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INVASION NOTE

Post-hurricane relief facilitates invasion and establishment of two invasive alien vertebrate species in the Commonwealth of Dominica, West Indies

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Abstract Invasive alien species (IAS) are a main driver of current global change and contribute significantly to decreases in biodiversity worldwide. To prevent new introductions and establishment of IAS, it is important to identify mechanisms of incursion. On 18 September 2017, Hurricane Maria, a category-5 Atlantic storm, made landfall on the Commonwealth of Dominica causing widespread destruction. Responding to the post-hurricane situation, countries and organizations provided a large range of aid including funds, medical and security support, and relief supplies. Here we report the incursion and establishment of two vertebrate IAS on Dominica during the aftermath of Hurricane Maria—the Common Green Iguana (*Iguana iguana*) and Cuban Treefrog (*Osteopilus septentrionalis*)—representing a 20% increase in vertebrate alien species on Dominica. We also report observations of Venezuela Snouted Treefrogs (*Scinax x-signatus*). Collectively, these species were found at four sites spread along the Caribbean and south coast of Dominica, within or near ports of entry. Invasions of *I. iguana* and *O. septentrionalis* are especially worrisome given their known impacts on native species on other Caribbean islands. Though understandable given the human impact caused by severe weather events, these incursions suggest that biosecurity is not implemented by aid-facilitating countries and organizations. With the predicted increase in hurricane intensity and frequency, we suggest basic biosecurity and training programs to reduce incursion threats of IAS during future relief and recovery initiatives. For Dominica, we recommend mitigation programs with additional biological surveys to control and better understand the number of incursion and their impact on post-Maria Dominica.

Keywords Biosecurity · Caribbean · Emergency aid · Hurricane · *Iguana delicatissima* · *Iguana iguana* · *Osteopilus septentrionalis*

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Introduction

Biological invasions are a main driver of current global biodiversity change (Mack et al. 2000) contributing significantly to its decrease across the planet (Bax et al. 2003; Bellard et al. 2016; Butchart et al. 2010; Vilà et al. 2011). Indeed, even remote, oceanic islands are not immune to the impacts of invasion (Moser et al. 2018). While humans, either intentionally or unintentionally, act as the most common transport agents for alien species to islands, severe climatic events such as hurricanes can also serve as a catalyst for invasions. Hurricane-force wind speeds and strong oceanic currents throughout geologic history have resulted in long-range overwater movements of propagules and terrestrial vertebrates, which have contributed to biogeographic patterns within the Caribbean (Heinicke et al. 2007). These same forces can accelerate the contemporary spread and establishment of invasive propagules and terrestrial vertebrates (Censky et al. 1998). Hurricanes can also accelerate the spread of already present invasive alien species (IAS) to novel areas on islands (Bellingham et al. 2005). With the predicted increase in intensity and frequency of hurricane events resulting from climate change (Webster et al. 2005), the frequency of hurricane-induced dispersal events could also increase.

The 2017 Atlantic hurricane season was the third most active on record during which an especially high ocean heat content produced six major hurricanes with wind speeds over 178 km/h (category 3 and higher on the Saffir-Simpson Hurricane Wind Scale) (Lim et al. 2018). On 18 September 2017, Hurricane Maria, the strongest hurricane on record to make landfall on the Commonwealth of Dominica, struck the island as a category-5 storm with sustained wind speeds of over 252 km/h (Pasch et al. 2018). In response, governments, organizations and concerned citizens provided funds, security support, volunteers, evacuation and medical ships, and relief supplies to Dominica. Many supplies were shipped in containers, a known transport agent for IAS (Hulme 2009). However, because of limited operational facilities, containers were forced to stopover temporarily on surrounding islands (e.g. Guadeloupe and Martinique), which are inhabited by at least 12 species of invasive vertebrates (see island accounts in Hailey et al. 2011). Here, we report how post-hurricane Maria conditions facilitated the spread of three existing IAS in the Eastern Caribbean, not by overwater dispersal mechanisms, but instead via relief shipping containers from surrounding nations to the Commonwealth of Dominica. These IAS species include the Common Green Iguana (*Iguana iguana*), Cuban Treefrog (*Osteopilus septentrionalis*) and Venezuela Snouted Treefrog (*Scinax x-signatus*).

Materials and methods

Study species

Common Green Iguana (Iguana iguana)

The Common Green Iguana has the broadest range of any Iguanine species, occurring from northern Mexico south through Central America and the northeast of South America to Paraguay and southeastern Brazil. It also occurs naturally on numerous Caribbean islands, including but not limited to Aruba, Bonaire, Curaçao, Grenada, Saba, St. Lucia, St. Vincent, Trinidad and Tobago (Bock et al. 2018; Stephen et al. 2013). This species was first recorded on native islands of Lesser Antillean Iguanas (*Iguana delicatissima*) in 1860, when it was introduced on Les Saintes, Guadeloupe archipelago. Subsequent invasions occurred on Guadeloupe (1950), Martinique (1960), St. Martin/Maarten (1990), Anguilla (1995), Antigua (1995), Barbuda (1995), St. Barthélemy (2006), Marie-Galante (2007), La Ramier (2013), St. Eustatius (2016), and La Désirade (2016) (van den Burg et al. 2018a; Vuillaume et al. 2015 and references therein). Of these invasions, two originated from a natural event (Censky et al. 1998) while others are presumed to have an anthropogenic origin, despite transport of *Iguana* ssp. being regulated since 1977 (CITES Appendix II). Additional non-native Common Green Iguana (NNGI) populations occur on Fiji, Japan, USA (Florida and Hawaii), and throughout the Caribbean: Cayman Islands, Hispaniola, Puerto Rico, Virgin Islands (UK/USA) and numerous Bahamian islands (Bock et al. 2018). In fact, all Greater and Lesser Caribbean islands have suitable habitat for NNGI to persist (Falcón et al. 2012), and could lead to inter-genus hybridization (Moss et al. 2017). Before 2018, Dominica was the last remaining large island native to Lesser Antillean Iguanas (excluding islets) where NNGIs were absent (van den Burg et al. 2018a).

Introductions of NNGIs to the Caribbean Lesser Antilles are the main cause of decline, through displacement and hybridization, for the regional endemic Lesser Antillean Iguana (Knapp et al. 2014; van den Burg et al. 2018a, b; Vuillaume et al. 2015). These displacement and hybridization processes continue at an alarming rate across the region, resulting in a recently revised threat status of Critically Endangered according to the International Union for Conservation of Nature (IUCN) Red List criteria (van den Burg et al. 2018a).

To our knowledge, invasions by NNGIs on islands in the Lesser Antilles have never been managed successfully, resulting in severe consequences to native populations of Lesser Antillean Iguanas including introgression and genetic extirpations of several populations. Both *Iguana* species reach maturity at 2–3 years (Bock et al. 2018; van den Burg et al. 2018a), and SVL $\geq$ 25 cm (Knapp et al. 2016; Pratt et al. 1994). However, Lesser Antillean Iguanas have a lower growth rate compared to *I. iguana*, which can reach snout-vent length (SVL) of over 20 cm within 420 days (Knapp and Perez-Heydrich 2012; Philips et al. 1993; van Devender 1982). In addition, NNGIs attain larger body sizes than Lesser Antillean Iguanas (Bock et al. 2018) and both NNGIs and *Iguana* hybrids produce larger clutches of eggs (mean = $\sim$35 eggs [range 9–71], Bock et al. 2018; van Wagensveld and van den Burg 2018) compared to Lesser Antillean Iguanas (mean = 12.5 eggs [range 4–26], Knapp et al. 2016).

These ecological advantages have caused rapid replacement of native Lesser Antillean Iguana populations. To date, the wider impacts of these replacements on local ecosystems have not been assessed, though NNGIs have negative impacts on local agriculture and infrastructure as well as on other native species. Namely, NNGIs consume native vegetation (Carlo and García-Quijano 2008), are considered strike hazards on airport runways (Engeman et al. 2005), and can cause coastal erosion and damage to infrastructure (López-Torres et al. 2012). In addition, NNGIs are associated with the presence of pet-trade bacterial skin infections and thus the presumed contagion for several native reptiles on St. Barthelemy including the Lesser Antillean Iguana (Hellebuyck et al. 2017).

Cuban Treefrog (Osteopilus septentrionalis)

The Cuban Treefrog is native to the Cayman Islands, Cuba, and The Bahamas but humans have played a major role in the dispersal of these treefrogs outside their native range. After becoming established in Florida, Cuban Treefrogs are now shipped across the Western Hemisphere facilitated by horticultural and building material shipments (Somma 2017), and are considered an IAS throughout a large part of the Caribbean region (Hedges et al. 2010; Heinicke et al. 2011). Importantly, under climate change conditions the potential distribution and the invasive spread of this species is projected to increase (Rödder and Weinsheimer 2010).

Cuban Treefrogs are opportunistic generalists that feed on invertebrates and to a lesser extent vertebrate native prey species, including indigenous frogs (Glorioso et al. 2012; Owen 2005; Wyatt and Forys 2004). They also compete with indigenous amphibian larvae and have a negative impact on their growth, reproduction and development (Rice et al. 2011; Smith 2005). Furthermore, Dominica is home to the last known wild breeding population of the Mountain Chicken Frog (*Leptodactylus fallax)*, one endemic and endangered treefrog (*Eleutherodactylus amplinympha*), and two regionally endemic treefrogs (*E. johnstonei* and *E. martinicensis*). The island is also home to additional potential prey items including an endemic anole (*Anolis oculatus*) and two species of regionally endemic dwarf geckos (*Sphaerodactylus fantasticus* and *S. vincenti*) (Malhotra et al. 2007). It is expected that Cuban Treefrogs will prey on and compete with Dominica's native wildlife, and further spread the chytrid fungal disease, which is partly responsible for the Critically Endangered status of the Mountain Chicken Frog (IUCN SSC Amphibian Specialist Group 2017).

Venezuelan Snouted Treefrog (Scinax x-signatus)

The Venezuela Snouted Treefrog is a widespread South American amphibian that inhabits non-forested habitats (Rodríguez et al. 2015). Currently, this species has a small reported invasive range, occurring only in the French West Indies (FWI): Guadeloupe, Martinique, Marie-Galante and La Désirade (Powell et al. 2011) and is thought to threaten indigenous frogs through competition (Global Invasive Species

database 2019). The first invasion to the FWI likely occurred around 2000 with subsequent spread among these islands, however its origin remains unknown.

Surveys

In April 2018, JLKB opportunistically observed and recorded wild non-native iguanas for the first time on Dominica (see "Results" section), which led to systematic surveys of targeted IAS across Dominica. From 4 January to 15 March 2019, we conducted systematic diurnal and nocturnal (using headlamps of > 800 lumens model type Ledlenser H14R.2) surveys for non-native iguanas at sites where NNGIs were observed previously (i.e., adjacent to shipping ports), and in areas where local residents suggested invasive iguanas might occur. These locations were primarily backyards of residents or vegetated ravines and hilltops, mostly in the northern natural areas and neighborhoods of Roseau, directly adjacent to the port. All sites were visited a minimum of three times. Our team of 2–5 people (mean = 2.8) performed a total of 24 surveys (mean = 2.4 surveys per week) with an average 4.4 h per survey (total person hours = 314). During these surveys we captured iguanas by hand or noose and recorded SVL (Fig. 1; Table 1). We also collected a blood or tissue sample for future molecular analyses. Hybrids and NNGI individuals were dispatched humanly by the Chief Veterinarian for the Dominican government. Further, we used morphological characteristics, identified by Breuil (2013), to assess and predict the degree of hybridization or pure iguanas (*I. delicatissima*, *I. iguana*, hybrid). We used presence/absence of tail stripes, head shape and presence/absence of occipital crest scales, presence/absence of nuchal tubercles, number and shape of gular spines, presence/absence of a subtympanic plate, and state of sublabial scales adjacent to the subtympanic plate.

For the nocturnally active Cuban Treefrog and Venezuela Snouted Treefrog, we conducted nocturnal surveys at locations where specimens were reported opportunistically. From July 2018 to March 2019, we surveyed the Longhouse Port and Port of Dubuc locations (Fig. 1). Our team of 3–14 people (mean = 5) performed 51 surveys for an average of 3 h per night (total person hours = 765). Specific sites were near or close to port boundaries and consisted primarily of overgrown vacant lots with dirt substrate

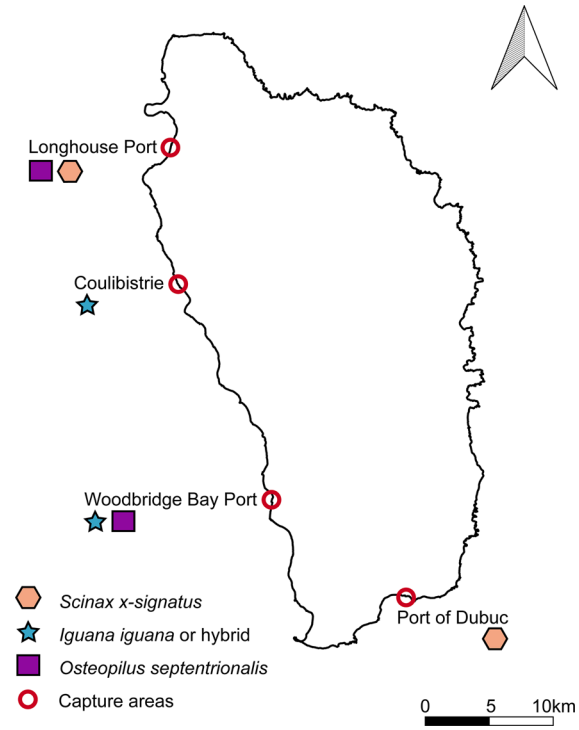

Fig. 1 Localities of invasive species found during 2018–2019 on the Commonwealth of Dominica

punctuated by water-filled cavities. In addition, we also investigated port areas themselves. We captured and measured frogs to the nearest mm and estimated the number of tadpoles observed in flooded pools. Frogs were preserved for future molecular and dietary analyses.

Results

Common Green Iguana (*Iguana iguana*)

In 2018, four NNGIs were recorded opportunistically (from 4 April to 27 December) either as road kills at Coulibistrie (n = 1) and Woodbridge Bay Port (n = 2) (Fig. 1) or as one confirmed sighting < 100 m from the Woodbridge Bay Port. During subsequent surveys, we captured an additional 118 hybrid and pure Common Green Iguanas within a 22-ha area located adjacent to, and across the coastal road from, the Woodbridge Bay Port in Roseau. Iguanas ranged in SVL from 10.1 to 40.2 cm (median = 19.9 cm with interquartile range [25–75%] of 13.9–24.1 cm).

Table 1 Invasive species identified on Commonwealth of Dominica during 2018–2019 including number of individuals, morphometrics, and location

Species	Individuals	SVL range (cm)	Area
Iguana iguana	9	12.1–31.4	Woodbridge Bay Port
Iguana iguana × *I. delicatissima*	1	34.1	Coulibistrie
Iguana iguana × *I. delicatissima*	112	10.1–40.2	Woodbridge Bay Port
Osteopilus septentrionalis	> 946	1.2–8.7	Longhouse Port
Osteopilus septentrionalis	2	–	Woodbridge Bay Port
Scinax x-signatus	1	–	Longhouse Port
Scinax x-signatus	2	3.4	Port of Dubuc

Except for two iguanas, all individuals were captured during nocturnal surveys because of the relative ease of spotting them using headlamps. We captured from 1 to 16 (mean = 5) iguanas each survey. Based on morphological characteristics of the 122 NNGIs in this study, we identified 113 iguanas as hybrids and 9 as pure Common Green Iguanas. Finally, during the 2018 opportunistic recording and the 2019 systematic surveys, we documented 11 adult females (> 25 cm SVL) of which seven were gravid with clutch sizes ranging from 18 to 37 eggs (mean = 29.4).

Cuban Treefrog (*Osteopilus septentrionalis*)

On 11 and 19 June 2018, we collected two live and two dead, adult Cuban Treefrogs on the property of the Longhouse Port in Portsmouth and in a shipping container at the Woodbridge Bay Port, respectively (Fig. 1; Table 1). The container containing the two dead Cuban Treefrogs came from St. Thomas, which is inhabited by these invasive frogs (Powell et al. 2011), but we are not aware if the container made a stopover in another country. During 51 surveys at the Longhouse Port and in adjacent habitats, from July 2018 to March 2019, we recorded and captured > 944 adult individuals (non-tadpoles) and > 10,000 tadpoles. Frogs were found in vegetated and degraded habitats throughout a 5-ha sized area. Frog SVL ranged from 1.2 to 8.7 cm (median = 4.0 cm with interquartile range [25–75%] of 3.0–5.0 cm).

Venezuelan Snouted Treefrog (*Scinax x-signatus*)

We recorded Venezuelan Snouted Treefrogs at the Port of Dubuc and the Longhouse Port on 23 October and 11 December 2018, respectively (Fig. 1). At the Port of Dubuc, we video recorded and captured one calling adult with a SVL of 3.4 cm. An additional adult was caught by fishermen, however, morphometric data were not collected. In addition, at the Longhouse Port we captured a single adult individual (sex and size not recorded). Since these initial recordings, we have not observed additional individuals nor heard calls during subsequent surveys at these localities.

Discussion

Herein we document the incursion and establishment of two invasive alien vertebrate species to the Commonwealth of Dominica, and an additional incursion of a third species, in the aftermath of Hurricane Maria. Common Green Iguanas or their hybrids have never been recorded in the wild on Dominica prior to the hurricane. The observations 7 months after the hurricane, and (with one exception) within or in close proximity to ports where relief containers were offloaded, suggest that NNGIs and hybrids were commensals on ships or within relief containers, and did not arrive following a storm-mediated event on floating debris. Most containers, regardless of their origin, went through inter-island transport from surrounding islands where these IAS are known to occur. In this study, we recorded NNGIs up to 40.2 cm SVL, along with seven female NNGIs (> 25 cm SVL) that were gravid, indicating that other NNGIs could have oviposited on the island. In total, 11 female NNGIs had body sizes associated with sexual maturity (> 25 cm; Pratt et al. 1994). Indeed, we also captured small (10.1 cm SVL) iguanas during surveys, and given that mean hatchling SVL for Common Green Iguanas is 7.6 cm (Knapp and Abarca 2009), suggests that these iguanas emerged from nests the previous summer. Though we cannot rule out that these small iguanas also arrived as commensals.

Prior to Hurricane Maria, Cuban Treefrogs had been observed once in 2016 at a housing development in Bellevue on the south end of Dominica where they were transported in shipping containers of building materials. In total eight frogs were removed and none have since been observed at the site or elsewhere until after Hurricane Maria struck and relief supplies began to arrive to Dominica. Incursion facilitated via relief containers is furthermore supported because our observations are limited to two ports, and sightings of reproductive activity and tadpole presence only started after Hurricane Maria made landfall and relief efforts were underway.

Prior to Hurricane Maria, 10 vertebrate IAS were present on Dominica (Global Invasive Species Database 2019). The invasions reported here (not including the sighting of Venezuelan Snouted Treefrogs) therefore represent a 20% increase in established vertebrate IAS since September 2017 (Table 2). We recorded IAS from four sites across Dominica. The number of recordings and distance between sites suggests at least two incursions for each IAS (Cuban and Venezuelan Snouted Treefrogs, and Common Green Iguanas). We cannot rule out that the single adult Common Green Iguana at the Coulibistrie location rafted—similar to the NNGI overwater dispersal to Anguilla during the 1995 hurricane season (Censky et al. 1998)—to that site from an adjacent island (e.g. Martinique) as a consequence of Hurricane Maria. However, no other NNGIs have been reported from the area and thus a more realistic postulation is that the iguana was transported from the Woodbridge Bay Port via truck on the well-travelled Caribbean coastal road.

Table 2 Invasive vertebrate species established on Commonwealth of Dominica

Species	Established before September 2017
Anolis cristatellus	Yes
Canus lupus familiaris	Yes
Columba livia	Yes
Hemidactylus mabouia	Yes
Felis catus	Yes
Mus musculus	Yes
Rattus norvegicus	Yes
Rattus rattus	Yes
Streptopelia decaocto	Yes
Sus scrofa	Yes
Iguana iguana	No
Osteopilus septentrionalis	No

Preventing future incursions of IAS onto Dominica is more challenging without knowledge of source populations and their pathways. With exception of the two dead Cuban Treefrogs discovered in a container at Woodbridge Bay Port on 19 June 2018 from St. Thomas, our ability to pinpoint the pathway of introduction is limited given the understandably logistical and biosecurity challenges in the wake of Hurricane Maria. As most shipments were transported from CARICOM States, the French West Indies, and the United States, these countries are the likely source of the IAS incursions on Dominica. However, the most realistic sources for NNGI and Venezuelan Snouted Treefrogs are the French West Indies; (1) given their proximity to Dominica, (2) the presence of these IAS on those islands (Global Invasive Species Database 2019), (3) and the high percentage (92.6%) of *I. delicatissima–I. iguana* hybrids in our 2019 surveys, which are widespread in the FWI.

Removing established, invasive Common Green Iguana populations has proven expensive and logistically challenging. Indeed, efforts to remove NNGIs on Grand Cayman have included large-scale and expensive culling operations resulting in over 300,000 NNGI being culled over a 6-week period in 2018–2019. Yet, more than 1 million remain. The current NNGI population on Dominica appears limited to the northern part of Roseau, seemingly still restricted within the boundaries of residential areas. The difficulty of containing this outbreak on Dominica is presumably high given the terrain, tree height, and accessibility challenges. If mitigation strategies are not implemented immediately, it is most likely that the genetically pure Lesser Antillean Iguanas inhabiting Dominica, the most important stronghold for the species (Knapp et al. 2014; van den Burg et al. 2018a), will eventually be replaced by NNGIs and *Iguana* hybrids.

We continue to survey sites with known invasive frogs or iguanas, as well as other ports of entry to prevent further expansions and new establishments. Genetic samples will be analyzed and compared to published data to understand source populations and give insight into possible pathways of IAS on Dominica (Heinicke et al. 2011; Miller et al. 2019;

Rodríguez et al. 2015; Stephen et al. 2013; Valette et al. 2013). Iguanas with questionable species status need to be kept in enclosures while awaiting genetic testing to prevent unnecessary culling of pure, critically endangered Lesser Antillean Iguanas. Further, genetic data will allow us to estimate effective population size and the number of initial introduced animals. Additionally, stomach contents of Cuban Treefrogs will be analyzed to predict its potential impact on Dominican biodiversity. Lastly, we will continue to distribute booklets addressing the presence of NNGIs on Dominica and urge the public to inform relevant authorities when they observe NNGIs. To help identify and prevent future invasions, we intend to raise public awareness through an outreach campaign, and hold an IAS identification workshop for port biosecurity agents.

Biosecurity is essential to prevent biological invasions, while mitigation protocols are critical for removing IAS at the early stages of invasion (Russell et al. 2008; Simberloff et al. 2005; Vilà et al. 2011). Although historically Dominica has been spared from numerous IAS incursions relative to other Caribbean islands (Global Invasive Species Database 2019), our work suggests that one extraordinary storm event, and the post-storm relief efforts, resulted in a 20% increase in IAS on Dominica. Dominica was overwhelmed by the humanitarian crisis and lacked the infrastructure to cope with the volume of containers coming from other countries. In fact, the influx of containers and supplies was so large that the capacity of the Woodbridge Bay Port (1.4 ha) was reached soon after humanitarian efforts began and scores of containers had to be stored outside port boundaries (totaling 1.06 ha, sometimes stacked to four containers high), making detection and containment of IAS even more challenging (Jeanelle L.K. Brisbane, pers. observations, 2018). Thus during this understandably challenging period, biosecurity was non-existent (port officer L. Lestrade, pers. comm.). This work also suggests that aiding countries and/or organizations did not implement biosecurity screenings during hurricane relief efforts, presumably and understandably to get aid supplies to Dominica as soon as possible. We acknowledge that biosecurity measures are time consuming and can increase cost. However, IAS incursions to countries recovering from disaster, facilitated by poor biosecurity measures from exporting countries, incurs an additional ecological cost to the already serious humanitarian and infrastructure challenges. In the aftermath of any hurricane it should be assumed that the capacity to perform biosecurity screenings in hurricane-affected regions or countries will be reduced or non-existent given the need to prioritize rapid humanitarian assistance, and/or the destruction of existing quarantine infrastructure. Therefore, responsibility should be shared, especially among countries in communal regions, to ensure that meaningful and effective screening procedures are implemented not only at ports of entry but also in exporting countries. As climate change is predicted to increase hurricane intensity and frequency in the Caribbean region (Mann and Emanuel 2006; Webster et al. 2005), the implementation of these and other biosecurity measures are critically important to reduce the chances of further intra-regional, and intra-island, spread of IAS.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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