

## Research Article

## Exotic predators may threaten another island ecosystem: A comprehensive assessment of python and boa reports from the Florida Keys

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### Abstract

Summarizing historical records of potentially invasive species increases understanding of propagule pressure, spatiotemporal trends, and establishment risk of these species. We compiled records of non-native pythons and boas from the Florida Keys, cross-referenced them to eliminate duplicates, and categorized each record's credibility. We report on 159 observations of six python and boa species in the Florida Keys over the past 17 years. Burmese pythons (*Python bivittatus*), boa constrictors (*Boa constrictor*), and ball pythons (*Python regius*) are the most frequently reported species, but credible records of three additional species were also reported. Among the most notable records, we report on three hatchling and multiple reproductive Burmese pythons captured on North Key Largo since 2016, indicating that the species is now established on that island. The expanding mainland Burmese python population and ongoing python and boa introductions via pet and cargo pathways are likely to keep propagule pressure high in coming years. Both effective public outreach to solicit reporting of sightings and effective early detection and rapid response networks may help to prevent further establishment and associated ecological impacts of python and boa species in the Florida Keys.

**Key words:** invasive species establishment, propagule pressure, constrictor snake, island ecology, early detection and rapid response, Boidae, Pythonidae

### Introduction

Geographic isolation allows island flora and fauna to evolve with limited competitors and predators (MacArthur and Wilson 1967), thus making the introduction of a new predator potentially catastrophic to island ecosystems (Bellard and Jeschke 2016; Russell et al. 2016; Vitousek 1988). Invasive mammals have caused many high-profile impacts to insular faunas including major population declines and extinctions (e.g., the small Indian mongoose [*Herpestes javanicus*; Hays and Conant 2007], domestic cats [*Felis catus*; Medina et al. 2011]). Invasive snakes, however, are

increasingly recognized as posing high risks to native species on islands around the world (Cabrera-Pérez et al. 2012; Monzón-Argüello et al. 2015; Quick et al. 2005; Reynolds et al. 2013; Rodda and Savidge 2007; Savidge 1987; Vázquez-Domínguez et al. 2012). Due to their low detection probability (Durso et al. 2011), early detection and reporting of invasive snakes may serve to identify species and areas at risk from newly established populations of invasive snakes.

The Florida Keys are a chain of limestone islands extending approximately 180 km from southeastern mainland Florida (Hoffmeister and Multer 1968) with mangrove, pine rockland, and tropical hardwood forests (Hilsenbeck 1976; Schomer and Drew 1982;

Snyder et al. 1990) that provide habitat for a diversity of native wildlife, including five endemic mammals deemed “in danger of extinction throughout all or significant portion[s] of [their] range[s]” (Key deer [*Odocoileus virginianus clavium* Barbour and Allen, 1922], Key Largo woodrat [*Neotoma floridana smalli* Sherman, 1955], lower Keys marsh rabbit [*Sylvilagus palustris hefneri* Lazell, 1984], Key Largo cotton mouse [*Peromyscus gossypinus allapaticola* Schwartz, 1952], and rice rat [*Oryzomys palustris natator* Chapman, 1893]), thereby listing them as endangered under the U.S. Endangered Species Act (U.S. House of Representatives 1973; USFWS 1999; USFWS 2018). All of these species may be impacted by the introduction of a new predator such as an exotic snake. Of particular concern is the Burmese python (*Python bivittatus* Kuhl, 1820), a large constrictor snake native to southeast Asia that is established on the Florida mainland adjacent to the Florida Keys and that has negatively impacted native mammal populations in the Greater Everglades Ecosystem (Dorcas et al. 2012; McCleery et al. 2015). Laboratory experiments (Hart et al. 2012) and multiple observations of Burmese pythons swimming several kilometers from the mainland in Florida Bay (EDDMapS 2018) and on islands in their native range (e.g., You et al. 2013) suggest that dispersal from the mainland to the Florida Keys is possible. Moreover, Burmese pythons are not the only exotic-snake introduction risk for the Keys; at least 15 other python and boa (Squamata: Boidae, Pythonidae) species were introduced to Florida in the past 50 years via the pet-trade or cargo pathways (Krysko et al. 2016). In short, both expanding populations elsewhere in the state and ongoing human-associated introductions may result in high propagule pressure for pythons and boas in the Florida Keys.

Greene et al. (2007) provided the first peer-reviewed report of an exotic constrictor snake from the Florida Keys, a Burmese python captured in 2007. However, we discovered previous reports during this investigation. The credibility of these and other subsequent reports is highly variable, and no critical examination of available evidence has been conducted. In this paper, we evaluate these reports to better understand propagule pressure, spatiotemporal trends, and establishment risk of exotic constrictor snakes in the Florida Keys. We also discuss likely invasion pathways, anticipated impacts, and possible management strategies.

## Methods

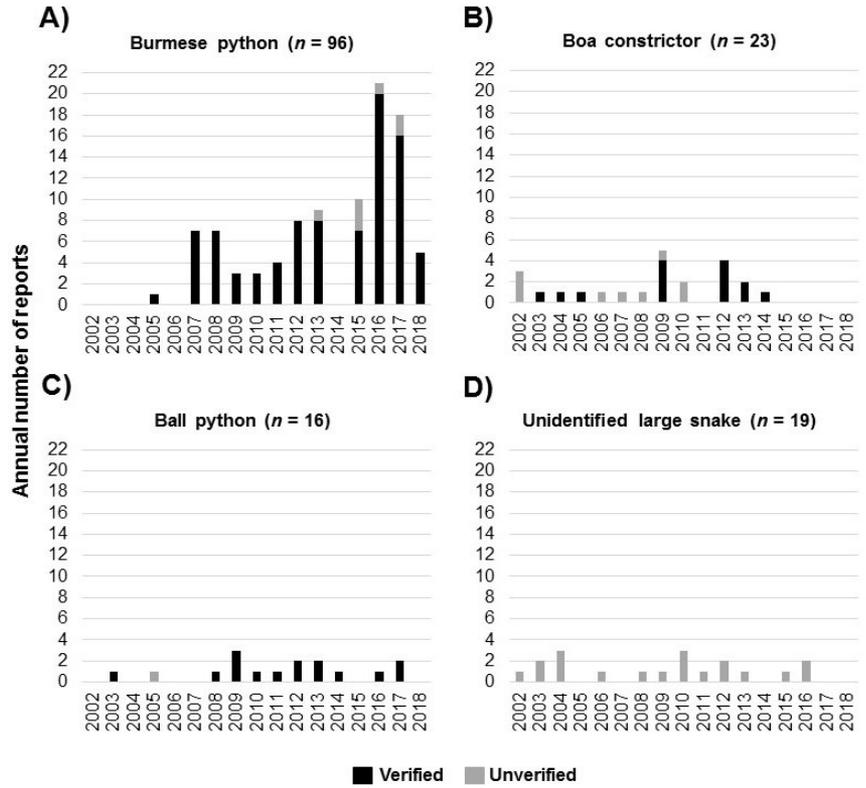
We compiled python and boa records from the Florida Keys using all sources we were aware of, including the Early Detection and Distribution Mapping System

(EDDMapS 2018), records from Everglades and Biscayne National Parks, Florida Museum of Natural History, Monroe County Sheriff’s Office, media accounts, and our own observations through March 2018. We considered a report to be from the Florida Keys if the snake was observed within the outermost boundary of the Florida Keys National Marine Sanctuary, on U.S. Route 1 south of and including mile marker 113 (25.252941°; -80.437029°), or in Florida or Biscayne Bays, with the northernmost boundary at Sands Key (25.518234°; -80.176573°; Supplementary material Figure S1). We cross-referenced all dates, locations, and reporter identities to find and delete duplicate records (per Falk et al. 2016) and categorized each record’s credibility as either verified (a photograph or specimen has been verified by an expert) or unverified (a photograph or specimen has not been verified by an expert).

We mapped each record in ArcMap 10.3.1 (Environmental Systems Research Institute [ESRI], Redlands, CA, U.S.A.). If coordinates were not included with a report, we used locality descriptions and Google Earth (Google LLC, Mountain View, CA, U.S.A.) to assign coordinates following the georeferencing practices described by Chapman and Wiczorek (2006). The terrestrial portion of our study area is divided into three previously established geographic regions: (1) the “Upper Keys” defined as the islands and man-made bridges from U.S. Route 1 mile marker 113 to 72 (24.842143°; -80.752388°) and Card Sound Road within the outermost boundary of the Florida Keys National Marine Sanctuary; (2) the “Middle Keys” defined as the islands and man-made bridges from U.S. Route 1 mile marker 72 to 47 (24.706895°; -81.12458°); and (3) the “Lower Keys” defined as the islands and man-made bridges from U.S. Route 1 mile marker 47 to zero (24.54694°; -81.812462°; Chiappone et al. 2005).

## Results

Between 08 March 2002 and 31 March 2018, 159 pythons and boas were reported from the Florida Keys (Supplementary material Table S1). Of these reports, 140 were identified to species, including Burmese python ( $n = 97$ ), boa constrictor (*Boa constrictor* Linnaeus, 1758;  $n = 24$ ), ball python (*Python regius* Shaw, 1802;  $n = 16$ ), white-lipped python (*Leiopython fredparkeri* Schleich, 2008;  $n = 1$ ), Kenyan sand boa (*Gongylophis colubrinus* Linnaeus, 1758;  $n = 1$ ), or Saharan sand boa (*Gongylophis muelleri* Boulenger, 1892;  $n = 1$ ). The remaining 19 reports were of large snakes estimated to be greater than one meter in total length with descriptions that did not match any native species. We classified these



**Figure 1.** Annual verified and unverified reports of A) Burmese pythons, B) boa constrictors, C) ball pythons, and D) unidentified large snakes with associated years in the Florida Keys through March 2018.

reports as “unidentified large snakes” (i.e., possible pythons or boas). Most reports (122 of 159, or 77%) were classified as verified.

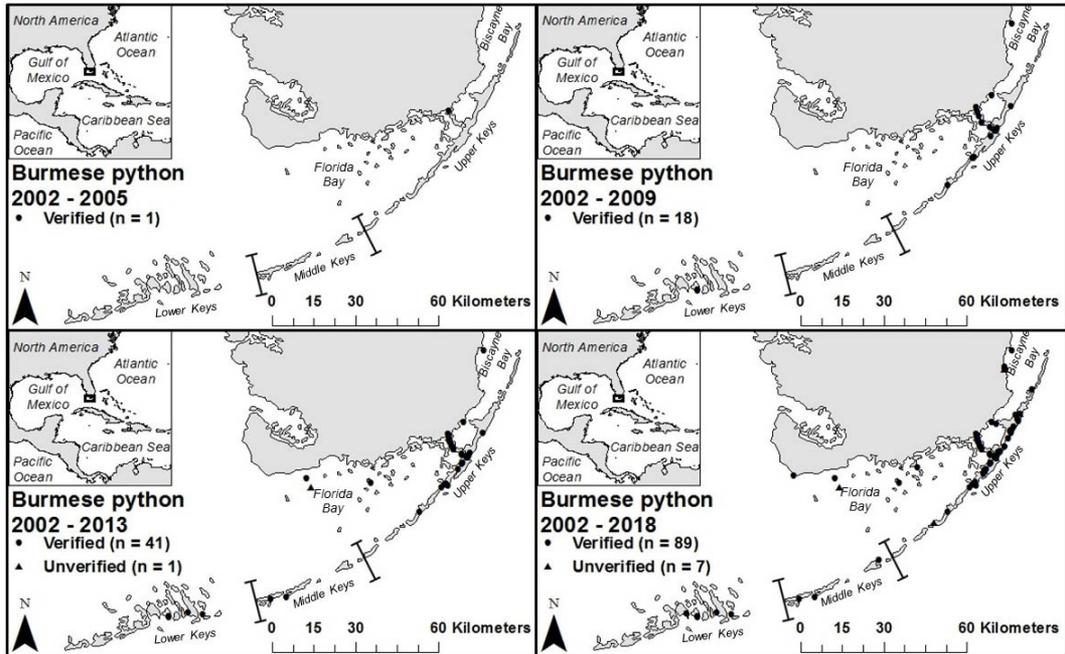
*Burmese python*

Ninety-seven Burmese pythons (verified = 89; unverified = 8) have been reported from the Florida Keys, with the first in 2005, none in 2006 or 2014, and a maximum of 21 in 2016. One Burmese python report had no associated observation date. The number of Burmese pythons reported each year has increased over time (Figure 1). Ten Burmese pythons were observed offshore in Florida Bay (5) or Biscayne Bay (5) and ranged from less than one to roughly seven kilometers from the mainland. Most (78) Burmese pythons were reported from the Upper Keys (Figure 2); of these, we tallied 50 verified individuals from Key Largo, the northernmost of the Keys connected by U.S. Route 1, with another four unverified and five more in nearby mangrove habitats that are largely contiguous with Key Largo. Three verified hatchlings were found within three kilometers of one another on Key Largo during 2–23 August 2016, representing the first hatchlings found on the island. Sex was determined for 38 of the

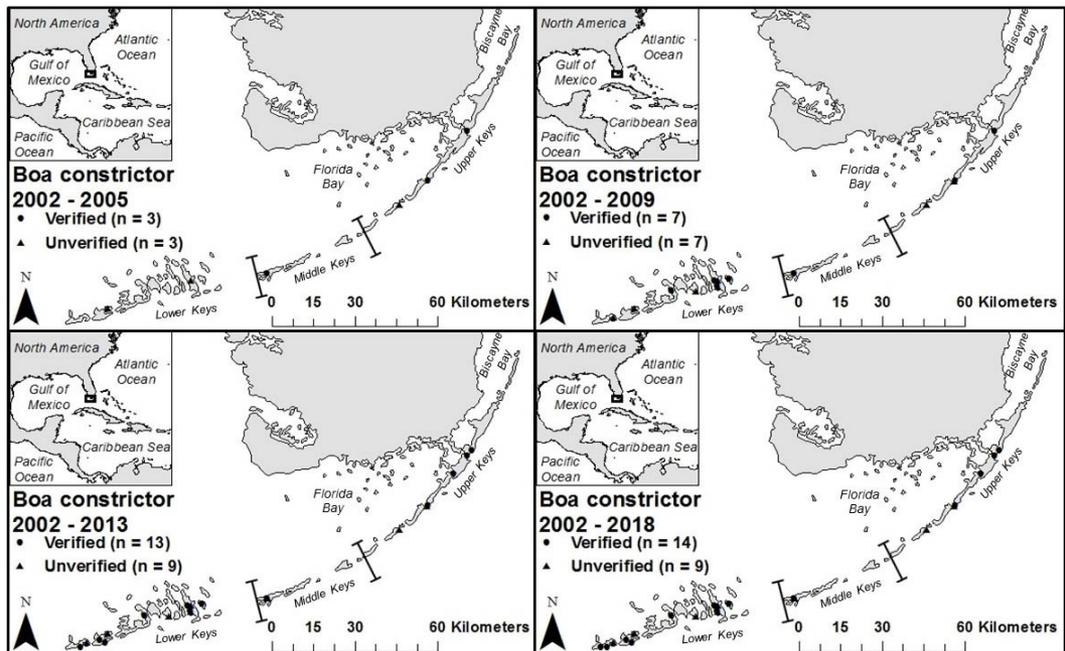
reported Burmese pythons, with 25 males and 13 females. Morphometric data were associated with 38 reports, including mass ( $n = 34$ ; mean  $\pm$  SD = 9,017.8  $\pm$  12,528.5 g; range = 122.0–75,400.0 g), snout-vent-length (SVL;  $n = 31$ ; mean  $\pm$  SD = 206.5  $\pm$  60.5 cm; range = 59.0–429.0 cm), and/or total length (TL;  $n = 35$ ; mean  $\pm$  SD = 233.5  $\pm$  73.2 cm; range = 45.7–477.0 cm).

*Boa constrictor*

Twenty-four boa constrictors (verified = 15; unverified = 9) have been reported from the Florida Keys, with the first in 2002, the most (5) in 2009, and none since 01 June 2014 (Figure 1). One boa constrictor report had no associated date. Of the 24 reports, 14 were reported in a six year timespan (2009–2014). Collectively, boa constrictors were reported from 11 islands throughout the Florida Keys (Figure 3). Most (16) were reported from the Lower Keys, including six from Big Pine Key. Sex was determined for three females and two males. Mass ( $n = 4$ ; mean  $\pm$  SD = 12,181.3  $\pm$  20,624.6 g; range = 684.0–43,091.3 g), SVL ( $n = 3$ ; mean  $\pm$  SD = 129.4  $\pm$  28.2 cm; range = 97.0–148.3 cm), and/or TL ( $n = 4$ ; mean  $\pm$  SD = 196.2  $\pm$  97.3 cm; range = 108.0–335.3 cm) measurements were associated with four reports.



**Figure 2.** Spatiotemporal display of Burmese python reports with associated years ( $n = 96$ ) within the Florida Keys through March 2018. The first panel displays all Burmese python reports during 2002–2005, and each subsequent panel displays cumulative reports of Burmese pythons for the subsequent four calendar years. Reports from 2018 only include the first three months of the calendar year. Ten Burmese pythons were observed offshore in Florida Bay (5) or Biscayne Bay (3) and ranged from less than one to roughly seven kilometers from the mainland. A majority of Burmese pythons (78) were reported from the Upper Keys.



**Figure 3.** Spatiotemporal display of boa constrictor reports with associated years ( $n = 23$ ) within the Florida Keys through March 2018. The first panel displays all boa constrictor reports during 2002–2005, and each subsequent panel displays cumulative reports of boa constrictors for the subsequent four calendar years. Reports from 2018 only include the first three months of the calendar year. Collectively, boa constrictors were reported from 11 islands throughout the Florida Keys. Most (16), however, were reported from the Lower Keys, including six from Big Pine Key.

### *Ball python*

Sixteen ball pythons (verified = 15; unverified = 1) have been reported from the Florida Keys, with the first in 2003 and the most (3) in 2009 (Figure 1). Half of all ball pythons (8) were observed or captured in the Lower Keys, with seven and one from the Upper and Middle Keys, respectively (Figure 4). Sex was determined for two males and one female. Morphometric data were associated with six reports, including mass ( $n = 3$ ; mean  $\pm$  SD = 1,860.7  $\pm$  312.9 g; range = 1,562.0–2,186.0 g), SVL ( $n = 4$ ; mean  $\pm$  SD = 108.7  $\pm$  22.2 cm; range = 75.5–116.7 cm), and/or TL ( $n = 6$ ; mean  $\pm$  SD = 122.9  $\pm$  20.7 cm; range = 81.0–135.0 cm).

### *White-lipped python*

A male white-lipped python (mass = 1,588 g; SVL = 161 cm; total length = 188.5 cm) was found dead on a road on Plantation Key (24.960236°; -80.568419°) on 20 December 2006 (UF-Herpetology 159916).

### *Kenyan sand boa*

A female Kenyan sand boa was captured on Sugarloaf Key (24.668089°; -81.538082°) on 14 August 2007 (UF-Herpetology 151512). The snake was transferred to a residence on Big Pine Key.

### *Saharan sand boa*

On 08 May 2009, a domestic cat killed a female Saharan sand boa (total length = 56.0 cm) on Big Pine Key (24.687468°; -81.35849°; UF-Herpetology 155335).

### *Unidentified large snake*

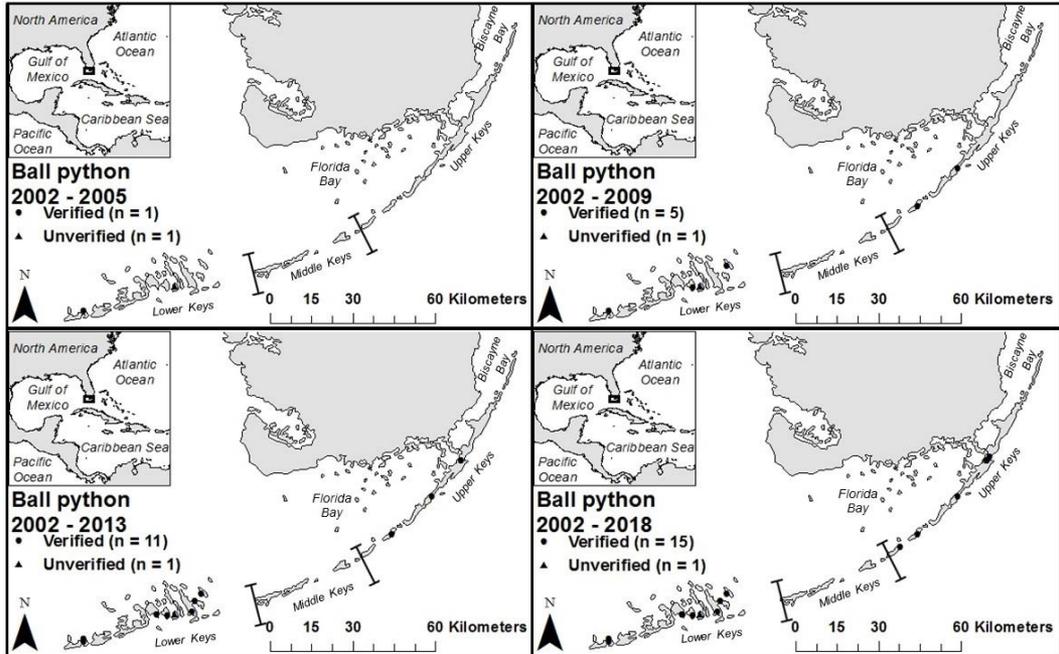
Nineteen unidentified large snakes (verified = 0; unverified = 19) have been reported from the Florida Keys, with the first in 2002, the most in 2004 (3) and 2010 (3), and none since 15 December 2016 (Figure 1). Eight were reported from the Lower Keys, and nine and two from the Upper and Middle Keys, respectively (Figure 5).

## Discussion

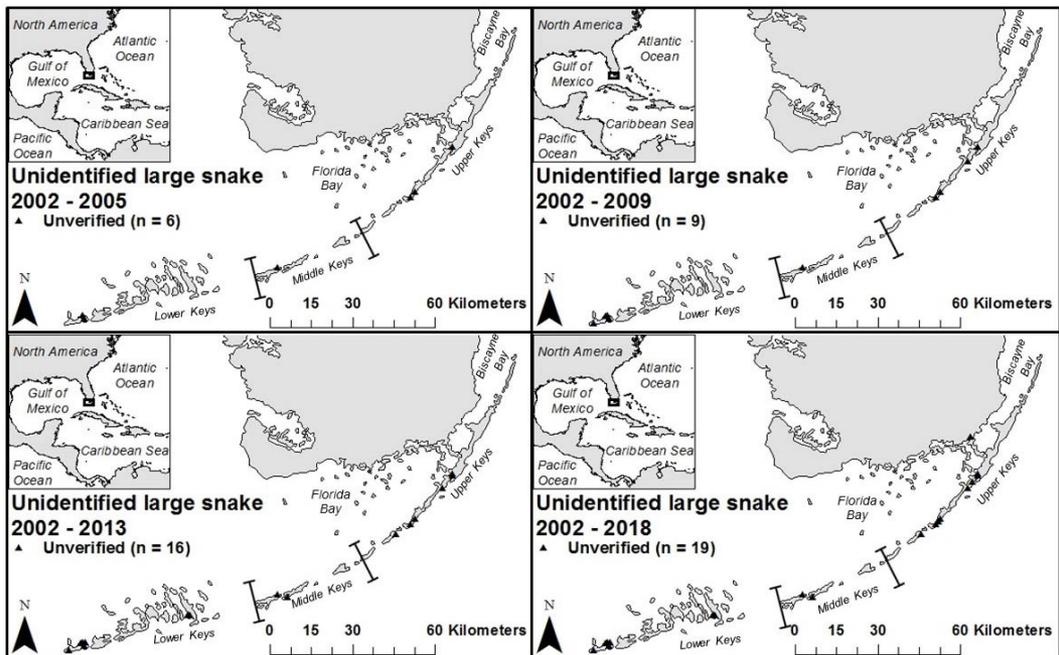
We compiled 159 reports of at least six python and boa species from the Florida Keys over seventeen years. The yearly number of Burmese python reports has increased over time, but, conversely, there have been fewer boa constrictor, ball python, and unidentified large snake reports in recent years. Single observations of three species (white-lipped python, Kenyan sand boa, Saharan sand boa) suggest that propagule pressure for these species is low. A concentration of

Burmese python reports from the Upper Keys (Figure 2) suggests that population increases on the mainland may be driving dispersal south. Similarly, habitat connectivity (e.g., mangroves) between the breeding population of boa constrictors in the Deering Estate at Cutler, Miami-Dade County (Snow et al. 2007a) and the Florida Keys presents risk of this species dispersing to the Keys. Our results, however, suggest that the pet trade is the most likely source of most boa constrictors found in the Keys, as reports are concentrated in the set of islands farthest from Deering Estate (the Lower Keys). If boa constrictors had dispersed from the Deering Estate, individuals would have likely been found closer to the source population (e.g., in Biscayne Bay, in the Upper Keys). Half of all ball pythons were also reported from the Lower Keys, and these records most likely represent released or escaped pets. Targeted searches to identify and delineate incipient populations would be justified for Burmese pythons on Key Largo, boa constrictors on Big Pine Key, and ball pythons in the Lower Keys. In fact, such efforts on Key Largo directly resulted in the removal of five Burmese pythons in 2017, including a large, sexually mature female (mass = 75.4 kg; SVL = 429.0 cm; total length = 477.0 cm; EDDMapS 2018; Metzger et al. 2017).

Public outreach and education are critical components of invasive species management, and pythons and boas in the Florida Keys are no exception. Several major outreach events occurred over the period covered by our dataset, including: 1) the launching of EDDMapS in 2005; 2) two batches of informational postcards created and sent out by the U.S. Geological Survey and collaborators requesting that residents of Key Largo report sightings of Burmese pythons – these were sent to 3,900 residences in 2010 and over 8,000 residences in 2016; and 3) two Python Challenges<sup>®</sup> (month-long Burmese python removal competitions) on the mainland in 2013 and 2016 directed by the Florida Fish and Wildlife Conservation Commission (Mazzotti et al. 2016; Python Challenge<sup>®</sup> 2015). Moreover, from 2008 to 2012, the U.S. Geological Survey conducted early-detection trapping efforts for pythons on Key Largo and engaged in extensive outreach. We observed an overall improvement in the quality of reports after 2010 (more descriptive, usually photographed, location data often included), a decrease in the proportion of unverified reports, and improvements to the reporting pipeline (i.e., reports reached the appropriate management agency in a timely manner). It is essential for managers to receive accurate reports as soon as possible after a sighting or capture to: 1) mount a rapid response effort, if appropriate; and 2) curate a good



**Figure 4.** Spatiotemporal display of ball python reports with associated years ( $n = 16$ ) within the Florida Keys through March 2018. The first panel displays all ball python reports during 2002–2005, and each subsequent panel displays cumulative reports of ball pythons for the subsequent four calendar years. Reports from 2018 only include the first three months of the calendar year. Half (8) of ball python were reported from the Lower Keys, and seven and one made up the remaining reports from the Upper and Middle Keys, respectively.



**Figure 5.** Spatiotemporal display of unidentified large snake reports with associated years ( $n = 19$ ) within the Florida Keys through 2017. The first panel displays all unidentified large snake reports during 2002–2005, and each subsequent panel displays cumulative reports of unidentified large snakes for the subsequent four calendar years. Reports from 2018 only include the first three months of the calendar year. Nine unidentified large snakes were reported from the Upper Keys, and eight and two made up the remaining reports from the Lower and Middle Keys, respectively.

dataset to assess trends and relative risks of various introduction pathways. More public outreach and education would be justified to continue improving non-native species reports, especially pythons and boas from the Florida Keys.

The potential impacts associated with established populations of exotic constrictor snakes to the Florida Keys could be severe for the islands' native vertebrate fauna and thus for ecosystem function. Comparable invasions are responsible for nearly eliminating entire taxonomic groups on Guam (Savidge 1987) and the Florida mainland (Dorcas et al. 2012), with possible cascading effects ranging from declines in native vegetation (Mortensen et al. 2008) to adverse impacts on human health (Hoyer et al. 2017). Remains of the federally endangered and endemic Key Largo woodrat have already been documented in the digestive tracts of Burmese pythons (Greene et al. 2007). Mammals and birds in the Florida Keys have been documented as python prey or are closely related to python prey species on the Florida mainland (Bartoszek et al. 2018; Dove et al. 2011; Falk and Reed 2015; Snow et al. 2007b). These species will likely be affected if the invasive Burmese python population continues to increase and expand south or if additional species of exotic constrictor snake (e.g., boa constrictors, ball pythons) become established.

A recent (2018) summary of the status of the endangered Key Largo woodrat (*Neotoma floridana smalli*; USFWS 2018) stated that at least 25 Burmese pythons had been found on Key Largo and that these invasive snakes represent a threat to woodrat population persistence. Our assessment revealed 50 verified records of Burmese pythons from Key Largo, with several more found in nearby mangrove habitats. Of these 50 pythons, over half (29) were found between January 2016 and the end of March 2018. The first seven Burmese pythons found on Key Largo (2007–2009) were all male, suggesting that they were wide-ranging males that had reached the island during mate-searching activities. Three females of reproductive size (Willson et al. 2014) have been found since 2016, as have three hatchlings and a breeding aggregation of a large female with several males. Taken together, these observations strongly indicate that Burmese pythons are established on Key Largo. If so, then this incipient population may further impact endangered endemic mammals in the Florida Keys as well as represent a new source population for invasion of islands to the south.

Our assessment of Florida Keys python and boa reports used an evolving dataset (i.e., new reports and updated information about past reports regularly surface) with small sample sizes for some species. A future updated summary will allow continued

improvement of our understanding of propagule pressure, spatiotemporal trends, establishment risk, and impacts of pythons and boas in the Florida Keys. Exotic constrictor snake management strategies as a whole are limited (Reed and Rodda 2009), but targeted search efforts, public outreach and education, and early detection and rapid response may be essential in preventing further establishment and associated ecological impacts of pythons and boas in the Florida Keys.

Note added in press: While this manuscript was being finalized, four more verified Burmese pythons were reported from the Florida Keys. The first was a male (mass = 3,160 g; SVL = 174.6 cm; total length = 203.3 cm) captured on 20 May 2018 on Little Torch Key (24.67789°; -81.39330°) in the Lower Keys, the second was a female (mass = 7,300 g; SVL = 242.0 cm; total length = 276.0 cm) captured on 8 June 2018 on a buoy in Biscayne Bay, over two kilometers off the mainland (25.545°; -80.29°; EDDMapS Record 5788330), the third was a male (mass = 2,988 g; SVL = 174.0 cm; total length = 200.7 cm) captured on 20 June 2018 on Key Largo (25.1825°; -80.36417°; EDDMapS Record 7624775), and the fourth was also captured in Biscayne Bay, but we have not yet received the capture data or specimen. These reports further emphasize the continuing risk that this species poses to the Keys via dispersal from the mainland.

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### Supplementary material

The following supplementary material is available for this article:

**Figure S1.** Map of the Florida Keys boundary delineated for this work, including Florida and Biscayne Bays and the Upper, Middle, and Lower Keys.

**Table S1.** Python, boa, and unidentified large snake reports from the Florida Keys through March 2018, including all known identification, species, date, location category and coordinates, credibility, sex, and morphometric data.

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