm, 2006; Stebbins and McGinnis, 2012; Brattstrom, 2013; Thomson et al., 2016). *P. blainvillii* is a California Species of Special Concern (Jennings and Hayes, 1994; Thomson et al., 2016).

The southern alligator lizard, *Elgaria multicarinata,* is native to most of Southern California and is found in most habitat types, including urban areas (Stebbins and McGinnis, 2012). Because *E. multicarinata* prefers areas with some moisture (Lemm, 2006), urbanization, and its concomitant increase in available water due to yard irrigation may allow this species to colonize areas that were historically unsuitable; indeed, it is now the most widespread lizard species in heavily urbanized regions of Southern California including the Los Angeles Basin and San Diego area (based on the RASCals dataset). Despite its prevalence, this species does not bask in prominent locations; thus, it can be difficult to detect, especially in dense grassland and other heavily vegetated regions.

The red-eared slider turtle, *Trachemys scripta elegans,* and the American bullfrog, *Rana catesbeiana* (=*Lithobates catesbeianus* of some authors), are both native to the eastern U.S., but are invasive species that are widely distributed and well-established throughout California. Both are also on the IUCN-ISSG list of "100 of the World's Worst Invasive Species" (Lowe et al., 2000). Red-eared sliders are particularly common in places with high human density and moderately to highly modified habitats (Spinks et al., 2003; Conner et al., 2005; Eskew et al., 2010; Thomson et al., 2010). Historically, little permanent water habitat existed in Southern California in which this highly aquatic turtle could survive, but it has become widespread in human-modified, permanent water settings such as reservoirs and urban ponds. Because this turtle basks prominently during the day, it is relatively easy for citizen scientists to photo-voucher.

The American bullfrog, *R. catesbeiana*, is now common throughout the Western United States (Hayes and Jennings, 1986). Neither urban development nor habitat modification have significant negative impacts on bullfrog populations (D'Amore et al., 2010; Ficetola et al., 2010; Gagne and Fahrig, 2010). As with *T. scripta elegans,* bullfrogs require permanent water and survive in Southern California largely because of human-created habitats. Bullfrogs are most active at night; during the day, they tend to hide in aquatic vegetation and will often flee with any nearby disturbance. As a result, they are less commonly photographed by citizen scientists.

Comparing Citizen Science and Museum Collection Data Over Time

To assess the efficacy of museum collections relative to citizen science for collecting records of our focal species over time, we compared VertNet records to RASCals records. We divided VertNet records by 20-year intervals and analyzed according to these divisions. For *E. multicarinata* and *P. blainvillii,* we divided records into intervals before 1930, 1931–1950, 1951–1970, 1971–1990, and after 1990. For *R. catesbeiana,* there were too few early records to make further divisions, so we combined all records from before 1970 into one interval. We did not divide records for *T. scripta elegans* into intervals because there were very few observations in VertNet and all were collected after 1970. Because RASCals data were all collected in a 27-month period (2013–2015), we did not divide these records. Given the importance of understanding how species are responding to urbanization, we were especially interested in examining the accumulation rate for modern voucher records. Thus, we specifically assess and compare the accumulation rate for RASCals records over the first 27 months of that project to the most recent museum records, which were accumulated from January 1991 to March 2015 (290 months).

Comparing Citizen Science and Museum Collection Data in Urban Areas

To compare traditional museum collection and citizen science as methods for obtaining species records specifically in urban areas, we mapped all records from both databases using ArcGIS (ArcMap 10.2.2, Esri). The spatial analyses incorporated county boundaries (California Department of Forestry Fire Protection, 2010), current protected areas of California (Commission for Environmental Cooperation, 2008), and percent impervious surface as of 2011 (United States Geological Survey, 2011a). Protected areas were defined according to the IUCN Protected Areas Categories System, and encompassed land managed by national, state, provincial or territorial authorities according to data assembled for the Commission for Environmental

Cooperation in 2008. We used percent impervious cover as a proxy for urbanization; we defined "urbanized areas" as areas of >50% impervious surface cover. We referred to non-protected areas of <50% impervious surface cover as "other" areas. We determined the types of land use that defined these "other" areas using 2011 land cover data from the National Land Cover Database (United States Geological Survey, 2011b). We used maps of modern percent impervious surface, modern protected areas, and modern land use for all past decades in order to determine how sampling within current urbanized and protected areas has changed over time. We determined how many observations of the four focal species in RASCals and in VertNet fell within protected areas or in urbanized areas for each division of decades.

RESULTS

Comparing Citizen Science and Museum Collection Data Over Time

For three of the four focal species, modern locality records collected through citizen science over a mere 27-month period far surpassed collection via museum records over a 290-month period (**Table 1**). Citizen science generated up to 23.8 times more modern records than museum collections. Even more impressively, for all species, the accumulation rate for modern records through citizen science was an order of magnitude greater than that for museum records (**Table 1**).

VertNet records of *E. multicarinata* and *P. blainvillii* demonstrated a marked decline since 1970, and for both species, museum records collected after 1990 declined by over 50% from the previous two decades (**Figures 1**–**3**, Supplementary Tables 2, 3). RASCals participants deposited nearly 400% more photo records of *E. multicarinata* ($n = 689$) and 70% more photo records of *P. blainvillii* ($n = 129$) than were accessioned into museum collections after 1990 (**Figure 1**, **Table 1**, Supplementary Tables 2, 3). These results are even more dramatic when rate of data collection is considered; for *E. multicarinata,* museum specimens yielded 7.2 records/year since 1990 while citizen science yielded 306.2 records/year (**Table 1**). These same rates for *P. blainvillii* are 3.2 museum records/year and 57.3 citizen science records/year (**Table 1**). There was a striking lack of modern records of *T. scripta* in VertNet ($n = 5$), despite the fact that RASCals participants demonstrated the clear presence of this species throughout Southern California (**Figures 1**, **4**, Supplementary Table 4; $n = 119$). In only 27 months, RASCals participants collected almost 24 times the number of modern records of *T. scripta* in VertNet (**Figure 1**, **Table 1**, Supplementary Table 4). *Rana catesbeiana* was the only focal species for which VertNet records increased after 1990 ($n = 204$) as compared to 1971–1990 ($n = 126$), and the only species for which there were fewer RASCals records ($n = 75$) than VertNet records after 1990 (**Figures 1**, **5**; Supplementary Table 5). Nevertheless, the accumulation rate of locality records was much greater for citizen science (33.3 records/year) than for museum specimens (8.4 records/year; **Table 1**).

Comparing Citizen Science and Museum Collection Data in Urban Areas

The extent to which RASCals participants increased the number of urban records compared to urban records in VertNet differed according to species. RASCals participants collected over 45 times more modern urban records of *E. multicarinata* ($n = 228$) than were contained in VertNet ($n = 5$; **Figures 1**, **2**, Supplementary Table 2). In contrast, nearly one-third of VertNet records of *E. multicarinata* from before 1970 were collected within areas that are currently urban (**Figures 1**, **2**, Supplementary Table 2). RASCals participants also collected many more records of *E. multicarinata* from urban areas ($n = 228$) than from protected areas ($n = 90$; **Figures 1**, **2**, Supplementary Table 2). Before 1930, *P. blainvillii* was recorded frequently in areas that are currently urban ($n = 119$; **Figures 1**, **3**, Supplementary Table 3). In contrast, *P. blainvillii* was poorly documented from urban areas by either database (RASCals: $n = 6$; VertNet: $n = 0$) (**Figures 1**, **3**, Supplementary Table 3), which is expected given that urbanization is a known factor in the decline of this species (Thomson et al., 2016, and references therein). Very few RASCals records of *T. scripta* ($n = 11$) or of *R. catesbeiana* ($n = 8$) were collected in urban areas (**Figures 1**, **4**, **5**, Supplementary Tables 4, 5). For both species, there are more RASCals records from protected areas (*T. scripta*: $n = 18$; *R. catesbeiana*: $n = 23$), though the majority of RASCals records come from "other" (i.e., not protected or urban) areas (**Figures 1**, **4**, **5**, Supplementary Tables 4, 5). For all species, over 90% of these "other" records were collected from five different land cover types according to the National Land Cover Database: developed open space, including parks, golf courses, and lawns; low intensity developed, primarily residential housing; medium intensity developed, primarily residential housing; scrub/shrub-land; and grassland/herbaceous cover. There were no VertNet records of *T. scripta* from urban areas, and very few of *R. catesbeiana* ($n = 9$; **Figures 1**, **4**, **5**, Supplementary Tables 4, 5). *Rana catesbeiana* was more frequently sampled in currently urban areas before 1970 ($n = 54$; **Figures 1**, **5**, Supplementary Table 5).

DISCUSSION

Our results demonstrate that citizen science can be an important tool for rapidly providing data about modern species distributions, particularly as specimen collecting has declined. For the four focal species, the RASCals citizen-science project generated modern locality records 4–252 times more rapidly than museum collections (**Table 1**). In 27 months, the RASCals citizen-science project generated 0.36–23.8 times more modern locality records than museum collections acquired over more than 24 years (**Table 1**). Thus, for three of our four focal species, citizen science provided more data about modern species distributions than the more than 250 natural history collections searchable through the VertNet database. The only species for which VertNet contained more modern records than were collected by RASCals participants was *R. catesbeiana.* However, citizen-science records for this species were being gathered

TABLE 1 | Modern Southern California locality records of the four focal species from citizen science (the RASCals project, 27 months) and from museum specimens (VertNet database, 290 months).

Species	No. of RASCals records (27 months)	No. of VertNet records (1991–2015)	Accumulation rate: RASCals (records/year)	Accumulation rate: VertNet (records/year)
Elgaria multicarinata	689	175	306.2	7.2
Phyrnosoma blainvillii	129	77	57.3	3.2
Rana catesbeiana	75	204	33.3	8.4
Trachemys scripta	119	5	52.9	0.21

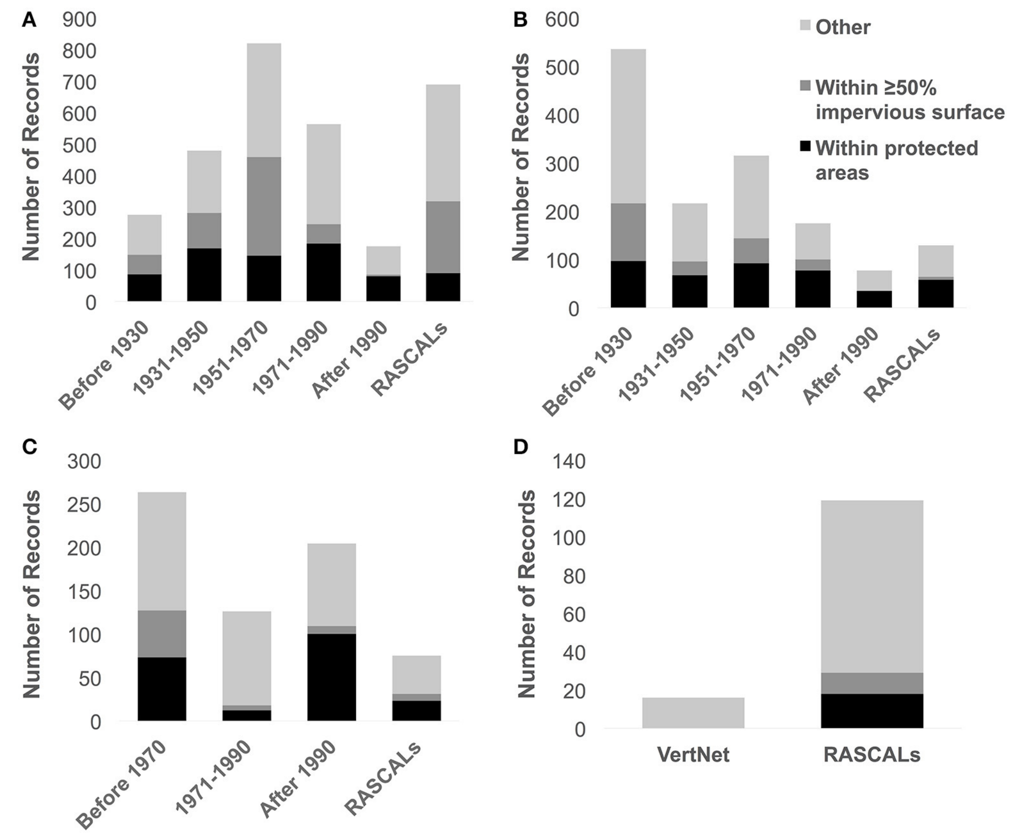

FIGURE 1 | Number of Southern California georeferenced specimen records from VertNet and collected by RASCals participants that are within protected areas or areas of ≥50% impervious surface for **(A)** *Elgaria multicarinata,* **(B)** *Phrynosoma blainvillii,* **(C)** *Rana catesbeiana,* and **(D)** *Trachemys scripta.*

much more rapidly than were museum records (**Table 1**; 33.3 records/year for citizen science vs. 8.4 records/year for museum records). Citizen science was also much more effective for sampling urban populations of our urban-adaptable focal species, providing urban-distribution data that VertNet lacked.

As funding for and the popularity of collecting specimens for museum collections has declined (Dalton, 2003; Gropp, 2003; Suarez and Tsutsui, 2004; Sullivan et al., 2009; Dickinson et al., 2010; LaDuc and Bell, 2010), citizen science can be an effective and inexpensive way to rapidly gain large amounts of data about species distributions. The RASCals citizen-science project worked particularly well for providing data about modern distributions of *E. multicarinata, P. blainvillii,* and *T. scripta*, all of which are diurnal reptiles found within a variety of habitats throughout Southern California (Hayes and Jennings, 1986; Thomson et al., 2010; Stebbins and McGinnis, 2012; Brattstrom, 2013). VertNet, in contrast, provided fewer modern records of all of these species, particularly *T. scripta*. The lack of modern records contained within museum collections is alarming, considering the rapid changes occurring to many species' ranges due to climate change, habitat loss, urbanization, and other anthropogenic forces (Franco et al., 2006; Sorte et al., 2010; Chen et al., 2011). Up-to-date records of species distribution are critical for understanding the effects of these forces on individual species and communities (Shaffer et al., 1998; Ponder et al., 2001; Thuiller, 2004; Chen et al., 2011).

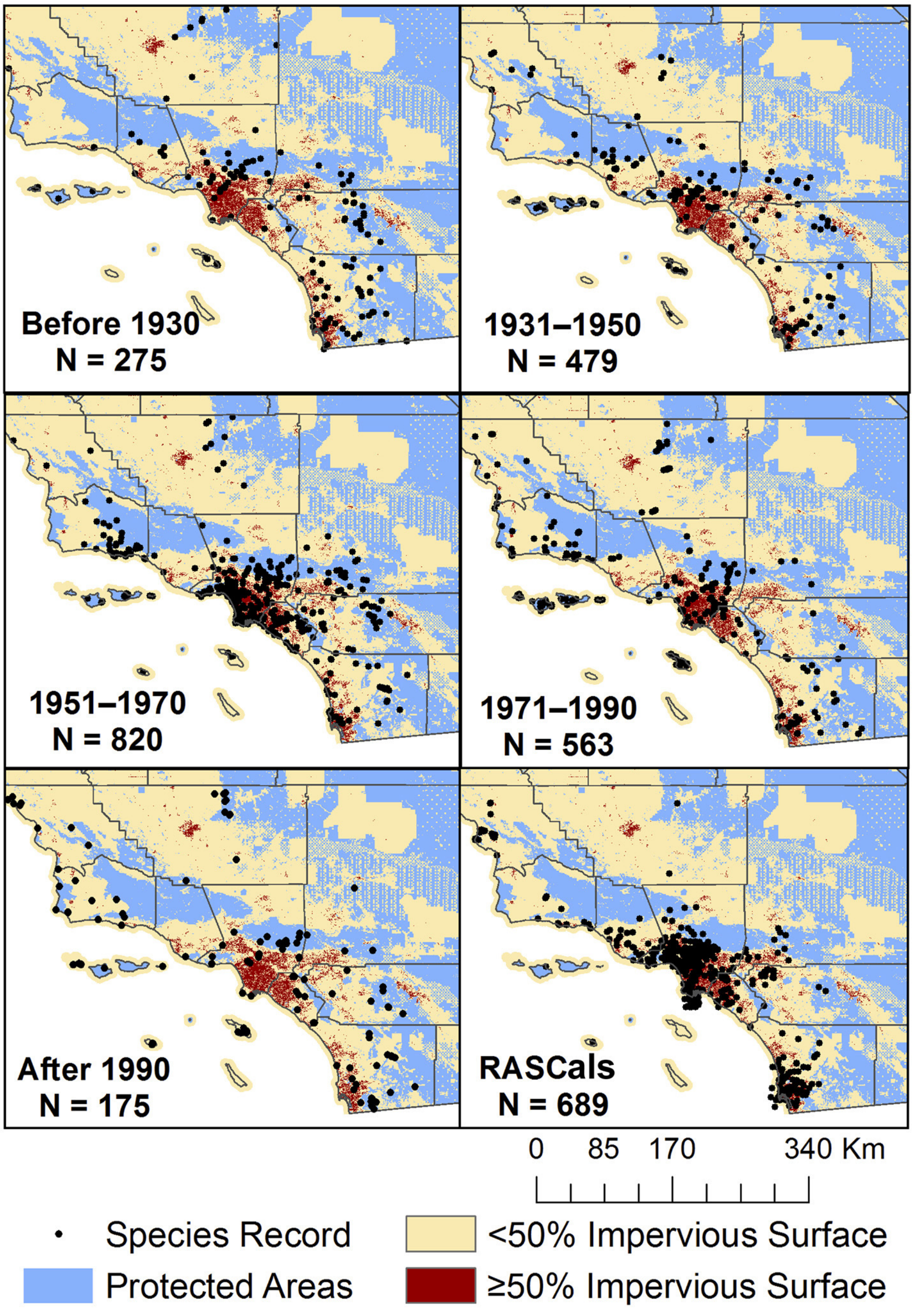

FIGURE 2 | Distribution of *Elgaria multicarinata* in Southern California according to all georeferenced VertNet database records from before 1930 ($n = 275$), 1931–1950 ($n = 479$), 1951–1970 ($n = 820$), 1971–1990 ($n = 563$), and after 1990 ($n = 175$) as of March 2015, as well as the distribution of research-grade observations by RASCals participants as of September 2015 ($n = 689$). County boundaries, protected areas, and percent impervious surface are shown.

Considering the potential effects of rapid urbanization on species distributions, the capability of citizen science for sampling urban areas is also promising (McCaffrey, 2005; Cooper et al., 2007; Paulos et al., 2008; Ballard et al., 2017). Standard methods for sampling biodiversity are often extremely challenging to implement in urban and suburban areas because of the high proportion of private property that professional biologists cannot easily access. Citizen science, however, can overcome this challenge by having local residents with increased access and increased local knowledge collect the relevant data. For example, of 1,012 total citizen-science records for our focal species, 253 were in "urban" and 570 were in "other" (primarily low- and medium-intensity suburban development), indicating that the majority of records were from urbanized areas. In contrast,

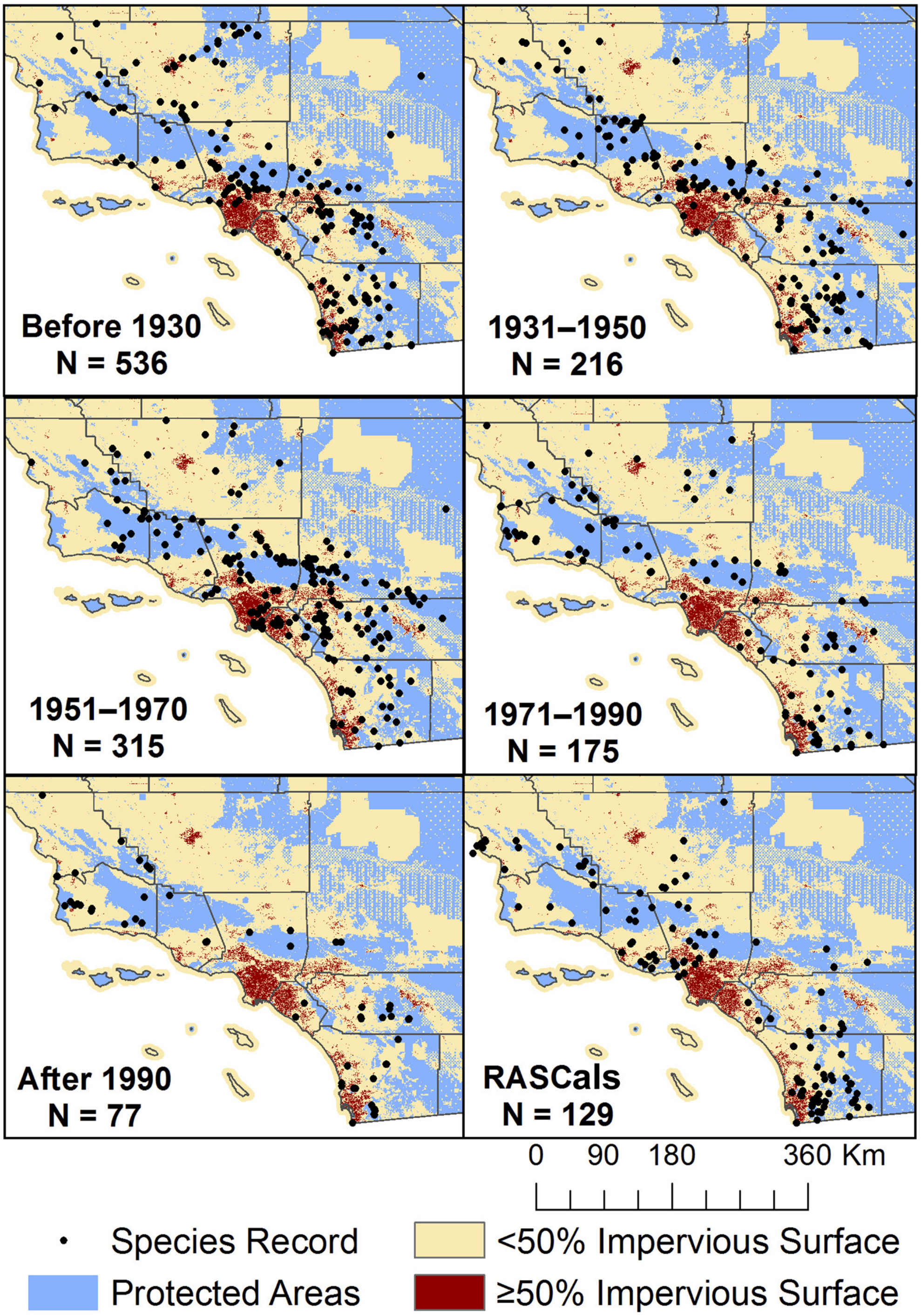

FIGURE 3 | Distribution of *Phrynosoma blainvillii* in Southern California according to all georeferenced VertNet database records from before 1930 ($n = 536$), 1931–1950 ($n = 216$), 1951–1970 ($n = 315$), 1971–1990 ($n = 175$), and after 1990 ($n = 77$) as of March 2015, as well as the distribution of research-grade observations by RASCals participants as of September 2015 ($n = 129$). County boundaries, protected areas, and percent impervious surface cover are shown.

very few modern museum records came from urbanized areas (Supplementary Tables 2–5). Past VertNet records of our focal species demonstrate that they were previously present in modern urban areas, suggesting that these regions may have been more heavily sampled in the past, before becoming so extensively urbanized, and/or that urban-sensitive species like *P. blainvillii* were historically more abundant in these regions. The abundance of urban and suburban records in RASCals also suggests that

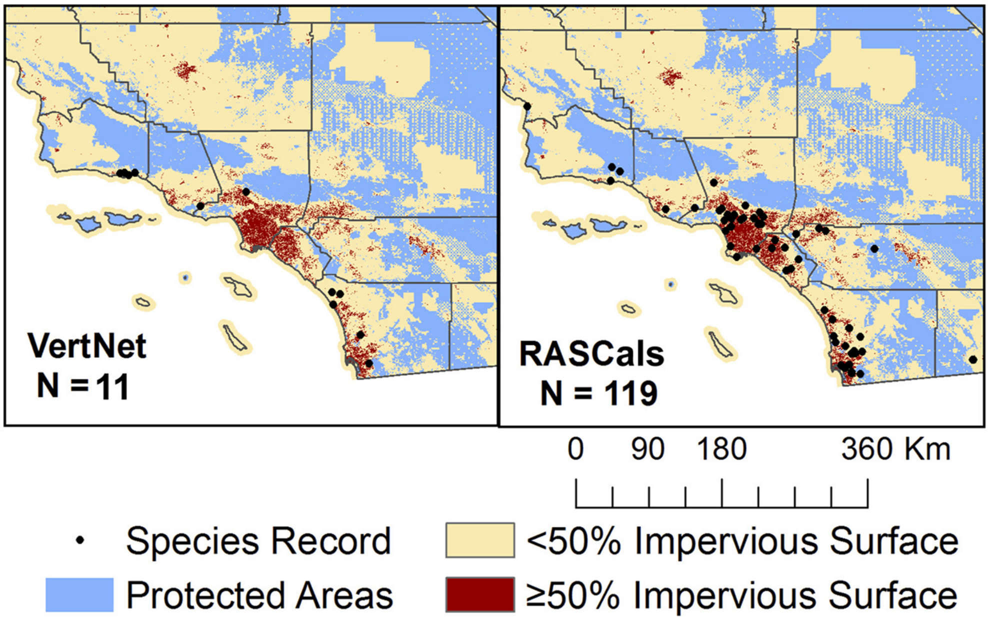

FIGURE 4 | Distribution of *Trachemys scripta* in Southern California according to all georeferenced VertNet database records ($n = 11$) as of March 2015, as well as the distribution of research-grade observations by RASCals participants as of September 2015 ($n = 119$). County boundaries, protected areas, and percent impervious surface cover are shown.

participants not only sample local parks or reserves, but also a broader variety of habitat types: the majority of records in our dataset came from suburban land of low and medium-intensity development, or from unprotected shrub land. Citizen science should be invaluable to the ongoing collection of similar suburban and urban distributional data for a wide variety of species. Moreover, in addition to generating biodiversity data, citizen-science projects in urban regions can also have important educational and societal benefits. For example, effectively managed citizen-science projects can convince participants that documenting the nature in their own neighborhoods is valid and important (Ballard et al., 2017).

The photographic method of data collection employed by the RASCals project may be especially valuable for collection of data about species of conservation concern, such as *P. blainvillii.* The designation of *P. blainvillii* as a species of special concern may in part explain the dramatic drop in museum specimens in recent decades, as such species are rarely collected for scientific purposes. Despite this species persisting only in protected areas and being largely cryptic, RASCals participants documented 129 sightings, demonstrating that citizen-science projects can provide modern data that helps fill gaps in museum collections. This result is consistent with the recent finding by Ballard et al. (2017) that citizen-science projects can have numerous conservation impacts.

The lack of VertNet records of the invasive *T. scripta* is also a point of concern. Knowledge of this turtle's spread may prove important to efforts to control it or to manage native species impacted by the spread of this highly invasive species. RASCals participants collected more than 10 times the number of records of *T. scripta* than are contained in VertNet. Citizen science has already proven effective at detecting and studying invasive species (Delaney et al., 2008; Crall et al., 2010, 2011; Gallo and Waitt, 2011). Indeed, RASCals participants were the first to record established populations of the Indo-Pacific Gecko, *Hemidactylus garnotii,* in California (Pauly et al., 2015a) and are also responsible for a number of new county records of other non-native lizard species (Bernstein and Bernstein, 2013; Larson et al., 2015; Pauly and Borthwick, 2015; Pauly et al., 2015b). Ongoing citizen-science projects like RASCals can be used to more effectively detect invasive species introductions and range expansions than intermittent specimen collection. Crucially, citizen-science discoveries can direct strategic specimen collection as happened in the aforementioned discoveries of new state and county records for non-native lizards.

It is similarly important to note the limitations of citizen science. The effectiveness of citizen science for providing distribution and biodiversity data is species-dependent: detectability varies widely by species, with cryptic and nocturnal species being under-recorded as compared to diurnal or easily-spotted species (Genet and Sargent, 2003; de Solla et al., 2005; Lotz and Allen, 2007; Fitzpatrick et al., 2009; Dickinson et al., 2010). Consider data collection for *R. catesbeiana:* this species is most active at night and while it can be observed along shorelines during the day, it often leaps into the water and hides when approached. As a result, photographic vouchers can be difficult to obtain, and the accumulation rate for bullfrog observations was the lowest among our focal species for the RASCals project (**Table 1**). In contrast, professional biologists can use a variety of

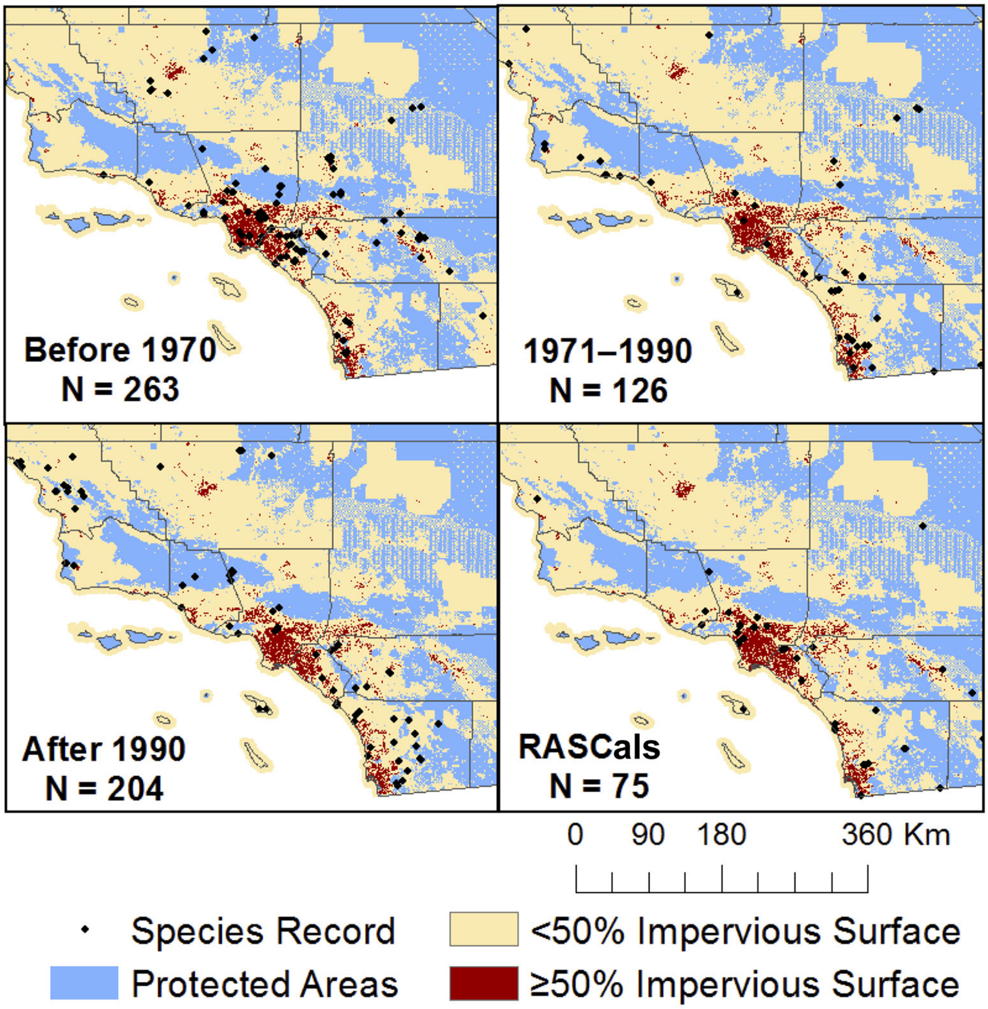

FIGURE 5 | Distribution of *Rana catesbeiana* in Southern California according to all georeferenced VertNet database records from before 1970 (n = 263), 1971–1990 (n = 126), and after 1990 (n = 204) as of March 2015, as well as the distribution of research-grade observations by RASCals participants as of September 2015 (n = 75). County boundaries, protected areas, and percent impervious surface cover are shown.

methods to relatively easily collect bullfrogs and often want to do so given the impact that this invasive species can have on native taxa; as a result, the modern museum specimen-accumulation rate was highest for this species relative to our other focal taxa (**Table 1**).

The difficulty of obtaining photo vouchers for *R. catesbeiana* highlights that other methods of data collection may be more effective for some species. For example, a number of citizen-science studies have used frog call surveys to successfully monitor frog populations (Genet and Sargent, 2003; de Solla et al., 2005; Lotz and Allen, 2007). Another drawback of photo-based citizen-science projects is that sampling is haphazard and so may not be even across the study region, and because participants may differ in their ability to detect different species, it is difficult to use citizen science to reliably document species absence or abundance (Kéry, 2002; Mackenzie, 2005; Dickinson et al., 2010). Some of these biases and pitfalls may be avoided by carefully designing studies or choosing sampling locations, and/or providing training for participants (Delaney et al., 2008; Dickinson et al., 2010). However, while systematic study designs and participant training allow citizen science to be used for more complex studies than simple distribution surveys, they can also limit the scale and flexibility that citizen-science projects like RASCals provide.

Most importantly, photo-based citizen-science projects provide photos, which will always have limited utility relative to a specimen. Photographs, like those accumulated through RASCals, are useful for collecting distribution and biodiversity data, but they cannot replace museum collections as invaluable sources of data about morphology, genetics, epidemiology, and disease spread, diet, or parasitism rates or the change in these variables through time (Roy et al., 1994; Fanning et al., 2002; Payne and Sorenson, 2002; Johnson et al., 2003; Suarez and Tsutsui, 2004; Babin-Fenske et al., 2008). Citizen science can and should be used to supplement, but not replace, the records contained within museum collections. Moreover, our results highlight the opportunity provided by combining citizen science and museum records in studying species responses to major environmental changes; museum records provide the historical localities while citizen science can provide the bulk of the modern locality data.

Our results also highlight the relevance of citizen science to studies of urban biodiversity. Urban areas are a mosaic of private properties that, depending on the taxon of interest, can be difficult or even impossible to survey using standard techniques. By partnering with citizen scientists, researchers can overcome this challenge. Because Southern California has both high biodiversity and a large human population, citizen science is an especially relevant method for studying biodiversity in this region. Nevertheless, this general approach is applicable to human-inhabited regions worldwide; the only requirements are that the project is of interest to local people, participants have access to the tools needed for data collection (smartphones, digital cameras, internet access, etc.), and data-collection techniques are appropriate for the research question.

As the RASCals project is ongoing, over time RASCals participants will likely contribute many more records of each of the focal species. The full value of this citizen-science project for increasing our understanding of the reptiles and amphibians of Southern California is still unfolding. Moreover, RASCals is one of many such ongoing projects sponsored by museums around the world as curators increasingly embrace citizen-science projects. As museum acquisitions continue to decline (Suarez and Tsutsui, 2004), citizen-science projects like RASCals may become a key tool that complements traditional specimen collecting efforts for obtaining data on species distributions throughout the world.

DATA AVAILABILITY

The data used in this manuscript are available as part of the RASCals citizen-science project on the iNaturalist platform (http://www.inaturalist.org/projects/rascals) and in the VertNet database (http://www.vertnet.org). See References for all VertNet data sources used in this study.

AUTHOR CONTRIBUTIONS

Conceived the study: all authors. Conceived and maintains the RASCals project: GBP. Accessed and organized VertNet data: DMS. Created maps and analyzed data: DMS. Drafted manuscript: DMS. All authors edited the manuscript.

ACKNOWLEDGMENTS

We are grateful to the thousands of citizen scientists who contribute observations to the RASCals Project. We also thank Lila Higgins, Miguel Ordeñana, Richard Smart, and the staff of the Urban Nature Research Center for their dedicated support of the Natural History Museum of Los Angeles County's citizen-science efforts. We would like to thank the creators and operators of iNaturalist for their citizen-science vision. We are grateful to Jonathan Feingold, Brenna Gormally, and Jessica Hernandez for providing support and advice throughout the data collection process. Finally, we greatly appreciate the help and support of the Pomona College Department of Biology.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fevo.2017.00086/full#supplementary-material

REFERENCES

Alvey, A. A. (2006). Promoting and preserving biodiversity in the urban forest. *Urban Forest. Urban Green.* 5, 195–201. doi: 10.1016/j.ufug.2006.09.003

Babin-Fenske, J., Anand, M., and Alarie, Y. (2008). Rapid morphological change in stream beetle museum specimens correlates with climate change. *Ecol. Entomol.* 33, 646–651. doi: 10.1111/j.1365-2311.2008.01018.x

Ballard, H. B., Robinson, L. D., Young, A. N., Pauly, G. B., Higgins, L. M., Johnson, R. F., et al. (2017). Contributions to conservation outcomes of natural history museum-led citizen science: examining evidence and next steps. *Biol. Conserv.* 208, 87–97. doi: 10.1016/j.biocon.2016.08.040

Barber, R. T., Vijayakumar, A., and Cross, F. A. (1972). Mercury concentration in recent and ninety-year old benthopelagic fish. *Science* 178, 636–639. doi: 10.1126/science.178.4061.636

Bernstein, W. L., and Bernstein, R. W. (2013). *Hemidactylus turcicus* (Mediterranean Gecko). *Herpetol. Rev.* 44:374.

Blair, R. B. (2001). "Birds and butterflies along urban gradients in two ecoregions of the U.S.," in *Biotic Homogenization*, eds J. L. Lockwood and M. L. McKinney (Norwell, MA: Kluwer), 33–56.

Brattstrom, B. H. (2013). Distribution of the coast horned lizard, *Phrynosoma coronatum*, in Southern California. *Bull. South. Calif. Acad. Sci.* 112, 206–216. doi: 10.3160/0038-3872-112.3.206

California Department of Forestry and Fire Protection (2010). *County Boundaries of California, U. S. A. [GIS shapefile].* Last updated March 25, 2015. Retrieved: March 25, 2015 using ArcGIS software version 10.2.2 [Esri].

Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., and Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science* 333, 1024–1026. doi: 10.1126/science.1206432

Collins, J. P., Kinzig, A., Grimm, N. B., Fagan, W. F., Hope, D., Wu, J., et al. (2000). A new urban ecology. *Am. Sci.* 88, 416–425. doi: 10.1511/2000.5.416

Commission for Environmental Cooperation (CEC) (2008). *Protected Areas of the Pacific States (USA). [GIS shapefile].* Last updated September 8, 2010. Retrieved March 25, 2015 using ArcGIS software version 10.2.2 [Esri].

Conner, C. A., Douthitt, B. A., and Ryan, T. J. (2005). Descriptive ecology of a turtle assemblage in an urban landscape. *Am. Midl. Nat.* 153, 428–435. doi: 10.1674/0003-0031(2005)153[0428:DEOATA]2.0.CO;2

Cooper, C. B., Dickinson, J., Phillips, T. B., and Bonney, R. (2007). Citizen science as a tool for conservation in residential ecosystems. *Ecol. Soc.* 2:11. doi: 10.5751/ES-02197-120211

Crall, A. W., Newman, G. J., Jarnevich, C. S., Stohlgren, T. J., Waller, D. M., and Graham, J. (2010). Improving and integrating data on invasive species collected by citizen scientists. *Biol. Invasions* 12, 3419–3428. doi: 10.1007/s10530-010-9740-9

Crall, A. W., Newman, G. J., Stohlgren, T. J., Holfelder, K. A., Graham, J., and Waller, D. M. (2011). Assessing citizen science data quality: an invasive species case study. *Conserv. Lett.* 4, 433–442. doi: 10.1111/j.1755-263X.2011.00196.x

Dalton, R. (2003). Natural history collections in crisis as funding is slashed. *Nature* 423:575. doi: 10.1038/423575a

D'Amore, A., Hemingway, V., and Wasson, K. (2010). Do a threatened native amphibian and its invasive congener differ in response to human alteration of the landscape? *Biol. Invasions* 12, 145–154. doi: 10.1007/s10530-009-9438-z

Davis, P. (1996). *Museums and the Natural Environment: The Role of Natural History Museums in Biological Conservation*. London: Leicester University Press.

Delaney, D. G., Sperling, C. D., Adams, C. S., and Leung, B. (2008). Marine invasive species: validation of citizen science and implications for national monitoring networks. *Biol. Invasions* 10, 117–128. doi: 10.1007/s10530-007-9114-0

de Solla, S. R., Shirose, L. J., Fernie, K. J., Barrett, G. C., Brousseau, C. S., and Bishop, C. A. (2005). Effect of sampling effort and species detectability on volunteer based anuran monitoring programs. *Biol. Conserv.* 121, 585–594. doi: 10.1016/j.biocon.2004.06.018

Dickinson, J. L., Zuckerberg, B., and Bonter, D. N. (2010). Citizen science as an ecological research tool: challenges and benefits. *Ann. Rev. Ecol. Evol. Syst.* 41, 149–172. doi: 10.1146/annurev-ecolsys-102209-144636

Ditchkoff, S. S., Saalfeld, S. T., and Gibson, C. J. (2006). Animal behavior in urban ecosystems: modifications due to human-induced stress. *Urban Ecosyst.* 9, 5–12. doi: 10.1007/s11252-006-3262-3

Eskew, E. A., Price, S. J., and Dorcas, M. E. (2010). Survival and recruitment of semi-aquatic turtles in an urbanized region. *Urban Ecosyst.* 13, 365–374. doi: 10.1007/s11252-010-0125-8

Fanning, T. G., Slemons, R. D., Reid, A. H., Janczewski, T. A., Dean, J., and Taubenberger, J. K. (2002). 1917 influenza virus sequences suggest that the 1918 pandemic virus did not acquire its hemagglutinin directly from birds. *J. Virol.* 76, 7860–7862. doi: 10.1128/JVI.76.15.7860-7862.2002

Ficetola, G. F., Maiorano, L., Falcucci, A., Dendoncker, N., Boitani, L., Padoa-Schioppa, E., et al. (2010). Knowing the past to predict the future: land-use change and the distribution of invasive bullfrogs. *Glob. Chang. Biol.* 16, 528–537. doi: 10.1111/j.1365-2486.2009.01957.x

Fisher, R. N., Case, T. J. (2000). "Distribution of the herpetofauna of coastal Southern California with reference to elevation effects," in *Second Interface Between Ecology and Land Development in California*, eds J. E. Keeley, M. Baer-Keeley, and C. J. Fotheringham (Sacramento, CA: US Geological Survey), 137–143.

Fisher, R. N., Suarez, A. V., and Case, T. J. (2002). Spatial patterns in the abundance of the Coastal Horned Lizard. *Conserv. Biol.* 16, 205–215. doi: 10.1046/j.1523-1739.2002.00326.x

Fitzpatrick, M., Preisser, E., Ellison, A., and Elkinton, J. (2009). Observer bias and the detection of low-density populations. *Ecol. Appl.* 19, 1673–1679. doi: 10.1890/09-0265.1

Franco, A., Hill, J. K., Kitschke, C., Collingham, Y. C., Roy, D. B., Fox, R. I., et al. (2006). Impacts of climate warming and habitat loss on extinctions at species' low-latitude range boundaries. *Glob. Chang. Biol.* 12, 1545–1553. doi: 10.1111/j.1365-2486.2006.01180.x

Gagne, S. A., and Fahrig, L. (2010). Effects of time since urbanization on anuran community composition in remnant urban ponds. *Environ. Conserv.* 37, 128–135. doi: 10.1017/S0376892910000421

Gallo, T., and Waitt, D. (2011). Creating a successful citizen science model to detect and report invasive species. *Bioscience* 61, 459–465. doi: 10.1525/bio.2011.61.6.8

Genet, K. S., and Sargent, L. G. (2003). Evaluation of methods and data quality from a volunteer-based amphibian call survey. *Wildl. Soc. Bull.* 31, 703–714.

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., et al. (2008a). Global change and the ecology of cities. *Science* 319, 756–760. doi: 10.1126/science.1150195

Grimm, N. B., Foster, D., Groffman, P., Grove, J. M., Hopkinson, C. S., Nadelhoffer, K. J., et al. (2008b). The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. *Front. Ecol. Environ.* 6:70147. doi: 10.1890/070147

Gropp, R. E. (2003). Are university natural science collections going extinct? *Bioscience* 53:550. doi: 10.1641/0006-3568(2003)053[0550:AUNSCG]2.0.CO;2

Hayes, M. P., and Jennings, M. R. (1986). Decline of ranid frog species in western North America: are bullfrogs (*Rana catesbeiana*) responsible? *J. Herpetol.* 20, 490–509. doi: 10.2307/1564246

Jennings, M. R. (1987). Impact of the curio trade for San Diego Horned Lizards (*Phrynosoma coronatum blainvillii*) in the Los Angeles Basin, California, 1885–1930. *J. Herpetol.* 2l, 356–358. doi: 10.2307/1563985

Jennings, M. R., and Hayes, M. P. (1994). *Amphibian and Reptile Species of Special Concern in California*. Rancho Cordova, CA: California Department of Fish and Game, Inland Fisheries Division.

Johnson, P. T., Lunde, K. B., Zelmer, D. A., and Werner, J. K. (2003). Limb deformities as an emerging parasitic disease in amphibians: evidence from museum specimens and resurvey data. *Conserv. Biol.* 17, 1724–1737. doi: 10.1111/j.1523-1739.2003.00217.x

Kéry, M. (2002). Inferring the absence of a species: a case study of snakes. *J. Wildl. Manage.* 66, 330–338. doi: 10.2307/3803165

Kowarik, I. (1995). "On the role of alien species in urban flora and vegetation," in *Plant Invasions—General Aspects and Special Problems*, eds P. Pysek, K. Prach, M. Rejmánek, and P. M. Wade (Amsterdam: SPB Academic), 85–103.

LaDuc, T. J., and Bell, C. J. (2010). Educating students on the importance of spatial and temporal bias in museum collections: an example using *Sonora semiannulata* from Texas. *Herpetol. Rev.* 41, 292–298.

Larson, G. C., Huntley, C., Pauly, G. B., Wolfmeyer, T., Singh, B., and Espinoza, R. E. (2015). Geographic distribution: USA, California, Ventura County: *Hemidactylus turcicus* (Mediterranean Gecko). *Herpetol. Rev.* 46, 59.

Lemm, J. M. (2006). *Field Guide to Amphibians and Reptiles of the San Diego Region*. *California Natural History Guides*. Berkley, CA: University of California Press.

Lister, A. M., and Climate Change Research Group. (2011). Natural history collections as sources of long-term datasets. *Trends in Ecol. Evol.* 26, 153–154. doi: 10.1016/j.tree.2010.12.009

Lotz, A., and Allen, C. R. (2007). Observer bias in anuran call surveys. *J. Wildl. Manage.* 71, 675–679. doi: 10.2193/2005-759

Lowe, S., Browne, M., Boudjelas, S., and De Poorter, M. (2000). *100 of the World's Worst Invasive Alien Species: A Selection from the Global Invasive Species Database*. Auckland: Invasive Species Specialist Group.

Mackenzie, D. I. (2005). Was it there? Dealing with imperfect detection for species presence/absence data. Australian and New Zealand Journal of Statistics 47, 65–74. doi: 10.1111/j.1467-842X.2005.00372.x

Mackin-Rogalska, R., Pinowski, J., Solon, J., and Wojcik, Z. (1988). Changes in vegetation, avifauna, and small mammals in a suburban habitat. *Pol. Ecol. Stud.* 14, 293–330.

McCaffrey, R. E. (2005). Using citizen science in urban bird studies. *Urban Habitats* 3, 70–86.

McCarthy, M. A. (1998). Identifying declining and threatened species with museum data. *Biol. Conserv.* 83, 9–17. doi: 10.1016/S0006-3207(97)00048-7

McIntyre, N. E. (2000). Ecology of urban arthropods: A review and a call to action. *Ann. Entomol. Soc. Am.* 93, 825–835. doi: 10.1603/0013-8746(2000)093[0825:EOUAAR]2.0.CO;2

McKinney, M. L. (2002). Urbanization, biodiversity, and conservation. *Bioscience* 52, 883–890. doi: 10.1641/0006-3568(2002)052[0883:UBAC]2.0.CO;2

Parmesan, C. (1996). Climate and species' range. *Nature* 382, 765–766. doi: 10.1038/382765a0

Paulos, E., Honicky, R., and Hooker, B. (2008). "Citizen science: enabling participatory urbanism," in *Urban Informatics: Community Integration and Implementation*, ed M. Foth (Hershey, PA: IGI Global), 413–436.

Pauly, G. B., and Borthwick, D. B. (2015). Geographic distribution. USA, California, Los Angeles County: *Anolis carolinensis* (Green Anole). *Herpetol. Rev.* 46:567.

Pauly, G. B., Wells, A., Espinoza, M. H., Wake, T. A., and Espinoza, R. E. (2015a). Geographic distribution. USA, California, Orange County: *Hemidactylus turcicus* (Mediterranean Gecko). *Herpetol. Rev.* 46:59.

Pauly, G. B., Yoshida, G. S., and Worrell, R. (2015b). Geographic distribution. USA, California: *Hemidactylus garnotii* (Indo-Pacific Gecko). *Herpetol. Rev.* 46:569.

Payne, R. B., and Sorenson, M. D. (2002). Museum collections as sources of genetic data. *Bonn. Zool. Beitr.* 51, 97–104.

Ponder, W. F., Carter, G. A., Flemons, P., and Chapman, R. R. (2001). Evaluation of museum collection data for use in biodiversity assessment. *Conserv. Biol.* 15, 648–657. doi: 10.1046/j.1523-1739.2001.015003648.x

Ren, G., Zhou, Y., Chu, Z., Zhou, J., Zhang, A., Guo, J., et al. (2008). Urbanization effects on observed surface air temperature trends in North China. *J. Clim.* 21, 1333–1348. doi: 10.1175/2007JCLI1348.1

Roy, M. S., Girman, D. J., Taylor, A. C., and Wayne, R. K. (1994). The use of museum specimens to reconstruct the genetic variability and relationships of extinct populations. *Experientia* 50, 551–557. doi: 10.1007/BF01921724

Shaffer, H. B., Fisher, R. N., and Davidson, C. (1998). The role of natural history collections in documenting species declines. *Trends Ecol. Evol.* 13, 27–30. doi: 10.1016/S0169-5347(97)01177-4

Sorte, C. J., Williams, S. L., and Carlton, J. T. (2010). Marine range shifts and species introductions: comparative spread rates and community impacts. *Glob. Ecol. Biogeogr.* 19, 303–316. doi: 10.1111/j.1466-8238.2009.00519.x

Spinks, P. Q., Pauly, G. B., Crayon, J. J., and Shaffer, H. B. (2003). Survival of the western pond turtle (*Emys marmorata*) in an urban California environment. *Biol. Conserv.* 113, 257–267. doi: 10.1016/S0006-3207(02)00392-0

Stebbins, R. C., and McGinnis, S. M. (2012). *Field Guide to Amphibians and Reptiles of California*: *Revised Edition. California Natural History Guides*. Berkeley, CA: University of California Press.

Suarez, A. V., Richmond, J. Q., and Case, T. J. (2000). Prey selection in horned lizards following the invasion of Argentine ants in Southern California. *Ecol. Appl.* 10, 711–725. doi: 10.1890/1051-0761(2000)010[0711:PSIHLF]2.0.CO;2

Suarez, A. V., and Tsutsui, N. D. (2004). The value of museum collections for research and society. *Bioscience* 54, 66–74. doi: 10.1641/0006-3568(2004)054[0066:TVOMCF]2.0.CO;2

Sullivan, B. L., Wood, C. L., Iliff, M. J., Bonney, R. E., Fink, D., and Kelling, S. (2009). eBird: a citizen-based bird observation network in the biological sciences. *Biol. Conserv.* 142, 2282–2292. doi: 10.1016/j.biocon.2009.05.006

Thomson, R. C., Spinks, P. Q., and Shaffer, H. B. (2010). Distribution and abundance of invasive red-eared sliders (*Trachemys scripta elegans*) in California's Sacramento River Basin and possible impacts on native western pond turtles (*Emys marmorata*). *Chelonian Conserv. Biol.* 9, 297–302. doi: 10.2744/CCB-0820.1

Thomson, R. C., Wright, A. N., and Shaffer, H. B. (2016). *California Amphibian and Reptile Species of Special Concern*. Berkeley, CA: University of California Press.

Thuiller, W. (2004). Patterns and uncertainties of species' range shifts under climate change. *Glob. Chang. Biol.* 10, 2020–2027. doi: 10.1111/j.1365-2486.2004.00859.x

United States Geological Survey (2011a). *"National Land Cover Database—Percent Imperviousness, Superzone 2". [GIS shapefile].* Last updated July 5, 2011. Retrieved March 25, 2015 using ArcGIS software version 10.2.2 [Esri].

United States Geological Survey (2011b). *"NLCD 2011 Land Cover." [GIS shapefile].* Last updated 2014. Retrieved January 5, 2017 using ArcGIS software version 10.4.1 [Esri].

Zhao, S., Da, L., Tang, Z., Fang, H., Song, K., and Fang, J. (2006). Ecological consequences of rapid urban expansion: Shanghai, China. *Front. Ecol. Environ.* 4, 341–346. doi: 10.1890/1540-9295(2006)004[0341:ECORUE]2.0.CO;2

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