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Non-native herpetofauna of Aruba island (Caribbean): patterns and insights

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Abstract Islands harbor a significant proportion of global biodiversity and also have disproportionately high richness of introduced species relative to continents. Given the sensitivity of island ecosystems to introduced species, data deficiencies on introduction pathways, patterns of establishment, and potential impacts of introduced species can hamper mitigation and conservation efforts on islands. The Caribbean region is emerging as a hotspot for introduced amphibian and reptile (herpetofaunal) species, but patterns associated with herpetofaunal introductions on specific islands are not well explored. Here, we perform a detailed investigation of Aruba, a small Caribbean island with an exceptionally high number of introduced herpetofaunal species. We compile a database from the literature of introduction pathways, introduction years, source locations, native ranges, establishment outcomes, habitat use, and ecological impacts for three newly documented species and the 12 previously documented introduced herpetofaunal species on Aruba. From this database we synthesize emergent introduction patterns on Aruba and highlight areas of data deficiency. Overall, the patterns on Aruba echo the patterns exhibited in the greater Caribbean region. Introduction rates on Aruba have been increasing exponentially, yet the introduction pathways and source locations of most species are unknown. Following introduction, most species successfully establish localized populations in anthropogenic habitat, but the ecological impacts of most species have not been well-assessed. We suggest increased monitoring of shipments will help identify potential pathways to slow the introduction of new species, and further studies of ecological impacts of introduced species are needed.

Keywords Amphibian · Caribbean · Invasion · Island ecosystem · Non-native species · Reptile

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Introduction

Despite occupying only 5.3% of the Earth's terrestrial surface area, islands harbor a disproportionately high amount of global biodiversity (Weigelt et al. 2013). Islands have 9.5 times higher levels of endemic vascular plant species and 8.1 times higher endemic vertebrate species than mainland areas (Kier et al. 2009). Housing 10% of the human population, island ecosystems are also some of the most impacted ecosystems on Earth, especially with respect to introduced species and habitat loss. Islands have disproportionately higher richness of introduced species per land area than mainland areas (Turbelin et al. 2017). While several theories have been proposed to explain high numbers of introduced species on islands, the importance of imported goods to island economies and the relatively unidirectional nature of this trade from continental to island systems is likely a significant and consistent factor across regions (Simberloff 1995; Hulme 2009). Furthermore, the impact of land use change and habitat loss is more intense on islands, which may help facilitate the establishment of species following colonization (Simberloff 1995; Kier et al. 2009; Delgado et al. 2017). Island ecosystems are also more vulnerable to the negative impacts of species introductions (Reaser et al. 2007). Given the biodiversity conservation value of islands and the pressure they are under from introduced species, it is imperative to understand the factors contributing to the spread of non-native species to islands.

The greater Caribbean region comprises over 700 islands and is emblematic of the global trends of increasing species introductions on islands. In particular, the Caribbean is a hotspot for introduced amphibian and reptile (herpetofauna) species; rates of species introductions have accelerated over time for all herpetofauna (Powell et al. 2011; Capinha et al. 2020; Gleditsch et al. 2023), and specific herpetofaunal groups like *Anolis* lizards (Helmus et al. 2014) and geckos (Perella and Behm 2020). Like many regions, these increased rates of herpetofaunal species introductions correlate to increased trade (Kraus 2009; Powell et al. 2011), yet this correlation has likely been enhanced by three synergistic factors unique to this species group and region. First, many herpetofaunal species, especially reptiles and toads, can withstand long, trans-oceanic voyages as stowaways in cargo as eggs, juveniles or adults (Perry et al. 2006; Kraus 2009; Tingley et al. 2018). Second, the Caribbean has ideal habitats and climates for many species that are introduced, likely facilitating their establishment following introduction (Kraus 2009; Bomford et al. 2009; Powell et al. 2011).

The third factor that likely contributes to the spread of non-native herpetofauna across the Caribbean is the high rates of endemism. The Caribbean is a reptile diversity hotspot due to these high rates of endemism where many species are found on only one or a few islands (Myers et al. 2000; Hedges 2011; Powell and Henderson 2012). As a result, Caribbean species that get translocated to a new location within the Caribbean are likely not native to the new location. The spread of herpetofaunal species among Caribbean islands in the 1800s and early 1900s reflected this high rate of endemism, at least for geckos, where the majority of introduced species were Caribbean endemics (Perella and Behm 2020). Then, in the later part of the 1900s and the 2000s, the expansion of trade with global partners accelerated introductions of species native to regions outside the Caribbean, including globally successful invasive herpetofaunal species (Bomford et al. 2009; Behm et al. 2019). This spread of globally successful invasive herpetofauna is frequently through the unintentional pathway of the plant trade and the intentional pathway of the pet trade (Kraus 2009; Powell et al. 2011; Perella and Behm 2020). On average, introduced herpetofauna in the Caribbean have high establishment rates, yet their impacts on the terrestrial ecosystems they invade remain largely unexplored (Powell et al. 2011; Kraus 2015; Perella and Behm 2020) with the exception of a few notable species (e.g., Quick et al. 2005).

Despite these assessments of regional trends in species introductions, there has been much less investigation of invasion details within Caribbean islands to determine if the same patterns in introduction rates, pathways, establishment, and impacts are echoed at this smaller scale. Since management decisions are mostly made at the island rather than regional scale, it is imperative to understand introduction and invasion patterns within islands to inform management actions. Here, we conduct an exploration of introduced herpetofaunal species on the island of Aruba. Aruba is a relatively small island (180 km^2), yet it has one of the highest numbers of introduced herpetofaunal species among Caribbean islands (Powell and Henderson 2012), making it an ideal focal island for our exploration. We conducted an in-depth literature review and generated a database of information surrounding the introductions of herpetofaunal species on Aruba. We analyzed these data to make inferences into introduction patterns including temporal trends, introduction pathways and sources, establishment success, and impacts to understand how herpetofauna are spreading and to inform management.

Materials and methods

Study area

Aruba is part of the leeward Dutch Antilles in the southern Caribbean, located ca. 30 km north of Venezuela (Fig. 1a). Aruba was first colonized by Spain in 1499, however due to its arid climate, large-scale agriculture was difficult, and it was eventually colonized by the Dutch in 1634. The discovery of gold and the establishment of a refinery to process Venezuelan oil on the island presented periods of economic growth in the nineteenth and twentieth centuries respectively, thus allowing the island to gain autonomy and subsequently secede from the Netherland Antilles in 1986 (Hartog 1961; Philpott 2002; van Buurt 2011). Since then, Aruba has become one of the most economically connected islands in the region which likely explains the high rate of introductions (Powell et al. 2011; Helmus et al. 2014). In addition, 51.1% of its land area is classified as anthropogenic habitat (urban development or agriculture; Fig. 1b) which is the highest of all Caribbean islands (Gleditsch et al. 2023). Aruba has 15 documented introduced herpetofaunal species with three of these newly documented within the past few years (Behm et al. 2022). Interestingly, unlike most Caribbean islands, the arid natural habitat may be difficult for species to invade if they are not adapted to those conditions. As a result, many of the non-native species may be using anthropogenic habitat that receives irrigation subsidies. Although the terrestrial environments of southern Caribbean islands often are overlooked relative to the lucrative marine environment that supports tourism, Aruba's government recently established Arikok National Park in 2000 which covers an appreciable 17.6% of Aruba's land area. Aruba's government has also has organized efforts to combat the impact of invasive species on the island, for example organizing bounty hunts of boa constrictors (Reinert et al. 2021).

Data collection

To identify patterns in herpetofaunal species introductions to Aruba, we compiled a database from the literature of information surrounding the introduction and establishment of each introduced species documented on Aruba. We first developed a list of all non-native herpetofaunal species that have been documented on Aruba from published species lists for Aruba (van Buurt 2005, 2011; Powell and Henderson 2012; van Buurt and Debrot 2012a) and recently documented species records (Behm et al. 2022). This resulted in a list of 15 non-native species introductions. For each species on this list, we searched the literature to compile all available information regarding its introduction to Aruba. To do this, we first reviewed all sources associated with each species cited by the published species list sources (van Buurt 2005, 2011; Powell and Henderson 2012; van Buurt

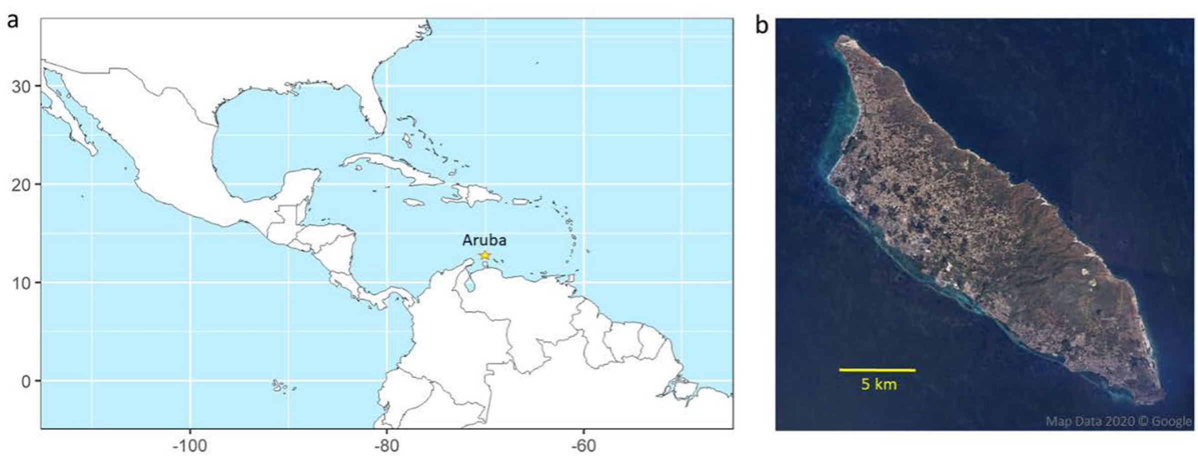

Fig. 1 **a** Aruba (yellow star) is located in the southern Caribbean just north of Venezuela. **b** Satellite image showing Aruba's land cover is 51.1% anthropogenic habitat (urban development and agriculture) concentrated predominantly in the northwestern portion of the island and along the southeastern coast

and Debrot 2012a). We then conducted additional literature searches in Google Scholar and Web of Science using the species' scientific and common names plus Aruba as our search terms. Please note we use the terms 'non-native' and 'introduced' interchangeably as the species introduced to Aruba are non-native.

From the literature sources we found for each species, we recorded the year of introduction, introduction pathway, introduction source, native range, establishment status, and habitat used. For the year of introduction, if it was not known with certainty, we used the year the species was first observed, estimated to have been introduced, or first documented. Using these years of introduction, we calculated a cumulative rate of species introductions over time on Aruba and determined whether a linear or exponential curve fit the data better using the statistical analysis software R (version 4.0.2, R Core Team 2020).

Identifying the introduction pathway and source location of introduced species is important for preventing future introductions, however, these are often not known. For the introduction pathway for each species on Aruba, we recorded the exact pathway if known or else included pathways that are not known with complete certainty but for which strong support exists. We categorized all pathways as intentional (e.g. pet trade, recreational release) or unintentional (e.g., cargo), and summarized the patterns of introduction pathways and the certainty of those pathway estimates. Where possible, we also recorded the geographic location of introduction sources and the certainty of those sources. For context, we also identified and summarized the geographic native range of the introduced species on Aruba, with the acknowledgement that many species are not directly introduced from their native range.

The establishment of species following introduction is the first step towards their spread from their point of introduction and potentially causing negative impacts (Blackburn et al. 2011). To determine the establishment status of species on Aruba, we used the last reported status for the species in terms of whether it is established or extirpated (Perella and Behm 2020). To understand the degree to which the established species have invaded Aruba, we summarized their relative abundance (rare or abundant) in their populations and whether they had localized or widespread populations (Colautti and MacIsaac 2004; Blackburn et al. 2011), resulting in four classifications: localized and rare (L–R), localized and abundant (L–A), widespread and rare (W–R) and widespread–localized and rare (W–L–R) (Table A1). This latter W–L–R category reflects species that have several localized, disjoint populations across the island, whereas species ranked as W–R are presumed to have more continuous distributions across Aruba and L–R and L–A species are restricted to a single locality. In addition, we identified the species' habitat use as anthropogenic (e.g., residential gardens, resort gardens) or natural (e.g., national park, scrub, forests). We contrasted the categorical distributions of the established species relative to their habitat use categorized as anthropogenic (e.g., resort and residential gardens), natural, or a mix of the two.

Finally, we summarized the ecological impact of established species on Aruba in the form of interactions with resident species. For these assessments, we used actual or predicted impacts of the invader on resident species on documented Aruba as suggested in the literature, if available, otherwise we included the ecological interactions of the species documented in other parts of its range if they are applicable to resident species on Aruba.

Results

Rate of introductions

There are 15 non-native herpetofaunal species that have been introduced to Aruba: 10 lizards, two snakes, two anurans, and one turtle (Table 1). For most species, the year it was introduced to Aruba is not known, therefore we used the year it was first observed (FO), if reported, otherwise we used the year of the publication first reporting it on Aruba (FR) (Table A1). The earliest documented species was *Gonatodes antillensis* in 1887 (Lidth de Jeude 1887) whereas the most recent species is *Anolis cristatellus* (Duméril and Bibron 1837), first observed in 2019 but estimated to have been introduced in 2018 (Behm et al. 2022). Overall, the rate of species introductions has accelerated over time resulting in an exponential growth pattern (linear model $R^2 = 0.79$; exponential $R^2 = 0.96$) culminating in the three most recently documented species estimated to have been introduced to Aruba in 2018 (Fig. 2).

Table 1 Introduction, establishment, and impacts of introduced herpetofaunal species in Aruba

Species	Year	Pathway[a]	Source locality	Native range	Establishment status	Habitat used[b]	Ecological impact[c]
Lizards-geckos							
Gonatodes albogularis	1940[1]	Unk[d]	Unk	Central and South America, Caribbean islands	Extirpated[2]	A[3]	NA
Gonatodes antillensis	1887[4]	Unk	Curaçao[5]	Bonaire; Curaçao; Venezuelan Antilles	Extirpated[2,3]	Unk	NA
Gonatodes vittatus[e]	Unk	Unk	Venezuela[6]	Northern South America, Trinidad and Tobago; Venezuelan Antilles	Established[2] (W-R)	A[7]	Unk
Hemidactylus frenatus	2018[8]	Unk	Unk	Southeast Asia	Established[8] (W-L-R)	A[8]	C[,9,10]
Hemidactylus mabouia	2002[5]	Unk	Unk	Africa	Established[2] (W-L-R)	A[11]	C[9,10]
Lizards-Anoles							
Anolis cristatellus	2018	U[8]	Unk	Puerto Rican Island bank	Established[8] (L-A)	A[8]	C[12–15]
Anolis gingivinus	2018[8]	Unk	Anguilla or Sombrero Banks	Anguilla and Sombrero island banks	Established[8] (L-A)	A[8]	C[16]
Anolis porcatus	2008[6,17]	U[17]	Cuba[17]	Cuba	Established[2] (L-R)	A[17]	Unk
Anolis sagrei	2008[6]	U[6]	Cuba[6]	Cuba; Bahamas; Caymans; Mexico; Belize	Extirpated[,2]	A[6]	NA
Lizards-whiptails							
Cnemidophorus arenivagus	1950-1953[6]	U[18,19]	Venezuela[18,19]	Northern South America	Established[2,5] (L-R)	A,N[5]	C[19]
Snakes							
Boa constrictor constrictor	1999[20]	I[20]	South America[20]	Central and South America; Mexico; Caribbean (Trinidad and Tobago)	Established[20] (W-R)	A,N[20]	P[20]; C[11,21]; F[22]
Ramphotyphlops braminus	2003[11]	Unk	Southeastern US states[2]	Africa and Asia	Established[2] (L-R)	A[6]	N[11]
Anurans							
Eleutherodactylus johnstonei	1990's[5]	U[5]	Venezuela[5]	Lesser Antilles	Established[5] (W-L-R)	A[5]	Unk
Rhinella marina	Early 1960's[5]	I[5]	Colombia[5]	Central America, Southern United States, Northern South America	Established[5] (W-R)	A,N[2]	C[5,11]

Table 1 (continued)

Species	Year	Pathway[a]	Source locality	Native range	Establishment status	Habitat used[b]	Ecological impact[c]
Turtles							
Trachemys scripta	Unk	Unk	Unk	Mexico; Southern United States	Established[2] (L-R)	A[6]	Unk

[a]Pathway categories: *U* Unintentional, *I* Intentional

[b]Habitat used categories: *A* Anthropogenic habitat, *N* Natural habitat

[c]Ecological impact categories: *C* Competition, *P* Predation, *F* Facilitation, *N* None

[d]Unk, unknown

[e]indicates it is disputed whether this species is native or introduced

Sources: **1.** (Hummelinck 1940b) **2.** (Powell et al. 2011) **3.** (Hummelinck 1940c) **4.** (Lidth de Jeude 1887) **5.** (van Buurt 2005) **6.** (van Buurt and Debrot 2012b)

7. (Behm, J. E., pers. obs.). **8.** (Behm et al. 2022) **9.** (Perella and Behm 2020) **10.** (Behm et al. 2023) **11.** (van Buurt 2011) **12.** (Malhotra et al. 2011) **13.** (Daniells et al. 2008) **14.** (Dufour et al. 2018) **15.** (Fitch et al. 1989) **16.** (Roughgarden et al. 1984) **17.** (Odum and Van Buurt 2009) **18.** (Lammerée 1970) **19.** (Schall 1973) **20.** (Quick et al. 2005) **21.** (Odum and Reinert 2015) **22.** (Goessling et al. 2015)

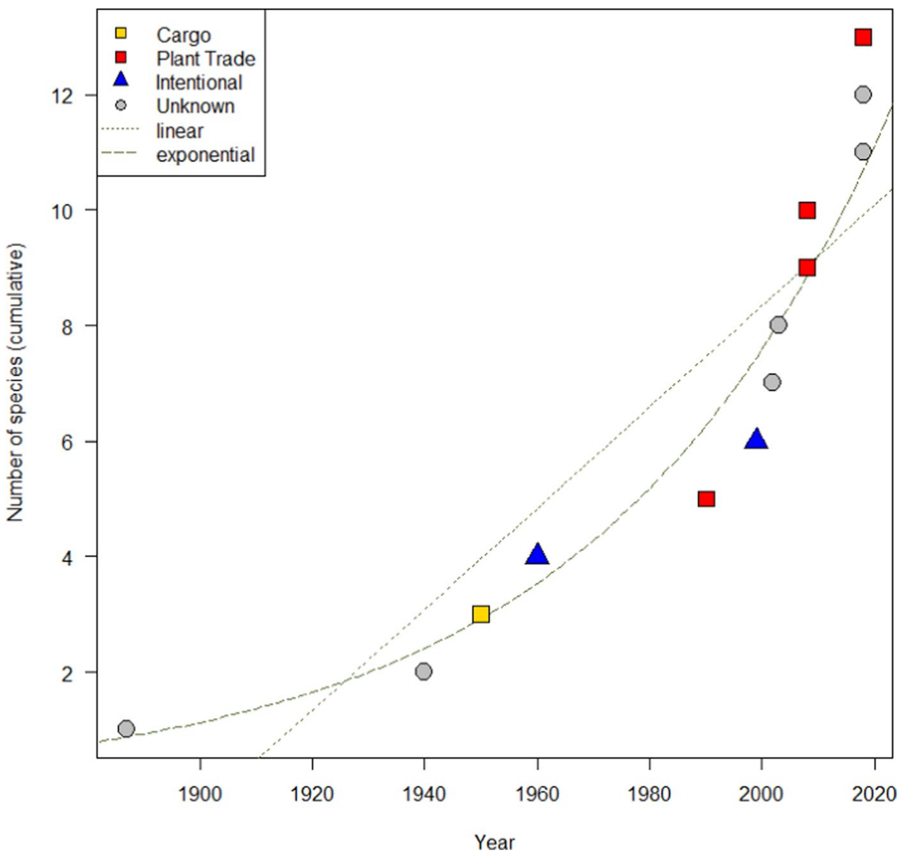

Fig. 2 Increasing rate of species introductions to Aruba over time. Cumulative number of introductions of herpetofaunal species to Aruba over time based on intentional (blue triangle: pet trade, recreational release), unintentional (square: plant trade [red], all other cargo excluding plant trade [yellow]) and unknown (circle) introduction pathways. The exponential model (dashed line) fits the data better ($R^2 = 0.96$) than the linear model (dotted line, $R^2 = 0.79$)

Introduction pathways and sources

On Aruba, the introduction pathway and source location of introduced individuals are only known with certainty for one species, *Rhinella marina* (Linnaeus, 1758), which was introduced intentionally. Categorized as a recreational release, an Aruban resident collected *R. marina* individuals on a trip to Colombia and released them in Aruba (van Buurt 2005). While the remaining species do not have definitively known pathways or sources, inference has been made by several authors documenting the introductions based on the locations and/or contexts in which the species were discovered. For example, because *Anolis sagrei* (Duméril and Bibron 1837) and *A. porcatus* (Gray 1840) were documented at the Radisson Resort garden shortly after its construction, it is inferred that they were unintentionally imported from Cuba with a shipment of palm trees the resort purchased during the garden's construction (Odum and Van Buurt 2009; van Buurt and Debrot 2012a). For the species where inferences were made about their introductions, we found that one species, *Boa c. constrictor* (Lineaus 1758), was likely introduced intentionally through the pet trade from which it later escaped and five species were likely introduced unintentionally through cargo (Fig. 2) (Quick et al. 2005; van Buurt and Debrot 2012a; Bushar et al. 2015). Of the five species likely introduced with cargo, four were likely introduced through the plant trade which has become a more prominent introduction pathway in Aruba this century (Fig. 2). All inferred introduction source locations are Caribbean islands or regions of North or South America close to the Caribbean (Fig. 3a). This

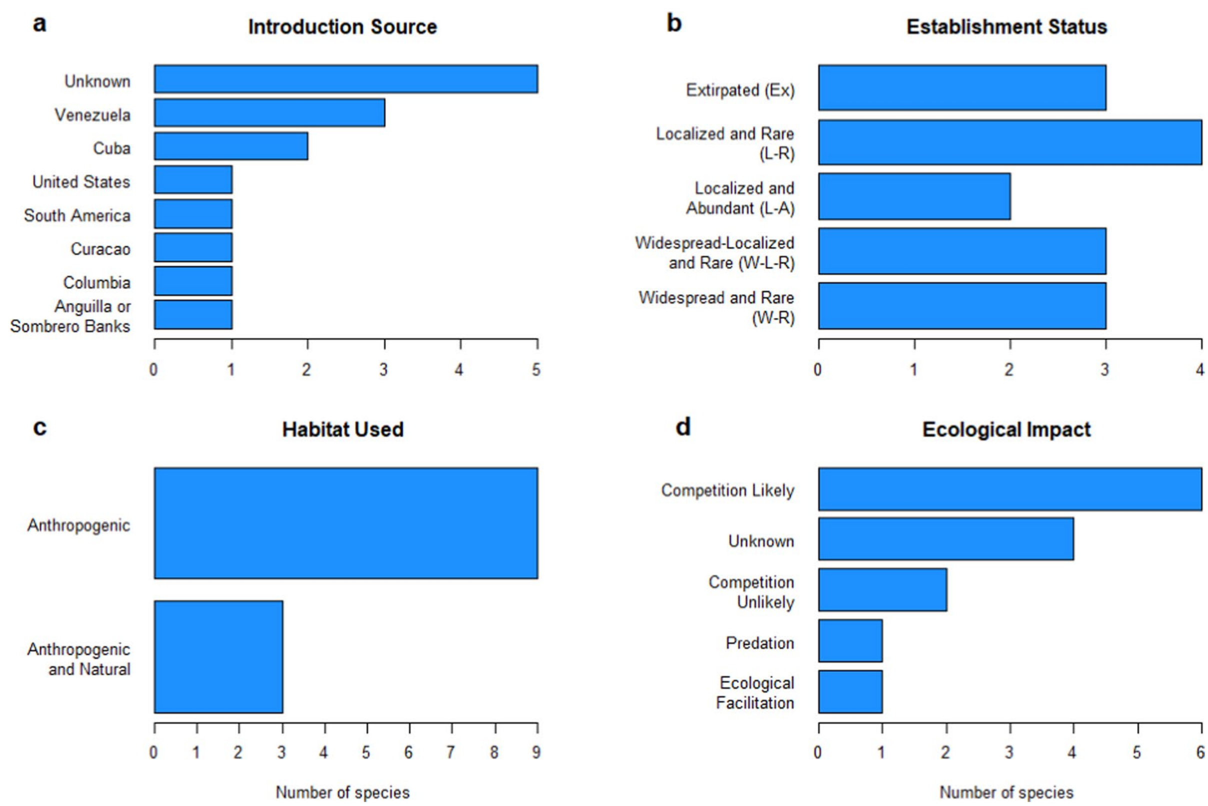

Fig. 3 Summarization of the invasion patterns for the introduced herpetofaunal species on Aruba. **a.** Number of species introduced from likely source locations; **b.** Number of species in each establishment status category ordered from the least advanced (extirpated) to most advanced (widespread and rare) invasion stages; **c.** Number of extant (non-extirpated) introduced species using anthropogenic only versus a mix of anthropogenic and natural habitat; **d.** The ecological impact of the extant introduced species on Aruba's resident species. *Note*: ecological impact categories are not mutually exclusive for introduced species

likely reflects global trade patterns whereby Aruba trades more frequently with close neighbors than distant nations.

Native ranges of introduced species

We found that 12 of the 15 species introduced to Aruba are native to islands and mainland areas within the Caribbean region (Fig. 4). In particular, five of these species are only native to islands within the Caribbean while the other seven species have native ranges that encompass both Caribbean island and mainland areas. The remaining three species, *Hemidactylus frenatus* (Duméril and Bibron 1836), *H. mabouia* (Moreau de Jonnès 1818), and *Ramphotyphlops braminus* (Daudin 1803), have native ranges outside the western hemisphere. It is important to note that the native ranges do not necessarily indicate the sources of introduced individuals, especially for *H. frenatus, H. mabouia* and *R. braminus* which are globally successful invasive species (Bomford et al. 2009) and have widespread introduced populations across the Caribbean (Powell and Henderson 2012; Behm et al. 2019). Since the majority of the species introduced to Aruba are native to the Caribbean, it may indicate that Caribbean species are pre-adapted to survive conditions in other Caribbean locations. Alternatively, it may simply be a reflection of trade patterns.

Establishment success and habitat use

Of the 15 species introduced to Aruba, 12 have established populations while *Gonatodes albogularis* (Duméril and Bibron 1836), *G. antillensis* (Lidth de Jeude 1887), and *A. sagrei* have not been observed since their first sightings in 1940, 1887, and 2008, respectively, and are presumed to be extirpated (Hummelinck 1940a; Powell et al. 2011; van Buurt and Debrot 2012a) (Table 1). Based on our four population categories, we found only three species classified as W-R, the farthest stage of invasion in our assessment: *Gonatodes vittatus* (Lichtenstein and Martens 1856), *Boa c. constrictor,* and *Rhinella marina* (Fig. 3b). *Boa c. constrictor* and *R. marina* were also categorized as using both natural and anthropogenic habitats (Fig. 3c), which likely facilitates their ability to disperse across the island. The localized populations of the other established species may reflect their intolerance of the natural arid conditions or lack of widespread survey effort. Notably, while many species have been confidently documented using anthropogenic habitat, few have confirmed absences reported for their use of natural habitat (Table A1). For example, although *G. vittatus* is categorized as W-R, it is not reported as using natural habitats, which is surprising given it is disputed whether it is a native species and this W-R categorization may simply indicate a lack of survey effort.

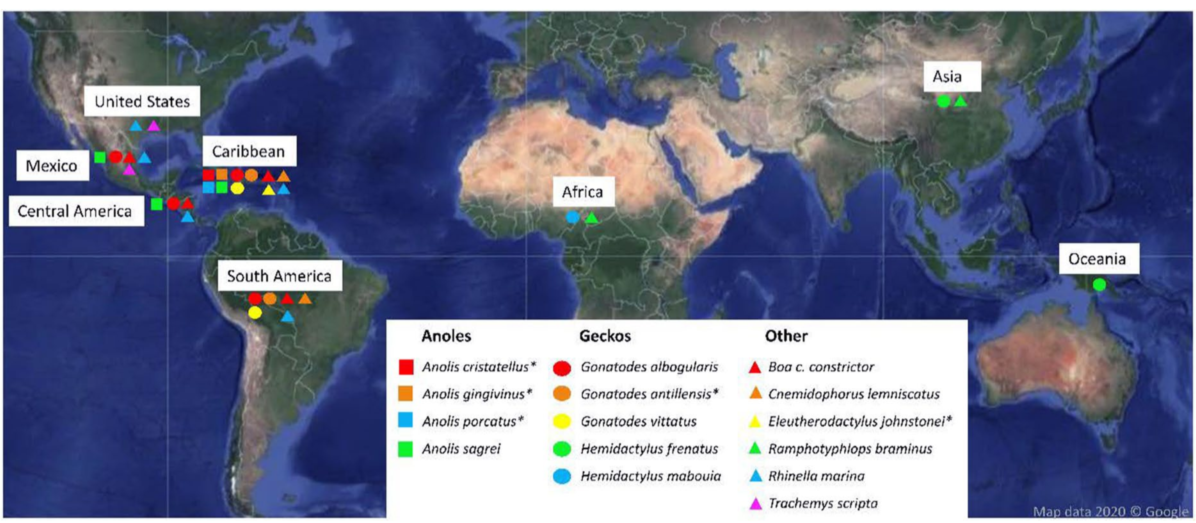

Fig. 4 Native ranges of herpetofaunal species introduced to Aruba. The majority of species introduced to Aruba are native to the Caribbean region with five species native to only islands (indicated with asterisks after the species name in the legend)

Cnemidophorus arenivagus (Cole and Dessauer, 1997) is the final species reported to use both natural and anthropogenic habitats yet has a localized distribution because it is restricted to areas with sandy soil in the southern part of Aruba. All remaining species are reported to use anthropogenic habitat only, including *Trachemys scripta* (Thunberg in Schoepff 1792) which uses human-created freshwater habitats. This use of anthropogenic habitats by introduced species on Aruba is consistent with reports of introduced herpetofaunal species using anthropogenic habitat on other Caribbean islands (Jesse et al. 2018), and may indicate that their establishment on Aruba is at least in part facilitated by human development.

Ecological impacts

Of all introduced species on Aruba, only *B. c. constrictor* has been formally assessed for ecological interactions with resident species (Fig. 3d). *Boa c. constrictor* is documented predating native bird and reptile species (Quick et al. 2005; Reinert et al. 2021), as well as facilitating the population of the native species, *C. arubensis* (Lidth de Jeude 1887), possibly through predation on its avian competitors or predators (Goessling et al. 2015). Of the remaining 11 introduced species, three had inferred interactions with native species based on anecdotal observations or the absence of ecologically similar competitors on Aruba, and interactions for four species were inferred based on interactions documented for that species elsewhere (Table A1). The most commonly inferred interaction between introduced and resident species is competition, with six introduced species predicted to compete with ecologically similar residents, likely with negative outcomes for the residents. However, it is noteworthy that most introduced species on Aruba feed on invertebrates, chiefly arthropods, which are poorly catalogued on Aruba, and the impact of these introduced predators on the resident arthropod biodiversity is unknown (Perella and Behm 2020).

Discussion

Overall, the patterns in the introduction of herpetofaunal species to Aruba largely echo the patterns documented in the Caribbean region as a whole: species introduction rates are increasing exponentially, introduction pathways and introduction source localities are largely unknown with certainty, species are mostly exploiting anthropogenic habitat, and impacts of introduced species remain underexplored. Perhaps the most striking pattern emerging from our study is the lack of certainty surrounding the introductions of most of the species. While it is likely impossible to fill in these knowledge gaps with certainty for the year of introduction, introduction pathways, and sources of the species that have already been introduced, future studies can better elucidate habitat use, species distributions, and impacts.

The exponential introduction rate we calculated on Aruba matches the exponential increase in trade globally that is associated with the spread of introduced species around the world, regardless of pathway (Westphal et al. 2008; Seebens et al. 2017), as well as the exponential introduction rates of all herpetofaunal species (Powell et al. 2011), anoles (Helmus et al. 2014), and geckos (Perella and Behm 2020) across the Caribbean region. For herpetofaunal species globally and in the Caribbean, two of the most prominent introduction pathways are from introductions intentionally through the pet trade and unintentionally through cargo (Kraus 2009; Powell et al. 2011)—two pathways with clear links to trade. The most likely speculated pathway for recent introductions to Aruba is unintentionally with cargo, specifically shipments of live plants, likely for landscaping in both commercial and residential settings. Inspections of plant shipments are clearly necessary to confirm the prominence of this pathway.

Identifying the source populations for introduced species is important for both curtailing their spread across the Caribbean region and understanding regional invasion dynamics. In particular, it would be useful to know if certain widespread species are being spread from a single source or multiple sources as there are implications for invasion success, species evolution and management (Wilson et al. 2009; Lockwood et al. 2013). Future work to elucidate the source localities of species on Aruba and across the Caribbean is needed. Recent work suggests that for reptiles, species native to the western Hemisphere with introduced populations are disproportionately native to islands (Jesse et al. 2022). The species on Aruba support this pattern where the 12 species native to the Caribbean have native ranges that either partially or totally encompass islands.

In the Caribbean, on average, introduced herpetofaunal species have high establishment rates in new locations (Kraus 2009; Powell et al. 2011; Perella and Behm 2020), which is consistent with the high establishment rate (80%) we found in Aruba. However, in Aruba most established species appear to be confined to anthropogenic habitats. These anthropogenic habitats are often irrigated and/or provide other resource subsidies that the arid natural habitat lacks. It is possible that the introduced species cannot spread into the natural habitats and are confined to these novel habitats created by humans. Alternatively, the introduced species may simply have localized populations in anthropogenic habitats because that is where they were introduced and there has not been enough time for them to spread. Additional work should explore the degree to which these possibilities are occurring. In addition, for the species that have been documented using anthropogenic habitat, few have documented absences for natural habitat. This may be due to the style of reporting, i.e. absences are inferred but not directly reported, or due to a lack of survey effort in natural areas. Consistent reporting of documented absences are needed to better assess species distributions.

From a conservation perspective, assessing the impacts of the introduced species on the ecosystems in Aruba is paramount. In general, the impacts of introduced herpetofaunal species are poorly understood and are predicted or inferred from only a handful of studies (Kraus 2015; Perella and Behm 2020). Because it is a large predator, there have been investigations into the impact of *Boa c. constrictor* on Aruba's ecosystem, documenting its predation on reptiles and birds, and investigations into its impact on the critically endangered native Aruban rattlesnake (*Crotalus unicolor*) are ongoing (Odum and Reinert 2015). However, further investigations into the impacts of other introduced species are needed.

In general, the documentation of newly introduced species requires a thorough inventory of resident biodiversity and regular monitoring of ecosystems for new arrivals. In terms of native vertebrate biodiversity, Aruba is relatively well documented, although questions still surround the native status of several herpetofaunal species [e.g. *Gonatodes vittatus, Pleurodema brachyops* (Cope 1869)]. Invertebrate and plant diversity are less well-inventoried. Recently, we documented three new lizard species on Aruba in surveys that covered only a small fraction of the island in less than a week (Behm et al. 2022). This likely indicates that regular surveys could be helpful in identifying new introduced species. Importantly, when newly introduced species are documented on Aruba, or elsewhere, comprehensive data must be collected and reported to facilitate the sharing of knowledge among stakeholders (Castro et al. 2023).

Conclusions

The processes occurring on Aruba that have led to the introduction of these species are not limited to Aruba. They are happening at locations across the globe, and together the establishment of introduced species at multiple locations results in the emergent global patterns of increased species introductions (Seebens et al. 2017) and homogenization of species assemblages (Capinha et al. 2020). If reversing the trend of increasing introductions of non-native herpetofaunal species is a goal for Aruba, we suggest increased monitoring of imports, particularly live plant shipments. Although shipment inspections are costly, eradication of established introduced species is often more costly and difficult than preventing new introductions in the first place (Mack et al. 2000; Kraus 2009) as Aruba is discovering with the *B. c. constrictor* invasion (Quick et al. 2005; Odum and Reinert 2015; Bushar et al. 2015). Estimations of the impacts of already introduced species and predicted likelihood for the species to spread from anthropogenic into natural habitats are also needed and would help inform management decisions. Finally, because Aruba is one of the Caribbean islands with the highest number of introduced herpetofaunal species, patterns identified and lessons learned on Aruba may help inform management elsewhere to help reverse this region-wide trend and protect the species within this biodiversity hotspot.

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Author contributions JEB and MRH conceptualized the study. GMB and JEB designed the data collection methods. GMB collected and compiled the database and analyzed the data. GMB and JEB wrote the first draft of the manuscript and all authors contributed to revisions. All authors read and approved the final version of the manuscript.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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