Non-Native Small Terrestrial Vertebrates in the Galapagos

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Introduction

Movement of propagules of a species from its current range to a new area—i.e., extra-range dispersal—is a natural process that has been fundamental to the development of biogeographic patterns throughout Earth's history (Wilson et al. 2009). Individuals moving to new areas usually confront a different set of biotic and abiotic variables, and most dispersed individuals do not survive. However, if they are capable of surviving and adapting to the new conditions, they may establish self-sufficient populations, colonise the new areas, and even spread into nearby locations (Mack et al. 2000). In doing so, they will produce ecological transformations in the new areas, which may lead to changes in other species' populations and communities, speciation and the formation of new ecosystems (Wilson et al. 2009).

Human extra-range dispersals since the Pleistocene have produced important distribution changes across species of all taxonomic groups. Along our prehistory and history, we have aided other species' extra-range dispersals either by deliberate translocations or by ecological facilitation due to habitat changes or modification of ecological relationships (Boivin et al. 2016). Over the last few centuries, human globalisation has led to the integration of most areas of the planet. Due to transportation advancements, humans and our shipments travel faster and further than ever before. Unintentionally or deliberately, thousands of species of flora, fauna and microorganisms have been translocated to places they would never have reached on their own and beyond the biogeographic barriers that typically prevented their spread in such a timeframe (Ricciardi 2007). However, most translocated species are already adapted to anthropogenic niches (especially the ones that are unintentionally introduced), and since their new arrival areas are usually also under anthropogenic impact, their adaptation process and possibility of survival are increased.

Non-native species contribute to Earth's biota homogenization, but ongoing scientific debates on the processes, effects, importance and management of non-native species are intense (Davis 2003; Brown and Sax 2004, 2005; Cassey et al. 2005; Dukes and Mooney 2004; Davis et al. 2011; Chew and Carroll 2011; Ricciardi et al. 2013; Simberloff et al. 2013; Chew 2015;

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Kuebbing and Simberloff 2015; Pereyra 2016; Sol 2016). Non-native species may modify biological communities and ecosystem functions by becoming, for example, predators, competitors, preys, seed dispersers, parasites, disease vectors, or ecosystem engineers (Daszak et al. 2000; Crooks 2002; O'Dowd et al. 2003; Doody et al. 2009; Capps and Flecker 2013; Ricciardi et al. 2013; Simberloff et al. 2013). Non-native species may have economic, social, cultural and health impacts on human populations (Vitousek et al. 1997; Pejchar and Mooney 2009). Non-native species that are successful and spread in their new areas become invasive, and have been described as major anthropogenic drivers of current changes in biodiversity (Vitousek et al. 1997; Chapin III et al. 2000; Mace et al. 2005; Clavero and García-Berthou 2005; Bellard et al. 2016; Doherty et al. 2016). Yet, evidence, scientific perspectives and practical implications for this assertion are still under examination (Gurevitch and Padilla 2004a,b; Ricciardi 2004; Didham et al. 2005; MacDougall and Turkington 2005; Young and Larson 2011; Russell and Blackburn 2017).

In spatially restricted ecosystems, such as island and wetlands, the effects of invasive non-native species on native biodiversity can be severe and lead to extensive transformation of native ecosystems and even the extinction of endemic species (Davis 2003; O'Dowd et al. 2003; Blackburn et al. 2004; Mace et al. 2005; Simberloff et al. 2013). The Galapagos Islands are a region of particular interest and relevance to the issue of species introduction and invasiveness. In the most recent comprehensive review on the Galapagos non-native vertebrates, Phillips et al. (2012a) pointed out that vertebrate introductions in Galapagos are shifting away from intentionally introduced species, such as domestic mammals, towards hitchhiking species, such as reptiles (Phillips et al. 2012a). Furthermore, the authors remarked that snakes and lizards—i.e., squamate reptiles—could pose the greatest threat the Galapagos' biodiversity in the future. Like an unfortunate prediction, while Phillips and collaborators were writing their article, the Common House Gecko *Hemidactylus frenatus*, a lizard profiled as highly invasive, had already arrived in Galapagos (Torres-Carvajal and Tapia 2011). Despite the fact that only five years have passed since Phillips et al. (2012a), the panorama of non-native terrestrial vertebrates in Galapagos has changed in important ways, in particular for non-mammals. Although Phillips et al. (2012a) and previous studies have dealt with the impacts and management of non-native species in Galapagos, most studies have focused on domestic species gone feral. Very little information is available on wild non-native species that have been unintentionally introduced. Thus, in this publication I analyse the current status of all non-native amphibians, reptiles and birds that have been reported in the Galapagos Islands, provide new evidence about their relationship with native and non-native species, comment on their invasiveness and impact potential, and propose that it is important to rethink about how we understand, manage and prevent introductions of non-native species. The new wave of introduced species in Galapagos is formed by small hitchhiker species that are easily overlooked, may travel in high numbers, and are highly linked to human-made environments.

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The Galapagos Islands: An overview

The volcanic marine islands of the Galapagos archipelago are separated from the nearest mainland—the coast of Ecuador—by ca. 930 km. Nineteen main islands (> 1 km^2) and over 100 islets and rocks constitute the archipelago, totalling ca. 7850 km^2 of land, spread out over ca. 430 km (straight line between the outermost islands: Darwin and Española). The largest islands are Isabela (4588 km^2), Santa Cruz (986 km^2), Fernandina (642 km^2), Santiago (585 km^2), San Cristobal (558 km^2), Floreana (173 km^2) and Marchena (130 km^2) (Snell et al. 1996).

The Galapagos are among the few Pacific islands that were not settled by aboriginal humans (Anderson et al. 2016). They were discovered by Fray Tomas de Berlanga in 1535. While pirate and whaling ships frequently visited the archipelago since the 16th century, the first settlement was only established in 1832. Nowadays, Santa Cruz, San Cristobal, Isabela and Floreana have human populations established on the lowlands and highlands. The main cities in each island are: Puerto Ayora (Santa Cruz), Puerto Baquerizo Moreno (San Cristobal), Puerto Villamil (Isabela) and Puerto Velasco Ibarra (Floreana). There are airports in Baltra, San Cristobal and Isabela islands, with connections to Guayaquil and Tababela (Quito) airports in mainland Ecuador. All populated islands have maritime ports for passengers and freight, with connections to several international and national ports, including the Ecuadorian ports of Guayaquil, Manta and Salinas (Cruz Martínez et al. 2007).

The climate of Galapagos largely depends on the oceanic currents and winds, resulting in vegetation distribution being determined by orogenic rainfall (Jackson 1993; Wiggins and Porter 1971). On the lowlands, all islands and islets are arid and warm. A narrow belt along coastal areas, called Littoral Zone[1], is dominated by salt-tolerant shrubs and small trees. Xerophytic low scrub, arborescent and shrubby cacti, and thorn woodland and deciduous forest are the main vegetation on lowlands, i.e., Dry Zone[1]. A Transition Zone[1], with taller trees, denser canopy and more mesic conditions than the Dry Zone, appears as elevation rises (plants here are a mix from lower and higher zones). Moist conditions exist in the higher islands above 300–600 m, where three vegetation zones have been recognised: Humid Zone[1], with incremented humidity and denser vegetation dominated by evergreen species, in particular the endemic Giant Daisy Tree genus *Scalesia*; Very Humid Zone, with very dense vegetation dominated by the endemic Galapagos Miconia *Miconia robinsoniana*; and Pampa Zone, treeless and dominated by sedges and ferns above regional treeline. An Upper Dry Zone[1]—a climatic inversion zone with drier conditions—exists on the Cerro Azul and Wolf volcanoes, which reach beyond 1000 m above the main cloud layer. This zone is covered by scrub vegetation dominated by *Opuntia* cacti or *Scalesia*. On the leeward side of islands, the Littoral, Dry and Transition zones rise higher and the moister zones may be absent (Wiggins and Porter 1971). The moist zones (Humid, Very Humid, and Pampa) are only present on the largest islands (i.e., Santa Cruz, San Cristobal, Pinta, Santiago, Floreana, Isabela, Fernandina). In addition to these natural vegetation zones, humans

[1] The ecological classification of vegetation is based on the proposal by Wiggins and Porter (1971).

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have modified large sections of the Dry, Transition, Humid and Very Humid zones on the four inhabited islands, transforming them into agro-urban areas, where a large amount of non-native plant species dominate (Wiggins and Porter 1971; Guézou et al. 2010). The Pampa zone has been enlarged by human activities and grazing by non-native mammals.

World-famous for their biodiversity and role in the formulation of the theory of evolution by natural selection, the Galapagos Islands are home to a vast array of endemic species of flora and fauna. Galapagos biodiversity evolved in isolation from its continental counterparts. Moreover, its uniqueness is not just due to differences between insular and continental species, but also due to a large level of inter-insular endemism. There are many taxa restricted to just one or few islands (Parent and Crespi 2006; Sequeira et al. 2008; Benavides et al. 2009; Hoeck et al. 2010; Poulakakis et al. 2012; Torres-Carvajal et al. 2014; MacLeod et al. 2015; Carmi et al. 2016). The Galapagos archipelago is home to no less than 211 terrestrial vertebrates, including: 6 endemic species of snakes of the genus *Pseudalsophis*, 24 endemic lizards (genus *Phyllodactylus*, *Amblyrhynchus*, *Conolophus*, *Microlophus*), 12 endemic giant tortoises of the genus *Chelonoidis*, 160 species of birds (of which 46 taxa are endemic), and 9 species of mammals (of which 7 taxa are endemic).

Human population in Galapagos has increased significantly over the last decades, and transportation links carrying local travellers, tourists and supplies have facilitated the arrival of non-native species (Mauchamp 1997; Causton et al. 2006; Tye 2006; González et al. 2008; Phillips et al. 2012a). Invasive non-native species have been identified as the principal threat to biodiversity in the Galapagos terrestrial ecosystems (Causton et al. 2006). For example, feral populations of Dogs *Canis familiaris*, Cats *Felis catus*, Pigs *Sus scrofa* and Black Rats *Rattus rattus* have been reported to predate upon several endemic species, causing serious declines on the populations of Galapagos Tortoises *Chelonoidis* spp., Galapagos Land Iguanas *Conolophus subcristatus*, Marine Iguanas *Amblyrhynchus cristatus* and Galapagos Penguins *Spheniscus mendiculus*, among others (Konecny 1987; Phillips et al. 2012a). Grazing and trampling by feral Goat *Capra hircus* have depleted the populations of several native and endemic plants, including the critically endangered Santiago Scalesia *Scalesia atractyloides* and Floreana Flax *Linum cratericola*, which are now at the verge of extinction (Schofield 1989; Aldaz et al. 1997; Simbana and Tye 2009). Feral Cattle *Bos taurus* aided the spread of the invasive non-native Common Guava *Psidium guajava* and other non-native plants by habitat engineering and seed dispersion (Phillips et al. 2012a). The parasitic fly *Philornis downsi* is causing significant excess mortality in the endemic and threatened Darwin's Medium Tree Finch *Camarhynchus puper* (O'Connor et al. 2010). Cottony-Cushion Scale *Icerya purchasi* has become a pest causing population declines in the endemic Thin-leafed Darwin's Shrub *Darwiniothamnus tenuifolius* (Calderón-Álvarez et al. 2012). Ambitious programs to control and eradicate non-native species have been established in the archipelago (e.g., Barnett 1986; Campbell et al. 2004; Cruz et al. 2005; Carrión et al. 2007).

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However, ecological interactions are of a complex nature and non-native species may in some cases contribute to maintaining ecosystem functions in ecosystems experiencing environmental change (Buckley and Catford 2016). For example, Black Rats have become a seed disperser of the endemic *Miconia robinsoniana* in some agricultural areas of San Cristobal Island (Riofrío-Lazo and Páez-Rosas 2015). Black Rats have also become the most important prey for the Galapagos Hawk *Buteo galapagoensis* since the eradication of feral Goats on Santiago Island (Jaramillo et al. 2016). Non-native species may also help managing invasive species, acting as biological controls. The Vedalia Beetle *Rodolia cardinalis* was deliberately introduced in Galapagos to control the spread of *Icerya purchasi* (Calderón-Álvarez et al. 2012).

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Definitions

The dichotomy of native/non-native species is a predominant concept in ecology, biogeography and conservation biology (Mace et al. 2005; Lomolino et al. 2010; Simberloff et al. 2013). It has been widely adopted in analysis of the conservation of Ecuadorian biodiversity, and particularly in relation to Galapagos (Josse 2001; Causton et al. 2006). However, a dichotomous approach is evidently simplistic and even artificial in any complex and dynamic system. The cornerstone term "native species" is part of an ongoing scientific and philosophical debate about its conceptual and operational definitions as well as its relevance and applicability in ecological, conservation, management, sociocultural and economic scopes (Chew and Hamilton 2011, Clavero 2014, Van Der Wal et al. 2015). A dichotomous approach is hard to make fully operational, especially in regions where it is difficult to assess the status of an archaeophyte/archaeozoan versus a native taxon, or where the distinction between native and non-native taxa is not absolute (Preston et al. 2004). However, these issues are greatly controlled in Galapagos due to the isolation of the archipelago and the specific date of human arrival. Although recognising issues associated with a dichotomous approach, I—for the sake of operational straightforwardness and due to the particular nature of Galapagos geography and history—use the following working definitions (modified from Pyšek et al. 2009):

Native taxa: Those that are originated in a given area, or that arrived from an area in which they are native by their own means. Their successful arrival is due to their adaptation for dispersal and survival in the physiological and ecological conditions across the dispersal routes, which are not acting as strict dispersal barriers. Complete or partial synonyms include terms like indigenous or autochthonous taxa.

Non-native taxa: Those that have arrived from an area in which they are non-native, or that arrived from their native range by extrinsic dispersal mechanisms (i.e., outside of their own natural dispersal potential). These extrinsic mechanisms provide specific conditions that allow these taxa to disperse across environments that otherwise would be severe natural barriers in the same timeframe. Complete or partial synonyms include terms like alien, exotic, non-indigenous or allochthonous taxa.

To establish working definitions on the basis of ecological and biogeographic criteria only, human intervention was intentionally left out. While human extra-range dispersals do facilitate the arrival of non-native taxa via direct or indirect extrinsic mechanisms, natural colonisations and human-mediated introductions and establishments of non-native species are nevertheless similar ecological processes (Buckley and Catford 2016; Hoffmann and Courchamp 2016). Several authors have argued that geographical origin of species should not be used as the only criteria guiding management/control decisions (Buckley and Catford 2016; Hoffmann and Courchamp 2016). However, a distinction between natural colonisations and human-mediated introductions is at least partially necessary when management and control issues are involved.

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For example, if a species reached a new area by its own means and without the intervention extrinsic dispersal mechanisms (incl. without human intervention), it would most probably be able to do so repeatedly as it is evidenced that the species has the capability to disperse across natural barriers that separated its geographical origin and new areas. Any proposed regulations to control its population would be insufficient and inefficient as new arrivals would most certainly keep occurring. On the other hand, a non-native species that solely depends on human-mediated extrinsic dispersal mechanisms, could be controlled by regulating the aforesaid mechanisms.

Therefore, all species that were established in the archipelago before 1535 are considered native. Species that have apparently reached the archipelago through their own means after 1535 and that have established populations because of their own successful oceanic dispersal capacities (and probably with several dispersal events) are also considered native. Due to the long distance between Galapagos and mainland (or even other islands), all non-native species in the Galapagos Islands seem to have arrived due to intentional or unintentional mediation of humans.

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Non-native amphibians, reptiles and birds

I report herein a total of 25 non-native amphibians, reptiles and bird species in the Galapagos Archipelago. The changes, when compared to Jiménez-Uzcátegui et al. (2007) and Phillips et al. (2012a), are in part explainable by a better understanding of some species' status (see species accounts below for details), but also due to the arrival of new non-native vertebrates (I include two species not reported in previous reviews). These non-native species are equivalent to 12% of all Galapagos native amphibians, reptiles and birds. Santa Cruz and San Cristobal are the islands with the largest amount of reported non-native amphibians, reptiles and bird species (18 spp. each). Twelve species are reported in Isabela Island, three in Baltra Island and two species in Marchena and Floreana. The islands of Genovesa, Pinta, Pinzon, and Santiago each have only one reported species (Table 1).

In any environment, there is an introduction-invasion continuum between the arrival of a non-native species, its establishment and its shift into invasive (Mack et al. 2000; Blackburn et al. 2011; Pereyra 2016). Non-native species introduced to Galapagos are heterogeneous in terms of their establishment, spread, dominance and impact. Only a fraction of the non-native species that arrives becomes established, and an even smaller portion is able to have spreading populations—i.e., become invasive. For example, out of 754 non-native vascular plants recorded by Guézou et al. (2010) in the inhabited areas of Galapagos, 35% have established populations; and Tye et al. (2002) classified 5% of those species as invasive. As for insects, 463 non-native species were reported by Causton et al. (2006) in Galapagos, with at least 73% of them having established populations and 13% species classified as invasive.

In order to provide a straightforward evaluation of the degree of establishment of non-native amphibians, reptiles and birds in Galapagos—independent of their conservation effects—I adopt the categories proposed by McGeoch and Latombe (2016), with some modifications (Table 3). This typology is based on three main aspects: degree of expansion, population size and time since arrival (McGeoch and Latombe 2016). Since all non-native species were introduced to Galapagos within the last two centuries, all could be classified herein as recent. However, I differentiate between historic (the last centuries) and recent (the last decades) translocations. Also, I take into account the fact that introductions have not been synchronised, and that some non-native populations are the result of more than one introduction event.

Information about establishment, spread, dominance and impacts of non-native amphibians, reptiles and birds in Galapagos biodiversity is still incomplete. Eleven non-native amphibians, reptiles and bird species reported in Galapagos did not become established (Table 1). Six species are established but only as domestic stock. *Columba livia*, a non-native species that was introduced as domestic and became established, was eradicated. *Gallus gallus* is the only species currently present in Galapagos with domestic and feral (or semi-feral) populations. Some feral chickens may have self-sufficient populations, but evidence is unclear. *Hemidactylus frenatus* is

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newly established, and self-sufficient populations are apparently small, but this species has a high potential not just to become more broadly established but to spread successfully, and therefore become invasive. Monitoring is urgently needed to understand the distribution, populations and impacts of *H. frenatus*. There is evidence that one non-native amphibian, three non-native reptiles and one non-native bird are established in Galapagos, having self-sufficient populations (Table 1). However, they do not have the same level of establishment. *Gonatodes caudiscutatus* is classified as constrained, by having large populations but only on a very limited geographic range, apparently unable to establish new populations despite being in Galapagos for ca. 200 years. *Scinax quinquefasciatus* is considered as incipient, by having established large populations but only on a limited geographic range, yet it was introduced recently (ca. 40 years). *Phyllodactylus reissii* is dispersing, with a large population in Santa Cruz established ca. 40 years ago, and a probably newly established population in Isabela. Finally, *Lepidodactylus lugubris* and *Crotophaga ani* are classified as successful by having large populations established on many islands. Since *L. lugubris*, *P. reissii* and *C. ani* have self-sufficient and spreading populations, they are further classified as invasive species.

Non-native amphibians in Galapagos

Amphibians have never been able to establish by their own means in Galapagos. Absence of native amphibians in Galapagos is not surprising, as most true oceanic islands are devoid of native amphibians (Zug 2013). Generally, amphibians are poor dispersers across oceanic barriers due to their high sensitivity to osmotic stress caused by salt water at all ontogenic levels (Balinski 1981; Duellman and Trueb 1986; Bernabò et al. 2013). However, a number of frog species have physiological adaptations to tolerate salinity (Balinksi 1981; Beebee 1985; Gomez-Mestre and Tejedo 2003) and oceans are not always strict barriers to the dispersal of amphibians (Hedges et al. 1992; Vences et al. 2003, 2004; Measey et al. 2007). The oceanic islands of Mayote, São Tomé and Principe have native frogs that seemingly reached the islands by rafting through ca. 400 km from Africa (Vences et al. 2003; Measey et al. 2007; Bell et al. 2015). The Seychelles Islands are extraordinary: despite the extreme distance of ca. 1000 km from Madagascar and ca. 1300 km from Africa, they have one endemic frog species (Maddock et al. 2014). Nevertheless, and contrary to the Galapagos Islands, all oceanic islands with native frogs generally have humid terrestrial ecosystems almost next to the coastlines, where frogs would have been able to establish. In contrast, frogs that might have rafted between mainland America and Galapagos, would have reached the arid Littoral and Dry zones, which are inhospitable to amphibians. Actually, evidence from palynological studies has revealed that the lower areas of the islands were even drier in the past glacial (Colinvaux 1972, Colinvaux and Schofield 1976).

Three non-native frogs[2] have reached the islands (Table 1):

[2] The Global Invasive Species Database (GISD 2010) erroneously reported *Eleutherodactylus coqui* at Galapagos, citing Snell and Rea (1999) as the source, yet those authors reported *Scinax quinquefasciatus*.

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- Jiménez-Uzcátegui et al. (2007) and Phillips et al. (2012a) reported a **Western Cane Toad *Rhinella horribilis*** at Galapagos (as *Bufo* sp. and *Chaunus marinus*, respectively[3]). Records at the Vertebrate Collection of the Charles Darwin Research Foundation (VCCDRS; CDF 2016) show that it was discovered in a house at Puerto Baquerizo Moreno, San Cristobal Island, on 5 February 1995. This species has a large native range from southern USA to the lowlands of western Ecuador and northwestern Peru (Frost 2016). It inhabits a large variety of ecosystems and is abundant in anthropogenic areas like pastures and gardens (Zug and Zug 1979). Although it can live in arid environments, it depends on water availability for reproduction (see Zug and Zug 1979 for information on its natural history). *Rhinella horribilis* is present in Manta, Guayaquil and Tababela (Quito), areas with cargo warehouses, maritime ports and airports with connections to Galapagos (pers. obs.). Apparently, only one population of *Rhinella horribilis* may have established completely outside of its native range (in Florida, King and Krakauer 1966; Easteal 1981)[4]. No information is available on potential or evidenced impacts by non-native *R. horribilis*. For comparison, the Eastern Cane Toad *Rhinella marina* has been extensively introduced worldwide (Easteal 1981; Lever 2003), and is one of the most studied introduced species, especially in Australia. The main evidenced ecological impact of *R. marina* is the declining of Australian native predators, due to its toxicity when ingested (Shine 2010).

- Snell (2000) reported an individual of **Striped Robber Frog *Pristimantis unistrigatus*** beside a dishwasher in a house on 17 March 2000 at Puerto Ayora, Santa Cruz Island. Phillips et al. (2012a) reported another *P. unistrigatus* from Isabela Island without providing further details. There are no specimens of *Pristimantis* at the VCCDRS. Frogs of the genus *Pristimantis* are part of the superfamily Brachycephaloidea (Frost 2016). Brachycephaloidean frogs are terrestrial breeders, laying their eggs on land, with no need of water, and eggs hatching directly into froglets, bypassing the tadpole stage. These features could provide clear advantages to establishing self-sufficient populations in islands with limited freshwater availability. Frogs of the Brachycephaloidean genus *Eleutherodactylus* have established spreading populations in Hawaiian and Caribbean islands, where they arrived as hitchhikers (Kraus et al. 1999; Kraus and Campbell 2002; Lever 2003; Olson et al. 2012). However, introduced populations of *Pristimantis* are

[3] The correct updated name of the toad that arrived to the Galapagos is *Rhinella horribilis*, assuming its origin was western Ecuador. Until recently, *R. horribilis* was a synonym of *Rhinella marina*. However, Acevedo-Rincón et al. (2016) recognised them as different species. *Rhinella marina* is now restricted to the east of the Andes. Further taxonomic changes are expected, and populations from western Ecuador could receive yet another (new) name (Vallinoto et al. 2010).

[4] The non-native populations of *Rhinella* in Florida have multiple origins, with first individuals coming from Surinam and Colombia. Toads from Surinam were probably *Rhinella marina*, while those from Colombia could be *R. horribilis* if their origin was western Colombia, or *R. marina* if they came from eastern Colombia.

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undocumented (Lever 2003, Kraus 2009), probably because most *Pristimantis* show high levels of endemism and high physiological specialisation. Nevertheless, a few species, like *P. unistrigatus*, are more widespread and have adapted to human-created habitats, showing potential to establish non-native populations if conditions for establishment are adequate. *Pristimantis unistrigatus* is native to inter-Andean highland valleys from southern Colombia to central Ecuador, where it can live in mildly arid environments with seasonal rains, and thrive in agricultural lands, gardens and other artificially watered areas (Lynch 1981). It is the most common frog in urban, suburban and rural green areas of the valley of Quito, including the surroundings of air cargo warehouses and the airport (pers. obs.).

- **Fowler's Snouted Treefrog *Scinax quinquefasciatus***[5] (Fig. 1) is the only amphibian established in the Galapagos. Snell et al. (1999) and Snell and Rea (1999) published the first reports of *S. quinquefasciatus* from Galapagos based on records from Isabela[6] and Santa Cruz islands. Although subsequent authors have commented on *S. quinquefaciatus* in Galapagos (Lever 2003; Jiménez-Uzcátegui et al. 2007; Phillips et al. 2012a; Zug 2013), many details about their introduction history remain unpublished. The VCCDRS (CDF 2016) holds several specimens of *S. quinquefasciatus* that offer valuable information to better contextualize its timeframe in the archipelago. The first specimen of *S. quinquefasciatus* (VCCDRS 2247) was collected on May 1973 at an unknown locality in Santa Cruz Island. Four additional specimens were collected in 1991–1992 at the dry lowlands of Santa Cruz Island, in urban areas of the town of Puerto Ayora. Between 1998 and 2013, one to four specimens were obtained in or around Puerto Ayora every year, except for 2011, when 10 specimens were collected. In 2001, the first *S. quinquefasciatus* (VCCDRS 1502) was collected at humid highlands in agricultural areas of Bellavista, Santa Cruz Island, with additional single treefrogs collected in 2003, 2008, 2011 and 2013. Seven treefrogs were collected in 2000 and one in 2001 in the dry lowlands of urban Puerto Baquerizo Moreno, San Cristobal Island. No further records have been reported since[7]. All six VCCDRS specimens of *S. quinquefasciatus* from Isabela Island were collected after its confirmed establishment at the lagoons near the town of Puerto Villamil on 1998. Since *S. quinquefasciatus* is insectivorous, predation of native invertebrate fauna has been identified as a potential impact on Galapagos biodiversity (Phillips et al. 2012a), but there are no studies regarding its diet or evidence about any real impact. *Scinax quinquefasciatus* is native to the Pacific lowlands and low montane

[5] This name is currently applied to different populations of *Scinax* that include at least one undescribed cryptic species (R.W. McDiarmid in litt. 2003; S. Ron pers. comm. 2013).

[6] Snell and Rea (1999) confused specimens from Isabela with "leptodactylid frogs", a common error due to the snout form and general appearance of *Scinax* frogs.

[7] Phillips et al. (2012) reported a "Tree frog 3 (*Hyla* sp.)" reported from San Cristobal in 1990. It is possible that it corresponds to early records of *Scinax quinquefasciatus*. Due to uncertainty with the identification and lack of voucher specimens, they are not included in these analyses.

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areas from southwestern Colombia to central-western Ecuador (Frost 2016). In its native distribution, *S. quinquefasciatus* occurs on a variety of habitats, as it is able to breed in small ponds in agricultural areas, herbaceous marshes and stream pools in arid zones, and wetlands with low salinity in river deltas (Duellman 1971; de la Riva et al. 1997; Cisneros-Heredia 2006a; Ortega-Andrade et al. 2010; pers. obs.). It is present in urban, suburban and green rural areas of Manta and Guayaquil, including the surroundings of air cargo warehouses and the airport (pers. obs.).

Non-native reptiles in Galapagos

Nine species of non-native reptiles have been recorded in Galapagos. All established populations are geckos—members of the squamate reptilian infra-order Gekkota. Worldwide, several species of geckos have adapted to live in anthropic or perianthropic conditions, dwelling in human-made buildings and surroundings. This close relationship has resulted in geckos being able to effectively colonise geographically distant regions by human-facilitated dispersion (Lever 2003, Gamble et al. 2008, Kraus 2009). Anthropophilic geckos are some of the most capable overseas dispersalists among non-volant, terrestrial vertebrates, having in some cases the largest distributions among reptiles and even attaining larger densities than in their natural habitats (Gamble et al. 2008; Ineich 2010). Presently, geckos have been introduced as non-native species far more frequently than any other lizard group (Lever 2003, Kraus 2009). Out of 503 introduction events involving gekkotan species analysed by Kraus (2009), about 45% resulted in successful population establishments, showing that geckos are among the most successful reptiles in establishing populations. Not all gekkotan families are involved, and Gekkonidae, Phyllodactylidae and Sphaerodactylidae are responsible for all introduction and establishment events in the world (Lever 2003; Kraus 2009). Non-native species of the three families are present in Galapagos.

- **Dwarf Gecko *Gonatodes caudiscutatus***[8] is found in small numbers at the town of Puerto Baquerizo Moreno[9], San Cristobal Island, where it is restricted to moist anthropic environments. It is abundant in the agro-urban highlands of San Cristobal, in El Progreso, where it has been able to establish also in natural areas (Garman 1892; Wood 1939; Mertens 1963; Wright 1983; Hoogmoed 1989; Lundh 1998; Olmedo and Cayot 1994; pers. obs.). During a survey in June 2009, I found three specimens of *G. caudiscutatus* in

[8] Garman (1892) described *Gonatodes collaris*, based on two specimens collected by George Baur at Wreck Bay, next to the town of Puerto Baquerizo Moreno, San Cristobal Island. Vanzolini (1965) proposed that *G. collaris* and *G. caudiscutatus* were actually synonyms, which was confirmed by Wright (1983).

[9] Several expeditions did not find *Gonatodes* in San Cristobal Island during the late 1800s and early 1900s (Cope 1889; Heller 1903; Van Denburgh 1912; Slevin 1935). Van Denburgh (1912), Slevin (1935) and Barbour and Loveridge (1929) suggested that the specimens reported by Garman (1892) were probably collected at Guayaquil, in mainland Ecuador. However, it is probable that *G. caudiscutatus* was overlooked due to its restricted distribution and low abundance in Puerto Baquerizo Moreno, and low activity during the dry season.

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gardens near Playa Man and the interpretation centre, and 10 specimens at orchards in El Progreso. The rarity of *G. caudiscutatus* in the lowlands is probably due to climate restrictions and predation by domestic and native species[10] (Wright 1983; Hoogmoed 1989; Olmedo and Cayot 1994; pers. obs.). There are reports of *G. caudiscutatus* in at least two other islands of Galapagos. Jimenez-Uzcátegui et al. (2007) reported it from Baltra, without further details. The VCCDRS (CDF 2016) has four specimens of *G. caudiscutatus* collected at Puerto Ayora, Santa Cruz Island: on 5 November 2003, 29 January 2006, and 20 July 2006. It is probable that a small population is already established at Santa Cruz Island. Impacts by *G. caudiscutatus* on Galapagos biodiversity are unknown, but have been suspected to be slight or even non-existent (Hoogmoed 1989; Olmedo and Cayot 1994; Phillips et al. 2012a). Competition or exclusion of endemic geckos is unlikely, due to body size, habitat and microhabitat differences[11]. Although *G. caudiscutatus* is insectivorous, it probably eats mainly non-native and widespread invertebrates, but there are no studies about its diet. *Gonatodes caudiscutatus* is native to the lowlands from central-western Ecuador and extreme northwestern Peru (Sturaro and Avila-Pires 2014). It is present in urban, suburban and green rural areas of Guayaquil, including the surroundings of air cargo warehouses and the airport (pers. obs.).

- **Peters' Leaf-toed Gecko *Phyllodactylus reissii*** arrived at Santa Cruz Island in the mid-1970s (Wright 1983, Hoogmoed 1989, Olmedo and Cayot 1994). Hoogmoed (1989) published a detailed study on the population in Puerto Ayora, where it was well established in the urban area (Hoogmoed 1989, Olmedo and Cayot 1994). Olmedo and Cayot (1994) reported one individual of *P. reissii* in natural areas next to Puerto Ayora (adjacent to Las Ninfas neighbourhood). On July 1997, I observed three *P. reissii* at the same area in natural vegetation. *Phyllodactylus reissii* has reached the highlands of Santa Cruz Island, at Bellavista (Phillips et al. 2012a). Torres-Carvajal and Tapia (2011) reported the first record of *P. reissii* at Puerto Villamil, Isabela Island, but the presence of an established population remains to be confirmed. During a survey in June 2009, I did not find *P. reissii* in San Cristobal Island. *Phyllodactylus reissii* inhabits dry forests and scrubland, and rural, suburban and urban areas from central western Ecuador to northwestern Peru (Dixon and Huey 1970). In Galapagos, *P. reissi* remains mostly restricted to urban, suburban and rural areas. In areas of Puerto Ayora where *P. reissi* is

[10] I observed San Cristobal Lava Lizard *Microlophus bivittatus* predating on *G. caudiscutatus* on June 2005. See account of Domestic Chicken *Gallus gallus* for details on a predation event on *G. caudiscutatus*.

[11] All endemic Galapagos geckos belong to the genus *Phyllodactylus*, are diurnal and nocturnal, and inhabit the arid lowlands. They are scansorial and arboreal, having dorsoventrally compressed digits with greatly expanded lamellae. *Gonatodes caudiscutatus* has a smaller body-size than all endemic geckos, is diurnal and mainly inhabits the humid highlands. It is terrestrial and semi-arboreal, having more restricted climbing abilities than the endemic geckos due to its cylindrical digits without expanded lamellae.

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dominant, it appears to have displaced the endemic *P. galapagensis*, and only rarely are both together (Hoogmoed 1989; Olmedo and Cayot 1994). No information about possible exclusion mechanisms or interactions has been published[12]. If *P. reissii* would expand to natural areas, it could impact endemic *Phyllodactylus* (Hoogmoed 1989; Olmedo and Cayot 1994; Phillips et al. 2012a).

- **Mourning Gecko *Lepidodactylus lugubris*** is native to Southeast Asia and islands of western Oceania (Hoogmoed and Avila-Pires 2015 and citations therein). It is a parthenogenetic species, which benefits the establishment of new populations (Kraus 2009; Phillips et al. 2012a; Hoogmoed and Avila-Pires 2015). It has become established in north-eastern Asia, the west coast of South America, Oceania and Pacific Ocean islands, including Galapagos (Lever 2003; Kraus 2009; Hoogmoed and Avila-Pires 2015). *Lepidodactylus lugubris* likely arrived to Galapagos during the early 1980s[13] (Hoogmoed 1989; Olmedo and Cayot 1994). It remained rare during the first decade[14], but subsequently became well established and expanded. Nowadays, it has fairly large self-sustained populations, but only on moist environments in coastal areas—i.e., artificially watered urban areas and mangroves—in the towns of Puerto Ayora, Puerto Baquerizo Moreno and Puerto Villamil (Olmedo and Cayot 1994; Sengoku 1998; Jiménez-Uzcátegui et al. 2007, 2015; Torres-Carvajal and Tapia 2011; Phillips et al. 2012a; pers. obs.). It has also established in the town of El Progreso, where it remains restricted to human buildings, and has not been found in farms (M. Altamirano, in litt. 12 June 2009). Jiménez-Uzcátegui et al. (2015) reported *L. lugubris* from Marchena Island, without further details. The consequences from the introduction of *L. lugubris* in Neotropical areas, incl. Galapagos, are not clear (Hoogmoed and Avila-Pires 2015). No impacts on Galapagos' biodiversity have been reported (Olmedo and Cayot 1994; Phillips et al. 2012). Competitive interactions between *L. lugubris* and Galapagos endemic geckos have apparently not affected endemic species (M. Altamirano 2002 cited in Phillips et al. 2012a). Although *L. lugubris* is insectivorous, it probably eats mainly non-native and widespread invertebrates. There are no studies yet about its diet.

- **Common House Gecko *Hemidactylus frenatus*** is a nocturnal species native to southeastern Asia (Lever 2003). It has invaded several areas across the planet, including many islands in the Indian and Pacific oceans and several areas of Africa and America, and currently has the widest worldwide non-native distribution of its genus (Lever 2003;

[12] At least one study on interactions between non-native and endemic geckos in Galapagos has been conducted but remains unpublished (M. Altamirano's PhD dissertation, cited by Phillips et al. 2012).
[13] Hoogmoed (1989) published the first mention of *Lepidodactylus lugubris* in Galapagos. However, he did not find the species, and cited the unpublished records obtained by John Wright at Puerto Ayora, Santa Cruz Island, in 1983.
[14] Marinus Hoogmoed did not find *Lepidoblepharis lugubris* during his intensive surveys of Puerto Ayora in 1988 (Hoogmoed 1989; Lundh 1998).

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Kraus 2009). Torres-Carvajal and Tapia (2011) reported the first record of *H. frenatus* in Galapagos, based on five individuals found at Puerto Villamil, Isabela Island, but an established population was not confirmed. On 24 October 2016, three *H. frenatus* were recorded at Puerto Villamil, thus suggesting that an established population is indeed present in Isabela Island (T. Schramer and Y. Kalki, in litt. 2016). It seems to have also established in Puerto Baquerizo Moreno, San Cristobal Island, where over 10 individuals were recorded between September and November 2016 in human buildings (T. Schramer and Y. Kalki, in litt. 2016). Due to its recent arrival, no information is available for any type of interactions or effects of *H. frenatus* on the endemic *Phyllodactylus* geckos. However, its arrival has raised concerns due to reported impacts on native fauna in other areas where it has established (Torres-Carvajal and Tapia 2011; Torres-Carvajal 2015). *Hemidactylus frenatus* has outcompeted and excluded non-native *Lepidodactylus lugubris* from several Pacific islands by competitive exclusion (Petren and Case 1998; Kraus 2009). Preliminary evidence suggests that *H. frenatus* may be also excluding *L. lugubris* in San Cristobal (T. Schramer and Y. Kalki, in litt. 2016). At the Mascarene Islands, *H. frenatus* contributed to the decline and population extirpation of endemic geckos of the genus *Nactus* (Cole et al. 2005). Furthermore, it could carry novel parasites that might impact native reptile species (Hoskin 2011).

- On 22 February 2014, a local inhabitant ran over a **Milksnake *Lampropeltis micropholis***[15] (Fig. 2) in the area of Santa Rosa, highlands of Santa Cruz Island. Photographs of the snake were quickly disseminated through social networks and Galapagos authorities were able to recover the specimen. Four days later, the specimen was delivered and deposited at the Laboratory of Terrestrial Zoology, Universidad San Francisco de Quito USFQ, by officials of the Ministry of Environment of Ecuador MAE in order to confirm its identification and preserve it as a voucher specimen. Morphology and colouration data suggest that the specimen belongs to the population distributed in the Pacific lowlands of Ecuador. In mainland Ecuador, *L. micropholis* inhabits the Pacific lowlands and Andean highlands in a large variety of ecosystems, from arid to moist habitats (Cisneros-Heredia and Touzet 2007). *Lampropeltis micropholis* is present in the surroundings of Guayaquil[16] and Quito (Williams 1988; Pérez-Santos and Moreno 1991;

[15] Until recently, *Lampropeltis micropholis* was a subspecies of *L. triangulum*. However, Ruane et al. (2014) raised it to species status. As currently understood, *L. micropholis* occurs from western Costa Rica to Ecuador. Further taxonomic changes are expected, and populations from the highlands of Ecuador could receive yet another (new) name (J. Valencia, in litt. 2012).

[16] *Lampropeltis micropholis* is rather frequent on the highlands, even in rural and suburban areas. However, there are few specimens from the lowlands (Cisneros-Heredia and Touzet 2007; pers. obs.). Williams (1988) reported it from Guayaquil, based on a specimen collected by Edward Whimper during the 1890s. Perez-Santos and Moreno (1991) reported the species from the province of Guayas, without providing details. Although no further information about *L. micropholis* from Guayaquil has been published, I am aware of two additional records: One individual collected ca. 18 km from Guayaquil and delivered to Jean-Marc Touzet (Fundación Herpetológica "Gustavo Orcés" FHGO) in February 1990

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Cisneros-Heredia and Touzet 2007). This snake is terrestrial, active during day and night, and eats a large variety of vertebrates and invertebrates (Williams 1988). There are no records of non-native populations of *L. micropholis* established outside of its range, or studies of insular populations. For comparison, a study of the diet of insular populations of *Lampropeltis polizona* at Isabel Island, Mexico, showed that they fed on different species of terrestrial lizards and nestlings of ground-nesting marine birds, incl. Blue-footed Booby *Sula nebouxii*, but avoided arboreal geckos and tree-nesting birds. The California Kingsnake *Lampropeltis californiae* became established in Gran Canaria Island, where its main evidenced ecological impact is predation of endemic lizards (Pether and Mateo 2007; Cabrera-Pérez et al. 2012).

- Several individuals of **Green Iguana *Iguana iguana*** have reached the Galapagos Islands (Cruz Martínez et al. 2007; Jiménez-Uzcátegui et al. 2007; Phillips et al. 2012a). Five specimens are deposited at the VCCDRS (CDF 2016). The earliest *I. iguana* (VCCDRS 571) was collected on 15 February 1982 at an unknown locality in Santa Cruz Island. Two additional specimens were found at a private house in the town of Puerto Ayora, Santa Cruz Island, on 14 August 2000[17] (CDF 2016). One *I. iguana* (VCCDRS 2218) was found at an unknown locality in San Cristobal Island, on April 19th, 2008; while another (VCCDRS 2153) was found in Isabela Island on 14 June 2010 (CDF 2016). Cruz Martínez et al. (2007) and Phillips et al. (2012a) mentioned an *I. iguana* found walking in the streets of Puerto Baquerizo Moreno, San Cristobal Island. Another was photographed on a dock at Puerto Ayora on 13 August 2015 (Christen 2015). *Iguana iguana* is native from Mexico to Paraguay and southern Brazil (Uetz and Hošek 2016). It is very common on the littoral and lowlands of western Ecuador (Ortega-Andrade et al. 2010), including the surroundings of cargo warehouses and the air and maritime ports of Guayaquil (Cruz Martínez et al. 2007; pers. obs.). *Iguana iguana* is able to disperse between islands by ocean rafting (Censky et al. 1998). However, I agree with Jiménez-Uzcátegui et al. (2007, 2015) and Phillips et al. (2012a) in classifying it as a non-native introduced species, as there is evidence of its hitchhiking behaviour (Cruz Martínez et al. 2007). In some islands where it has been introduced, *I. iguana* has displaced the native *I. delicatissima* by hybridisation (Lever 2003; Powell and Henderson 2005; Kraus 2009; Powell et al. 2011; Vuillaume et al. 2015). Since inter-generic hybridisation has been reported in iguanas (Rassmann et al. 1997; Jančúchová-Lásková et al. 2015), the establishment of *I. iguana* in Galapagos could pose a threat for the endemic iguanas of the genus *Amblyrhynchus* and *Conolophus*.

(Touzet JM pers. comm.); and another photographed by Keyko Cruz at Cerro Blanco, ca. 8 km from Guayaquil (Cruz 2015).

[17] However, Jiménez-Uzcátegui et al. (2007) reported that only one *Iguana iguana* was found in Santa Cruz in 2000, while the other was found in San Cristobal.

- One **Yellow-footed Tortoise *Chelonoidis denticulata*** in Santa Cruz Island, one **Yellow-spotted River Tortoise *Podocnemis unifilis*** in San Cristobal Island and a single **Common Slider Turtle *Trachemys scripta*** in Santa Cruz and San Cristobal islands were intercepted (Jiménez-Uzcátegui et al. 2007, 2015; Phillips et al. 2012a). All individuals were apparently brought to Galapagos as pets, and these three species are commonly traded as pets in mainland Ecuador (Carr and Almendáriz 1989; Cisneros-Heredia 2006b; pers. obs.). *Chelonoidis denticulata* and *P. unifilis* are native to the Amazonian lowlands. They are illegally caught and occasionally offered in pet stores of Quito and Guayaquil (pers. obs.). *Trachemys scripta* is native to the western USA and Mexico and it is the most common pet turtle and the most widely released reptile species in the world (Kraus 2009).

- A gravid **Five-lined skink *Plestiodon inexpectatus*** was intercepted as a pet in Galapagos. Jiménez-Uzcátegui et al. (2007) and Phillips et al. (2012a) cited the island of interception as San Cristobal. However, VCCDRS data indicate that it was intercepted at the Baltra airport on 26 May 2005 (CDF 2016).

Non-native birds in Galapagos

Twelve species of non-native birds have been recorded in the Galapagos Islands (Table 1):

- **Domestic ducks**[18], **Domestic Turkey *Meleagris gallopavo***, **Domestic Goose *Anser anser***, **Domestic Quail *Coturnix japonica***[19], **Domestic Guineafowl *Numida meleagridis*** and **Green Peafowl *Pavo muticus*** occur in the Galapagos only in agro-urban areas under human care (Gottdenker et al. 2005; Jiménez-Uzcátegui et al. 2007; Phillips et al. 2012a). None of them have established self-sustaining populations outside of farms. The 2014 Census of Agricultural Production (CGREG 2014) reported 926 ducks and 28 turkeys, all free-range, in Santa Cruz, San Cristobal and Isabela islands (Table 2). While the number of turkeys declined by one-third when compared with the census of 2000, the population of ducks increased by 117% (CGREG 2014).

- **Domestic Fowl or Chicken *Gallus gallus*** has been introduced across the planet as domestic poultry, with over 21 billion reported in 2014 (FAO 2015). Several populations have become feral, especially in the Pacific islands, incl. Galapagos (Phillips et al. 2012a; McGowan and Kirwan 2016). The 2014 Census of Agricultural Production (CGREG

[18] Domestic ducks in Galapagos seem to be a mix of descendants from the Mallard *Anas platyrhynchos* and the Muscovy Duck *Cairina moschata*.

[19] Japanese Quail *Coturnix japonica* and Common Quail *C. coturnix* are distinct but closely related species (Johnsgard 1988; McGowan and Kirwan 2016). *Coturnix japonica* was domesticated in eastern Asia several centuries ago, and domesticated quails are derived from *C. japonica* and its hybrids with *C. coturnix* (Guyomarc'h 2003). While *C. coturnix* is a partially migratory species, the domestic *C. japonica* lost its migratory impulse during domestication (Derégnaucourt et al., 2005; Guyomarc'h, 2003).

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2014) reported that 22,180 free-range and 70,750 intensive poultry chickens were in Galapagos. Domestic Chickens are found in all four inhabited islands of Galapagos: Santa Cruz, San Cristobal, Floreana and Isabela (Table 2). While Floreana Island holds the largest number per inhabitant and the greatest density in agricultural lands of free-range chicken, San Cristobal and Santa Cruz are the islands with the greatest density of free-range chickens (Table 2). Vargas and Bensted-Smith (2000), Gottdenker et al. (2005), Wiedenfield (2006) and Phillips et al. (2012a) reported feral (or semi-feral) populations of chickens established on the four inhabited islands. However, it remains unclear if those populations are indeed self-sufficient and truly feral—i.e., completely independent of human care.

The main potential impact of Domestic Chicken on native fauna is the spreading of infectious diseases to native birds (Wikelski et al. 2004; Gottdenker et al. 2005; Hernandez-Divers et al. 2008; Soos et al. 2008; GISD 2010; Deem et al. 2012). Yet, this threat has not been demonstrated and the evidence remains theoretical and correlative (GISD 2010; Baker et al. 2014). The Global Invasive Species Database (GISD 2010) mentions that *G. gallus* could negatively impact native vertebrates, but their only reference (Varnham, 2006) is anecdotal and based on a different species (Green Junglefowl *Gallus varius*). Phillips et al. (2012) noted: "no impacts [by *G. gallus*] to the [Galapagos] native biota have been documented".

I present here the first evidence of predation on squamate reptiles by Domestic Chickens in Galapagos. On June 2009, I observed a hen attacking a small Galapagos Racer *Pseudalsophis biserialis* in a private yard next to the road between Puerto Baquerizo Moreno and El Progreso, San Cristobal Island. The hen pecked on the snake's head and body, after which it seized the snake with its beak and started to run, chased by another hen. Eventually, the hens carrying the snake took cover inside a shed. In July, 2009, I observed a hen chasing a small Dwarf Gecko *Gonatodes caudiscutatus*, apparently found while foraging among some leaf litter and rocks in a private yard at El Progreso, San Cristobal Island. The gecko managed to flee and hide under rocks. In July 1997, I observed a rooster pecking and eating a dead Peters' Leaf-toed Gecko *Phyllodactylus reissi* in a vacant urban lot at Santa Cruz Island.

Gallus gallus mainly eats seeds and other plant material, although it is an omnivorous bird. Red Junglefowl, the wild ancestor of the Domestic Chicken, occasionally eats lizards and snakes (Ali and Ripley 1980). Reports of attacks and predation on squamate reptiles by Domestic Chicken are rare but worldwide (Guthrie 1932, Bell 1996; Powell and Henderson 2008; Mesquita et al. 2009; Sasa et al. 2009; pers. obs.). Scarcity of records would suggest that chicken predation on lizards and snakes is an opportunistic yet atypical behaviour. However, it could also be due to under-reporting and paucity of

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herpetologists surveying chicken yards. Free-range chickens can move over hundreds of meters away from their shelters to forage, usually towards hedges and borders where encounters with small snakes and lizards would be more prone to occur, though remaining unwitnessed.

- Four **Domestic Pigeon *Columba livia*** were brought to Floreana Island during the early 1970s to establish a dovecote (Harmon et al. 1987). Within the next decade, pigeons were introduced to Santa Cruz, San Cristobal and Isabela islands (Harmon et al. 1987). The population increased rapidly, and ca. 550 pigeons were present in Galapagos by 2001—most of them semi-feral or feral (Phillips et al. 2003). The main potential impact of Domestic Pigeon on Galapagos fauna was the spreading of the protozoan parasite *Trichomonas gallinae* to the endemic Galapagos Dove *Zenaida galapagoensis* (Harmon et al. 1987; Phillips et al. 2003). Indirect evidence for this threat was anecdotal and correlative, based on the presence of the parasite in *Z. galapagoensis* on islands where pigeons occurred (and their absence in pigeon-free islands), and the decline of *Z. galapaoensis* on islands populated by pigeon (Baker et al. 2014; Wikelski et al. 2004). In 2000, on the basis of the precautionary principle, Galapagos National Park Service and Charles Darwin Research Station started an eradication program (Phillips et al. 2012b). *Columba livia* was declared eradicated from Galapagos in 2007 (Phillips et al. 2012b).

- **Red-masked Parakeet *Psittacara erythrogenys*** was reported from Puerto Baquerizo Moreno, San Cristobal Island, in April 1996 (Vargas 1996, as *Aratinga erythrogenys*). Vargas (1996) obtained reports from local inhabitants of the presence of two or three parakeets, and he observed one *P. erythrogenys* flying between the town and the surrounding natural areas. These parakeets were possibly escaped pets and probably did not establish, and they have not been reported since (Wiedenfeld 2006; Phillips et al. 2012a). *Pssitacara erythrogenys* is endemic to central-western Ecuador and south-western Peru, where it inhabits deciduous and semi-deciduous forest (Ridgely and Greenfield 2001). It is among the most common birds illegally caught and traded (Juniper and Parr 1998), and freed pets can be found almost anywhere in Ecuador (pers. obs.). There are self-sustained non-native populations of *P. erythrogenys* in Spain and the USA.

- **Smooth-billed Ani *Crotophaga ani*** has naturally[20] expanded its distribution from South America to southern Florida, the Caribbean and Central America during the 20th century (Terborgh and Faaborg 1973; Terborgh et al. 1978; Quinn and Startek-Foote 2000; Payne and Kirwan 2016). Humans apparently introduced *C. ani* in the Galapagos Islands as a possible biological control against ticks (Harris 1973; Grant and Grant 1997; Phillips et

[20] *Crotophaga ani* expansion across America has not been mediated by humans. The species is not listed within the GISD (2010).

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al. 2012a)[21]. The first records of *C. ani* in Galapagos were in 1962, at Isabela Island. It progressively expanded to all major islands of the archipelago (Harris 1973; Grant and Grant 1997; Wiedenfeld 2006; Connett et al. 2013). At present, the estimated population of *C. ani* in Galapagos is over 250,000 individuals (Connett et al. 2013). *Crotophaga ani* is mainly insectivorous, but it also consumes plant material (especially fruits) and vertebrates (incl. lizards, snakes, frogs, birds and mice) (Bent 1940; Skutch 1959; Olivares and Munves 1973; Rosenberg et al. 1990; Burger and Gochfeld 2001; Payne and Sorensen 2005; Repenning et al. 2009; Connett et al. 2013). Predation on animal material seems to increase during the breeding period, which coincides with the wet season, when *C. ani* apparently prefers grasshoppers and other orthopterans (Davis 1940; Payne and Sorensen 2005; Repenning et al. 2009). Hymenopteran insects, such as euglossine bees and social wasps *Polystes* spp., have been reported as part of the diet of *Crotophaga ani* (Skutch 1959; Rosenberg et al. 1990; Raw 1997; Burger and Gochfeld 2001; Repenning et al. 2009). Two studies on the diet of *C. ani* at the Santa Cruz Island showed the presence of hymenopterans. Rosenberg et al. (1990) reported hymenopterans in only 4 of 24 dissected gizzards. Connett et al. (2013) found 12 *X. darwini* in the gizzards of 12 *C. ani*, but in this case, it was the single most frequent invertebrate species.

Four potential impacts by *Crotophaga ani* on Galapagos biodiversity have been postulated (Rosenberg et al. 1990; Grant and Grant 1997, Dvorak et al. 2004; Fessl et al. 2010):

(i) Propagation of invasive plants. Available evidence suggests that *Crotophaga ani* has a high potential to propagate introduced plants, including the invasive Raspberry *Rubus niveus* and Wild-sage *Lantana camara* (Guerrero and Tye 2011).

(ii) Predation on native fauna. Rosenberg et al. (1990), Guerrero and Tye (2011), and Connett et al. (2013) reported predation of Galapagos native invertebrates, lizards and Darwin Finch nestlings by *Crotophaga ani*.

(iii) Competition with native avifauna, which remains untested and speculative.

(iv) Introduction of avian diseases, also untested and speculative.

Nonetheless, Phillips et al. (2012a; *contra* Rosenberg et al. 1990) stated that the Smooth-billed Ani is “a low priority alien species, not having been attributed with any serious impacts to native species, although it is likely that it has some effects on native [fauna]”.

I present herein information that constitutes the first evidence of a probable major impact on an endemic invertebrate due to predation by *Crotophaga ani* (Fig. 3) Between 8 and 16 June 2009, I observed six groups of *C. ani* predating assiduously on Galapagos

[21] Still, this introduction hypothesis remains an assumption, mainly based on the apparently low capacity of anis to self-disperse through long distances across oceans (Harris 1973; Grant and Grant 1997; Phillips et al. 2012).

Carpenter Bee *Xylophaga darwini* at six different locations on San Cristobal Island. Carpenter bees in high densities were foraging on blooming trees in the Dry Zone, usually near the coast. I observed one group of *C. ani* over a 30-minute period and the other five groups during 15-minute periods each. In total, the six groups consumed 661 bees over the observation periods. Each bird captured an average of 8.5±4.4 (range = 4–15) bees per 15 minutes. *Crotophaga ani* continued preying upon bees after each observation period ended. Despite the continuous attacks, the bees did not disperse and more kept coming attracted by the flowers. Although large numbers of the non-native Social Wasp *Polistes versicolor* were also present, as well as some butterflies, *C. ani* largely ignored them.

- An individual of **Saffron Finch *Sicalis flaveola*** was intercepted in 2014 at Baltra Island's airport, where it arrived as a hitchhiker on an airplane from Quito (Jiménez-Uzcátegui et al. 2015). Interestingly, after its interception, it was returned to Quito where local staff misidentified it as a Galapagos endemic bird and sent it back to the archipelago[22] (Jiménez-Uzcátegui et al. 2015). In Ecuador, *S. flaveola*'s native distribution is in arid semi-open areas with scattered trees or shrubs, and agricultural areas of south-western Ecuador, both lowlands and inter-Andean highland valleys (Ridgely and Greenfield 2001). During the 21st century, *S. flaveola* started to expand along central-western lowlands and northern inter-Andean highland valleys of Ecuador (Henry 2005; Buitrón and Freile 2006; Cisneros-Heredia et al. 2015). It is now a frequent species in the valley of Quito, including the surroundings of air cargo warehouses and the airport (Cisneros-Heredia et al. 2015; pers. obs.).

- Phillips et al. (2012a) and Jiménez-Uzcátegui et al. (2015) reported an individual of **Great-tailed Grackle *Quiscalus mexicanus*** captured at the town of Puerto Ayora, Santa Cruz Island in 2010. However, there is a previous record of this grackle that remained unreported: One *Q. mexicanus* was filmed at Santa Cruz Island on May 2005 (Fig. 4). *Quiscalus mexicanus* has a broad distribution, from central USA to the Pacific coasts of Ecuador and northern Peru (Fraga 2014). It has expanded considerably its distribution along northern USA and Caribbean islands (Dinsmore and Dinsmore 1993; Wehtje 2003; Fraga 2016). *Quiscalus mexicanus* was first reported from the Caribbean islands in the mid-2000s (Mejía et al. 2009; Paulino et al. 2013; Levy 2015). Currently, it seems to be established at least in Jamaica and Hispaniola (Paulino et al. 2013; Levy 2015). Grackles have been observed to hitchhike on passenger boats (Norton 1902), and Haynes-Sutton et al. (2010) mentioned that *Q. mexicanus* probably reached Jamaica with cargo. The paucity of records of *Q. mexicanus* in islands suggests that it is a poor disperser across oceanic barriers, but cargo and passenger boats may offer aid for oceanic trips. The same

[22] When it arrived to Galapagos for the second time, it was weak and died by the next day (Jiménez-Uzcátegui et al. 2015)

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transport mechanism was probably used by *Q. mexicanus* to reach Galapagos (although this remains an assumption). Thus, I include this species as a non-native introduced species, rather than as a vagrant.

Nine species of terrestrial birds recorded at Galapagos have reached the islands most probably by natural dispersion from mainland South America in recent (historic) times[23]: Snowy Egret *Egretta thula*, Little Blue Heron *Egretta caerulea*, Cattle Egret *Bubulcus ibis*, Black-bellied Whistling-Duck *Dendrocygna autumnalis*, Masked Duck *Nomonyx dominicus*, Paint-billed Crake *Neocrex erythrops*, Purple Gallinule *Porphyrio martinicus*, Eared Dove *Zenaida auriculata*, Gray-capped Cuckoo *Coccyzus lansbergi* and Bananaquit *Coereba flaveola* (Wiedenfeld 2006; Jiménez-Uzcátegui et al. 2015). While most of these species have few records in the archipelago, the following species have become regular visitors or have established self-sufficient populations: *Egretta thula* with several records in Santa Cruz, Isabela, Floreana and San Cristobal islands (Wiedenfeld 2016; Hendrickson et al. 2015; pers. obs. at El Junco lagoon in July 2009); *Neocrex erythrops* with nesting populations in Santa Cruz and Floreana islands, and probably in San Cristobal and Isabela islands; *P. martinicus* with "with long periods of residence, bordering on being a permanent resident in recent years" (Wiedenfeld 2006), and *B. ibis* with breeding colonies on the main islands and widespread across the archipelago (Wiedenfeld 2006). All of these species are considered herein as native species of Galapagos. Although some of them may have established more easily due to human habitat modification, humans did not mediate in their arrival process.

Bubulcus ibis has been commonly identified as a non-native invasive species at the Galapagos Islands. However, its arrival to the Galapagos was not human-mediated but was instead a natural colonisation based entirely on the species' adaptations to successfully disperse across oceanic routes. The original distribution of *B. ibis* included the south of the Iberian Peninsula and parts of sub-Saharan and meridional Africa. During the 19th century, *B. ibis* underwent an enormous expansion, and it has currently colonized all continents except Antarctica (Martínez-Vilalta and Motis 1992; Martínez et al. 2017). Its natural arrival to Galapagos was a matter of time and its establishment would have happened with or without anthropic areas, since it may inhabit swamps and mangroves. The existence of agricultural areas in Galapagos only facilitated the expansion of *B. ibis* in the archipelago. Its situation is very similar to *Neocrex erythrops*, also a recent arrival that has benefited from agricultural and other anthropic areas.

[23] While all other bird species recorded as vagrants at Galapagos can be classified as oceanic wanderers or as stray boreal migrants (Wiedenfeld 2006; Jiménez-Uzcátegui et al. 2015).

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Discussion

Arrival mechanisms

Eight (32%) non-native amphibians, reptiles and birds in Galapagos arrived as domestic animals, five (20%) as pets and one (4%) as (unsuccessful) biocontrol (Table 1). All domestic animals, pets and biocontrols were brought to the islands deliberately. However, most (44%) non-native amphibians, reptiles and birds reached the Galapagos Islands as hitchhikers aboard airplanes or ships, unintentionally translocated (Table 1). While data for most species is not complete, this hypothesis is supported by VCCDRS specimens of *Scinax quinquefasciatus* collected on a ship at Santa Cruz and at the airport of San Cristobal, and by *Sicalis flaveola* found inside of an airplane (CDF 2016).

Six hitchhiking species arrived to Galapagos before the quarantine inspection system began in June 2000, and nine species were first recorded afterwards. Among the hitchhikers, *Rhinella horribilis* is a large toad (> 70 mm in old juveniles, >100 mm in adults), thus unlikely to bypass quarantine inspections. The only known record of *R. horribilis* in Galapagos was made five years before the quarantine system began. *Lampropeltis micropholis* and *Iguana iguana* are large reptiles (> 600 mm) and both have reached Galapagos after 2000 (it is uncertain how they bypassed quarantine). In contrast, *Scinax quinquefasciatus*, *Pristimantis unistrigatus*, *Gonatodes caudiscutatus*, *Phyllodactylus reissii*, *Lepidodactylus lugubris*, and *Hemidactylus frenatus* are relatively small and with rather cryptic colorations (brownish). They could thus be easily overlooked during quarantine inspections, and multiple translocations could have occured. Gill et al. (2001) reported live interception cases of *S. quinquefasciatus* (in Ecuadorian banana shipments), *L. lugubris* and *H. frenatus* in New Zealand, showing its ability to be translocated and to survive physiological stress during long trips.

Most hitchhiking species that have reached Galapagos occur in the surroundings of air and maritime ports, or of cargo warehouses. However, not all translocations come directly from ports of shipment. *Lepidodactylus lugubris* does not occur in areas with air or maritime ports in mainland Ecuador with connections to the Galapagos, incl. Manta, Guayaquil or Quito. *Lepidodactylus lugubris* was first recorded in mainland Ecuador at Esmeraldas in 1963 (Fugler 1966). Currently, it inhabits along the humid lowlands and foothills of north-western Ecuador, restricted to urban and suburban areas in the provinces of Esmeraldas and Santo Domingo de los Tsachilas (Fugler 1966; Schauenberg 1968; Hoogmoed and Avila-Pires 2015). It is absent from the arid central and south-western lowlands of Ecuador. The translocation of *L. lugubris* to Galapagos was possibly achieved via horticultural cargo coming from Esmeraldas, or from other countries where the species was already present, such as Colombia or Panama[24].

[24] The first specimen of *Lepidodactylus lugubris* from America was collected in Panama in 1916 (Fugler 1966; Hoogmoed and Avila-Pires 2015). G.K. Noble collected it during his trip for the Harvard Peruvian Expedition (Collection catalogue, Herpetology, Museum of Comparative Zoology, Harvard University).

Human-facilitated transportation has provided opportunities for amphibians, reptiles and birds to reach Galapagos, independent of their physiological adaptations to salinity or to long trips. However, upon arrival, they still need to withstand the arid environments of the Littoral and Dry zones, where freshwater is almost absent under natural conditions on most islands. While all non-native frogs, reptiles and birds reported in Galapagos are able to survive in arid environments to some degree, at least frogs and small geckos are still dependent of some humidity. Local and regional climate changes can have an important effect on the establishment and distribution of non-native species in Galapagos (Snell and Rea 1999). Higher rainfall during El Niño events (e.g., 1997–1998 and 2009–2010) was a major factor in the establishment of *Scinax quinquefasciatus* populations in Isabela, and for the expansion of *Crotophaga ani* (Snell and Rea 1999; Pazmiño 2011). El Niño in 1997–1998 increased environmental humidity and diluted salinity in the lagoons of Puerto Villamil, allowing *S. quinquefasciatus* to thrive. After the El Niño event of 2009–2010, *S. quinquefasciatus* was able to reach the humid agricultural areas of Bellavista (Pazmiño 2011).

Artificially watered green urban and suburban areas, such as parks and gardens, have played an important role in the establishment of non-native amphibians and reptiles in Galapagos. They can act as refuges for newly established species, providing resources for locally large populations and facilitating intra and inter-island dispersion across inhabited areas (Ineich 2010). All non-native geckos are mainly found in green urban and suburban areas. Genetic evidence from Isabela Island populations of *Scinax quinquefasciatus* (Pazmiño 2011) and recurring records of *S. quinquefasciatus* from Santa Cruz Island and *G. caudiscutatus* at San Cristobal suggest multiple introduction events for both species. Before El Niño's thrusts, these populations were apparently able to survive thanks to artificially watered green urban and suburban areas[25].

Most hitchhiking amphibians and reptiles are usually translocated inside freight or dwelling within spaces and crevices of airplanes and ships. However, they can be transported inside tourist luggage too. On August 2009, a live *L. lugubris* was unintentionally translocated in my handbag from San Cristobal Island to Guayaquil. It probably entered my bag at a restaurant near the dock, since I never saw *L. lugubris* at the USFQ Galapagos campus, where I stayed. I noticed its presence after opening my bag in Guayaquil. Furthermore, this shows that non-native species translocations may work on both ways, exchanging individuals between populations of Galapagos and the continent.

The gecko was collected just two years after the opening of the Panama Canal, and was probably translocated on boats coming from Hawaii or Oceania (Smith and Grant 1961). By 1941, *L. lugubris* had already reached Colombia (Daza et al. 2012; Hoogmoed and Avila-Pires 2015).

[25] In comparison with Santa Cruz Island, the area of urban and suburban gardens in San Cristobal is reduced. This limited habitat availability is apparently the reason why *Gonatodes caudiscutatus* holds small and restricted populations in the lowlands of San Cristobal, and why *Scinax quinquefasciatus* has not become established in that island (despite its first record in 2000).

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Large hitchhiking reptiles and birds can accidentally enter closed areas inside freight airplanes and ships, although they are easily detected and intercepted (like the individual of *Sicalis flaveola* in Galapagos). However, probably the most common hitchhiking situation takes place when large reptiles and birds stay on decks and other exterior structures of passenger and cargo ships. They can hitchhike after the ships have gone through departure port inspections, survive for several days, remain overlooked, and swim or fly towards land before the ship reaches controls in the arrival ports. *Iguana iguana* and *Quiscalus mexicanus* have likely arrived in this way to Galapagos. Several hitchhiker bird species are known to have arrived and established in islands around the world: House Sparrow *Passer domesticus* in the Canary and Maldives islands, Spanish Sparrow *Passer hispaniolensis* in the Canary Islands, Pale-billed Mina *Acridotheres cinereus* in Borneo island, Red-vented Bulbul *Pictonotus cafer* in the Marshall and Hawaii islands, House Crow *Corvus elegans* in the Socotra Islands and Australia and Great-tailed Grackle *Quiscalus mexicanus* in Jamaica (Haynes-Sutton et al. 2010; Lever 2005 Suleiman and Taleb 2010).

Vulnerable islands

If further amphibian, reptile and bird introductions are to be stopped in Galapagos, it is important to establish the vulnerability of islands to those introductions, and to understand the general profile of potential hitchhikers.

The four populated islands are the most vulnerable to translocation of non-native species because they have: (i) established and active air and maritime ports, thus arrival mechanisms and dispersal events of non-native species are facilitated in repetitive occasions; (ii) large flux of local population and tourists, which means large amount of baggage and freight where non-native species may hide, find adequate microenvironments to survive the oceanic dispersion and be transported to different areas of the islands; (iii) human-modified environments where anthropophilic non-natives may find suitable niches.

Isabela Island is apparently the most vulnerable island to the establishment of amphibians because of its freshwater wetlands next to the city and harbor[26]. Santa Cruz, San Cristobal and Floreana islands have coastal lagoons with significantly more salinity than Las Diablas lagoon in Isabela (Gelin and Gravez 2002), thus amphibians probably do not become easily established. The highland moist zones of all populated islands are especially vulnerable to the introduction of non-native amphibians, reptiles and birds, due to the presence of mesic environments with extensive agro-urban areas and wetlands. Furthermore, the moist zones on the highlands of Isabela are closer to the coast, making it easy for non-native species to reach a mesic environment in which to survive and establish.

[26] The largest coastal lagoon of Isabela, Las Diablas, is next to the town of Puerto Villamil. Its low salinity levels (6–10 gL-1, Gelin and Gravez 2002) allow the reproduction of *S. quinquefasciatus*.

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Potential hitchhikers

Intentionally introduced species, such as pets and domestic animals, are rather easy to detect and identify because they are usually conspicuous and recognisable. However, hitchhiking species are the real predicament of quarantine officials. Hitchhiking species are usually inconspicuous, difficult to identify and hard to find. There is not a single set of characteristics that ascertains the potential of vertebrates to become a successful hitchhiker or to become established in insular ecosystems. Several publications have reviewed and proposed different methods for predicting introduced species. Since I am analysing three different phylogenetically diverse groups of terrestrial vertebrates, I will use basic criteria for each group, which were selected after studying the following references: Kolar and Lodge (2001), Hayes and Barry (2008), Van Wilgen and Richardson (2012), Buckley and Catford (2016). I think this criteria set allows for fast and simple identification of potential species in mainland Ecuador that could hitchhike to Galapagos. A key factor for the control of hitchhiking species is that personnel at ports and crew in airplanes and ships receive training to correctly identify, restrain and handle non-native hitchhiking animals. Although the species lists provided herein could be improved, I hope they will provide valuable information for the Agency for Regulation and Control of Biosecurity and Quarantine for Galapagos (ABG), and other organisations involved in the conservation and management of the archipelago (incl., Consejo de Gobierno del Régimen Especial de Galápagos CGREG, Ministerio de Agricultura, Ganadería, Acuacultura y Pesca MAPAG, Parque Nacional Galápagos PNG, Ministerio del Ambiente MAE).

A cautionary note: some reptiles and birds from mainland Ecuador may look similar to those native to Galapagos. For example, the Galapagos endemic geckos of the genus *Phyllodactylus* could be confused with the non-native *Phyllodactylus reissii*; and the native Setophaga petechia has been confused in the past with the non-native Sicalis flaveola. Guides and manuals specifically focused on crew or control personnel should be produced to avoid confusion and reinforce control measurements.

Amphibian and reptile species with higher hitchhiking potential for Galapagos seem to be characterised by: (i) having inconspicuous colouration and small to medium body size[27]; (ii) being adapted to arid environments or anthropogenic areas[28]; (iii) occurring frequently in the

[27] Which contributes to their hard detection and improves their survivorship (Olson et al. 2012)
[28] Adaptation to desiccation conditions has also enhanced tolerance to salinity in some amphibians (Balinsky 1981; Wells 2007), thus making it easy for them to survive in low-salinity lagoons like Las Diablas in Isabela Island. The three species of *Scinax* that have become established in islands as cargo hitchhikers have adapted to arid environments or anthropogenic areas on their native distributions: *Scinax quinquefasciatus*, *S. x-signatus* and *S. ruber* (Breuil and Ibéné 2008; Breuil 2009; Kraus, 2009; Powell et al. 2011). The first two are also known to be adapted to breed in marshes with low salinity (Jiménez-Uzcátegui et al. 2007; Rios-López 2008; pers. obs.). It seems that *Scinax* species, which are able to adapt to open habitats, show some tolerance to salinity.

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surroundings of cargo warehouses or in agricultural areas[29]; and (iv) living in the Pacific lowlands of central Ecuador, where habitats have environmental conditions similar to those found in the Galapagos[30], and the main ports of freight airplanes and ships to Galapagos are located.

In mainland Ecuador, there are six frog species matching this hitchhiker profile (Fig. 5): *Scinax quinquefasciatus*, *Pristimantis achatinus*, *Barycholos pulcher*, *Engystomops pustulatus*, *Trachycephalus jordani*, *T. typhonius* and *Rhinella horribilis*. While the first species is already established in Galapagos, the remaining five, if allowed to reach the archipielago, have a high probability of settling there. Furthermore, these species have additional advantages favoring their establishment in insular environments: *Pristimantis achatinus* and *B. pulcher* are terrestrial breeders with direct development; *E. pustulatus*, *S. quinquefasciatus* and *R. horribilis* are opportunistic breeders that can reproduce even in small puddles; and *E. pustulatus*, *T. jordani* and *T. typhonius* can inhabit extremely arid environments with low seasonal rainfall, similar to the lowlands of Galapagos. Live *T. jordani* have been intercepted as far away as the USA and New Zealand in banana shipments from mainland Ecuador (Hartweg 1955; Gill et al. 2001). Although large adult *R. horribilis* should be intercepted during quarantine, juveniles are small and inconspicuous. However, desiccation is a major mortality factor for juveniles (Zug and Zug 1979), but if they were to find shelter and wet conditions, they could survive travelling to Galapagos. There are 11 species of squamate reptiles matching the hitchhiker profile in mainland Ecuador (Fig. 5): *Gonatodes caudiscutatus*, *Hemidactylus frenatus*, *Phyllodactylus reissii*, *Iguana iguana*, *Lampropeltis micropholis*, *Boa constrictor*, *Dipsas elegans*, *Erythrolamprus epinephelus*, *Mastigodryas* sp. (cf. *boddaerti*), *Mastigodryas pulchriceps* and *Oxybelis aeneus*. The first five of these species have already been recorded in Galapagos.

Although little information is available on hitchhiker birds, at least the following features seem to profile potential hitchhiker birds to the Galapagos: (i) being adapted to arid environments or anthropogenic areas, which would allow them to survive in the lowlands of Galapagos; (ii) occurring frequently in the surroundings of main ports of freight airplanes and ships to Galapagos, with higher probability of entering closed areas inside of freight airplanes and ships or wandering around boat decks; (iii) habit of flying at least short distances over the sea, so they can reach departed ships; and (iv) adaptability to build nests within human-made structures, thus attracting reproductive adults to the ships. Since birds are active and noticeable animals, their detection and capture should be fairly easy during quarantine procedures.

[29] Frogs that are common in these have easy access to freight or have a great chance to be packed along with horticultural products (Kraus et al. 1999).
[30] Species that establish successful self-sufficient populations usually come from areas that have a similar climate to the jurisdiction where they are introduced (Bomford et al. 2009).

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To guide such training, I provide a shortlist of birds from mainland Ecuador that match the potential hitchhiker profile (Fig. 5): Eared Dove *Zenaida auriculata*, *Thaupis episcopus*, Saffron Finch *Sicalis flaveola*, Rufous-collared Sparrow *Zonotrichia capensis*, Shiny Cowbird *Molothrus bonariensis*, Great-tailed Grackle *Quiscalus mexicanus* and House Sparrow *Passer domesticus*. Of these birds, two have been already recorded at Galapagos and are discussed above. There are records of *Z. auriculata* at Champion islet, Santa Cruz and Baltra islands (Wiedenfeld 2006; Loranger 2012). Although all these areas are in or close to inhabited islands, their origin cannot be directly assigned to hitchhiking since this species is capable of oceanic dispersing (Baptista et al. 2013). Of all the birds herein listed, *M. bonariensis* could be a major threat if established in Galapagos. It is a brood parasite and can seriously affect bird species with small populations (Oppel et al. 2004). Its populations have expanded in the surroundings of the two air and maritime ports of Guayaquil and Quito (Cisneros-Heredia et al. 2015; Crespo-Pérez et al. 2016; pers. obs.).

Effects, management and control

Chickens have become the dominant domestic birds in all inhabited islands in Galapagos. Several studies have discussed the possible transmission of disease from chickens to native Galapagos fauna, its potential impacts and control measures (Wikelski et al. 2004; Gottdenker et al. 2005; Soos et al. 2008; Deem et al. 2012). Free-range (and feral) chickens seem to have some degree of predatory impacts on Galapagos fauna, as evidenced in this publication. However, chicken predation on endemic fauna is probably uncommon, because endemic snakes and lizards prefer dry lowland areas and most free-range and feral chickens occur in moist highland areas (CGREG 2014). In contrast, it is possible that chickens have significant impacts on the populations of the introduced gecko *Gonatodes caudiscutatus*, the only squamate reptile of Galapagos that occurs mainly in moist highland areas; i.e., agricultural lands at San Cristobal Island. Nevertheless, chicken predation probabilities increase in urban and suburban areas, where endemic snakes and endemic and non-native lizard and chickens co-occur.

Soos et al. (2008) suggested several regulatory and management procedures focused on preventing the spread of poultry diseases to wild birds, including the elimination or reduction of free-range chickens. To eliminate free-range farming could be impractical due to cultural, social and economical factors. A more plausible option would be to promote free-range poultry farming with biosecurity measures that reduce the interaction between chickens and wildlife. Some measures should include: well-kept fences to prevent chickens leaving the farm and to stop them from foraging on hedges and other vegetated areas; a peripheral ring without vegetation, rocks or wreckage around the fences, coops and troughs; and clean fenced-in pastures for poultry roaming to prevent attracting wildlife inside chicken yards. These and other measures must be established and reinforced with the active participation of Galapagos poultry owners and local and national authorities dealing with agricultural practices and wildlife conservation (incl., ABG, Consejo de Gobierno del Régimen Especial de Galápagos CGREG, Ministerio de Agricultura, Ganadería,

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Acuacultura y Pesca MAPAG, Parque Nacional Galápagos PNG, Ministerio del Ambiente MAE).

Of all non-native species, *Crotophaga ani* is the only species with established, self-sufficient populations expanding into anthropic and natural areas in Galapagos. Data presented herein show that the Smooth-billed Ani *Crotophaga ani* can heavily predate on the Galapagos Carpenter Bee *Xylocopa darwini*. Large body size and slow flight of carpenter bees probably make them an easy and more nutritious prey for *C. ani*, in comparison with other similar species of invertebrates. Observations of six different groups of *C. ani* with an intensive predatory behaviour on *Xylocopa darwini* in San Cristobal Island suggest that this is not a unique habit. Furthermore, this behaviour may be widespread since *X. darwini* is known to be part of the diet of *C. ani* in Santa Cruz Island (Rosenberg et al. 1990; Connett et al. 2013). If similar patterns of predation are constant—at least during the breeding period—*C. ani* may have a severe impact on local carpenter bee populations. *Xylocopa darwini* is the only endemic bee from the archipelago (Gonzales et al. 2010, Rasmussen et al. 2012). It is a keystone pollinator species in the islands, being the most important flower visitors and responsible for the vast majority of insect pollination in Galapagos (Linsley 1966, Linsley et al. 1966, McMullen 1985, 1989, Phillip et al. 2006, Chamorro et al. 2012). As a dominant and keystone pollinator, negative impacts on its populations may have significant effects on the plant-pollinator networks of the islands.

Eradication of established non-native populations is costly and rarely successful (Mack et al. 2000), and control policies seem to have effects only before species are widespread (Olson et al. 2012; Pitt et al. 2012). In this context, the Agency for Regulation and Control of Biosecurity and Quarantine for Galapagos (ABG) plays a decisive role in preventing new introductions of non-native amphibians, reptiles and birds in Galapagos, especially hitchhikers. Furthermore, for non-native species already established, it is important to stop new or multiple introductions of the same species, since they will increase reproductive output and genetic diversity (Lambrinos 2004; Van Wilgen and Richardson 2012). Quarantine officers should pay particular attention to horticultural trade and temperature-controlled freight, which because of their constant temperatures, are non-lethal for amphibians and reptiles (Work et al. 2005). Decks and exposed cargo on ships are another source of non-native species, especially large body-size hitchhikers such as snakes, iguanas and birds.

If the eradication of non-native established species is of interest, the eradication program of *Columba livia* is a successful but rather unique story (Phillips et al. 2012b). The success was due, in part, to the availability of adequate and updated knowledge about the species' natural history, distribution, ecological relationships, effects and eradication methods (Phillips et al. 2012b). In contrast, eradication attempts of other non-native species that are poorly known have been

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unsuccessful, e.g., *Scinax quinquefasciatus*[31]. In fact, it is probable that after a non-native species has become established and self-sufficient, management policies could be better focussed on guiding its control rather than to “undertake the daunting (and often illusory) task of eradicating them” (David et al. 2017).

Very little information has been published about the natural history of most non-native amphibians, reptiles and birds in their native distribution in mainland Ecuador. Knowledge on non-native species is paramount to understand whether their control should be a conservation goal in the archipelago, and if so, how it could be best achieved. Even the species’ identity of some species is uncertain (e.g., *Rhinella horribilis*, *Scinax quinquefasciatus* and *Lampropeltis micropholis*). Furthermore, knowledge about Galapagos populations remains in many cases unpublished[32]. Most terrestrial non-native hitchhikers in the Galapagos are geckos and their effects on Galapagos biodiversity have usually been considered as low or absent. Unfortunately, Marinus Hoogmoed’s (1989) words are still valid today: “these are only speculations based on few observations”. With all these restrictions, control policies are not sufficiently evidence-based. Future research on non-native species should provide information on habitat and microhabitat use, physiology and growth, intra-population tolerance to abiotic and biotic factors, reproductive biology and population dynamics, diet and trophic interactions, both in Galapagos and in its native distribution.

Fundamentally, we need to rethink about how we understand, manage and prevent introductions of non-native species. Available information about non-native terrestrial vertebrates in Galapagos is still basic, and not enough to even understand their natural history and general ecological patterns. We need to go beyond the paradigm that the main impact of non-native species is framed by their direct effects on native species, i.e., direct competition or predation. It is necessary to understand the ecosystemic effects of non-native species, for example on nutrient dynamics and cumulative effects on food webs through trophic and non-trophic interactions (e.g., mutualisms or ecosystem engineering). We also need more research on how native species are evolving when confronted and living with non-native species, since often native species rapidly evolve traits to better tolerate or exploit invaders (David et al. 2017).

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[31] Eradication attempts by hand-capture, spraying caffeine, and increasing the salinity of the lagoons were unsuccessful (Jiménez-Uzcátegui et al. 2007; Phillips et al. 2012).

[32] For example, available knowledge about the populations of *Scinax quinquefasciatus* in Galapagos remains in two unpublished dissertations: Pazmiño (2011) described the genetic diversity and origin of the Galapagos populations of *S. quinquefasciatus*, and Vintimilla (2005) analysed the control potential of increasing water salinity.

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1749 **TABLE 1. List of non-native amphibians, reptiles and bird species in the Galápagos Islands.**

1750

Suprataxa	Family	Genus	Species	Establishment Status	Biogeographic Origin	Arrival method	Islands
Amphibia	Bufonidae	*Rhinella*	*marina*	Non-established	Non-native	Human mediated	San Cristóbal
Amphibia	Hylidae	*Scinax*	*quinquefasciatus*	Incipient	Non-native	Human mediated	Santa Cruz, San Cristóbal, Isabela
Amphibia	Craugastoridae	*Pristimantis*	*unistrigatus*	Non-established	Non-native	Human mediated	Santa Cruz, Isabela
Squamata	Colubridae	*Lampropeltis*	*micropholis*	Non-established	Non-native	Human mediated	Santa Cruz
Squamata	Sphaerodactylidae	*Gonatodes*	*caudiscutatus*	Incipient	Non-native	Human mediated	Santa Cruz, San Cristobal, Baltra
Squamata	Gekkonidae	*Lepidodactylus*	*lugubris*	Successful	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela, Marchena
Squamata	Gekkonidae	*Hemydactylus*	*frenatus*	Newly established	Non-native	Human mediated	Isabela
Squamata	Phyllodactylidae	*Phyllodactylus*	*reissii*	Dispersed	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela
Squamata	Iguanidae	*Iguana*	*iguana*	Non-established	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela
Squamata	Scincidae	*Plestiodon*	*inexpectatus*	Non-established	Non-native	Human mediated	San Cristobal
Testudines	Bataguridae	*Trachemys*	*scripta*	Non-established	Non-native	Human mediated	Santa Cruz, San Cristobal
Testudines	Pelomedusidae	*Podocnemis*	*unifilis*	Non-established	Non-native	Human mediated	San Cristobal
Testudines	Testunidae	*Chelonoidis*	*denticulata*	Non-established	Non-native	Human mediated	Santa Cruz
Aves	Anatidae	*Anas/Cairina*	*platyrhynchos/ moschata*	Domestic	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela
Aves	Anatidae	*Anser*	*anser*	Domestic	Non-native	Human mediated	Santa Cruz, San Cristobal

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Aves	Columbidae	*Columba*	*livia*	Eradicated	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela
Aves	Cuculidae	*Crotophaga*	*ani*	Successful	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela, Floreana, Genovesa, Marchena, Pinta, Pinzon, Santiago
Aves	Phasianidae	*Coturnix*	*japonica*	Domestic	Non-native	Human mediated	Santa Cruz
Aves	Phasianidae	*Gallus*	*gallus*	Domestic | Dispersed	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela, Baltra
Aves	Phasianidae	*Meleagris*	*gallopavo*	Domestic	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela
Aves	Phasianidae	*Numida*	*meleagris*	Domestic	Non-native	Human mediated	Santa Cruz, San Cristobal, Isabela
Aves	Phasianidae	*Pavo*	*muticus*	Domestic	Non-native	Human mediated	San Cristobal
Aves	Icteridae	*Quiscalus*	*mexicanus*	Non-established	Non-native	Human mediated	Santa Cruz
Aves	Thraupidae	*Sicalis*	*flaveola*	Non-established	Non-native	Human mediated	Baltra
Aves	Psittacidae	*Aratinga*	*erythrogenys*	Non-established	Non-native	Human mediated	San Cristobal

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TABLE 2. Free-range Domestic Chicken *Gallus gallus* in the Galapagos Islands based on data reported by the 2014 Census of Agricultural Production (CGREG 2014). Free-range chickens were defined as those allowed to move freely in outdoors. Census did not include areas where stock was raised entirely for self-consumption, thus total numbers might be slightly underestimated.

Island	Number of ducks	Number of turkeys	Number of free-range chicken	Chickens per 100 inhabitants	Density in agricultural lands: Chickens per 1 km^2 of agricultural land	Density in the whole island: Chicken per 10 km^2 of total land area
Santa Cruz	407	3	10340	57	108	105
San Cristobal	328	21	7286	86	131	131
Isabela	191	4	3973	147	110	9
Floreana	0	0	581	387	253	34

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TABLE 3. Topology to evaluate the degree of establishment of non-native amphibians, reptiles and birds in Galapagos, independent of their conservation effects. It is based on McGeoch and Latombe (2016), with some modifications.

Category	**Degree of expansion**	**Population size**	**Time since establishment**
Non-established	Intercepted	None	None
Domestic	Human-dependant	Human-dependant	Recent/Historic
Newly established	Narrow	Small	Recent
Incipient	Narrow	Large	Recent
Dispersed	Wide	Small	Recent
Successful	Wide	Large	Recent
Eradicated	Wide/Narrow	None	Recent/Historic
Non-common	Narrow	Small	Historic
Constrained	Narrow	Large	Historic
Sparse	Wide	Small	Historic
Highly Successful	Wide	Large	Historic

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FIGURE 1. Juvenile of *Scinax quinquefasciatus* at Santa Cruz Island, Galapagos. Photo: Luke Smith.

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FIGURE 2. Specimen of *Lampropeltis micropholis* collected at Santa Rosa, Santa Cruz Island, Galapagos.

FIGURE 3. *Crotophaga ani* predating on Galapagos Carpenter Bee *Xylocopa darwini*. Photo by Zell Lundberg and Christina Mitchell.

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FIGURE 4. *Quiscalus mexicanus* at Santa Cruz Island, Galapagos, on May 2005. Photo by Kevin Dowie (www.kevindowie.com)

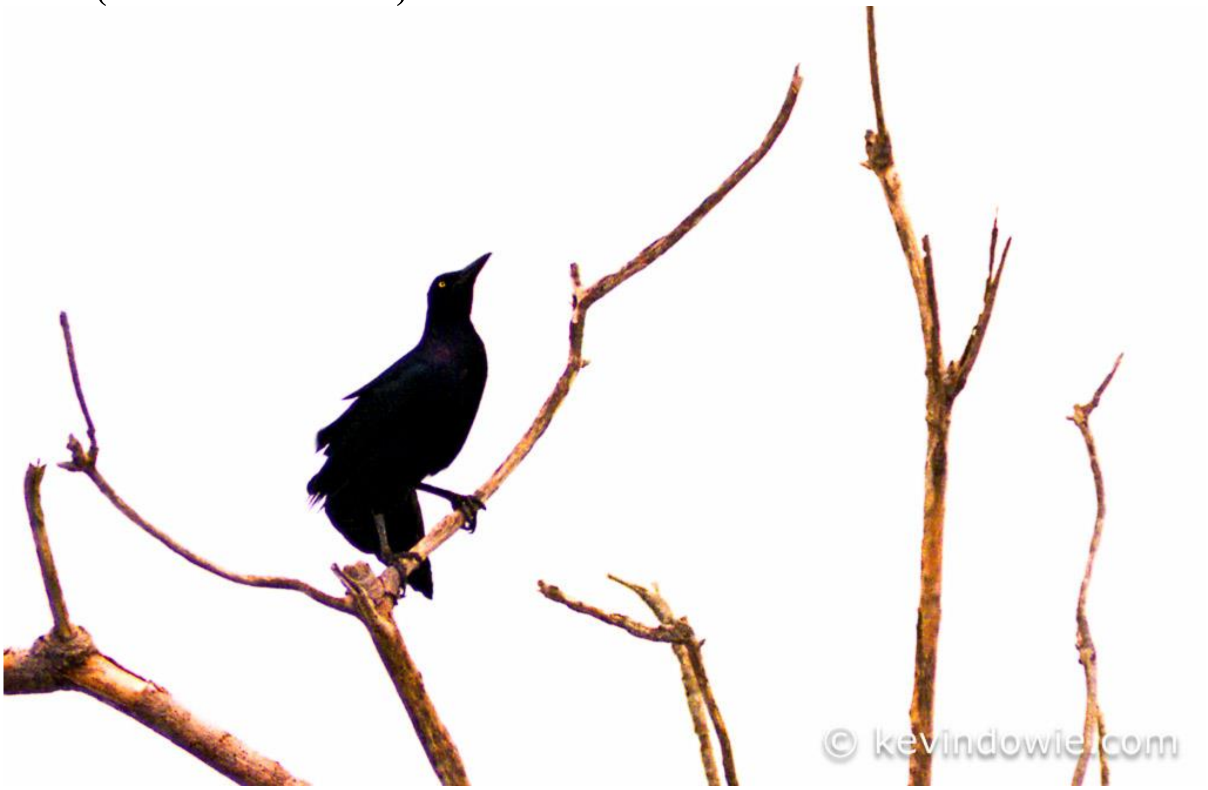

FIGURE 5. Species of amphibians, reptiles and birds from mainland Ecuador that could be potential hitchhikers in the Galapagos islands.