Chapter 10
Domestic and Peridomestic Animals in Galapagos: Health Policies and Practices

Luis R. Padilla, Nicole Gottdenker, Sharon L. Deem, and Marilyn Cruz

Abstract The wildlife of the Galapagos Islands faces the threat of disease due to spillover from introduced domestic and peridomestic species. Many domestic species benefit the roughly 25,000 residents and 250,000 visitors that travel to the islands every year. Although expanded human activities and the necessary agricultural and trade practices to support them are a potential concern for long-term sustainability of endemic species, the thriving economy behind this prime ecotourism destination is a possible asset and solution to protect it. Local agencies and strong, comprehensive management policies that are adaptable to rapidly changing conditions must be in place to guard against known and unknown disease threats.

Keywords Introduced species • Disease threat • Pathogen spillover • Conservation agencies

10.1 Introduction

Europeans arrived in the Galapagos Islands in the 1500s, and the islands have been permanently inhabited by humans since the 1800s. In the last two centuries of human settlement, many animal species have been introduced for agricultural use, human

L.R. Padilla (✉)
Department of Animal Health, Saint Louis Zoo, St. Louis, MO, USA
e-mail: padilla@stlzoo.org

N. Gottdenker
Department of Veterinary Pathology, University of Georgia, Athens, GA, USA
e-mail: gottdenk@uga.edu

S.L. Deem
Institute for Conservation Medicine, Saint Louis Zoo, St. Louis, MO, USA
e-mail: deem@stlzoo.org

M. Cruz
Agencia de Regulación y Control de la Bioseguridad y Cuarantena para Galápagos, Galápagos, Ecuador
e-mail: marilyn.cruz@abgalapagos.gob.ec

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companionship, and others have been inadvertently introduced as the result of human activities. Habitat modification and degradation by humans or introduced animals, globalization of commerce, trade, transport, and the ease of international travel have been driving factors for recent introductions. Continued introduction of species exotic to the Galapagos Islands is a significant threat whose impact is difficult to predict. Rapid population growth, tourism, and the need to support human activities in the Galapagos Islands present challenges that, while not unique to this archipelago, require mitigation practices to protect and support its unique endemic biodiversity.

The effects of introduced species on endemic species are well documented elsewhere and include direct and indirect competition, predation, morbidity, and mortality caused by introduced pathogens. Infectious disease spillover from introduced to native species is a significant and potentially catastrophic threat to island endemic species, as they may have evolved in the absence of many pathogen pressures. In order to maintain healthy, robust, and self-sustaining populations of endemic species, comprehensive management policies must be in place to prevent disease introductions and cannot be limited by only mitigating the known species or the pathogens that they are known to carry: they must be based on best practices to exclude possible as well as known risks.

The Galapagos Islands is an area of rapid, recent population growth. A 2015 census by the Ecuadorian National Institute of Statistics and Censusing (ecuadorencifras.gob.ec) showed that the population had grown roughly by 9.5% in the previous 5-year period to 25,244 residents. The tourism industry is booming, with 223,587 visitors in 2015 (Boletin Galapagos 2015), and averaging 13 days per visit. Tourism revenue in the Galapagos Islands in 2015 was an estimated 268 million US dollars. Supporting this thriving tourism industry and growing local population creates a high demand for agricultural production, imports, and other services to sustain them. The people of Galapagos (residents and visitors) are as much a part of the current Galapagos Islands and its heritage as the endemic wild species that make it a prime global ecotourism destination. The conservation and preservation of the Galapagos Islands hinges directly on the success of efforts to manage the interplay between humans, domestic animals, wildlife, and ecosystems.

An understanding of the existing policies and the agencies that establish them, as well as what threats they mitigate, is important to continually revise and strengthen the necessary long-term sustainable management practices. Because threats are likely to change over time, agencies and policies must be accordingly adaptable. Without these policies, unmitigated anthropogenic forces threaten to become the major evolutionary force in the Galapagos Islands (Deem et al. 2010a). Chapter 2 (Colonization of Galapagos birds—identifying the closest relative and estimating colonization) summarizes the 12 bird species that were introduced by humans and how they made it to the Galapagos Islands, and acknowledges the threat of pathogen introduction and transmission to native birds. In this chapter, we first summarize disease threats that introduced species pose to native species. These threats can be grouped into some general categories:

1. By causing habitat degradation and/or loss, or through ecological interactions such as competition or predation, introduced species can impact the population size and distribution of native species, increasing the severity of a disease epidemic on reduced populations (or more densely distributed populations).
2. By modifying habitat, introduced species can increase the habitat's suitability for maintaining a pathogen.
3. By serving as primary sources or vectors of infectious disease, introduced species can transmit pathogens to naive and susceptible endemic species.
4. By serving as maintenance hosts for diseases with epizootic potential, introduced species can increase the possibility of outbreaks in the endemic populations.
5. By introducing their own host-adapted strains of common pathogens, introduced species may alter the prevalence of existing, circulating pathogen strains, possibly diluting the endemic strains that may have co-evolved with endemic host species. An endemic species may then be exposed to a different strain, increasing the likelihood of disease epizootics.
6. By changing the social structure, behavior, and population dynamics of native species, introduced species can lead to altered disease transmission processes in native species.
7. By being managed in some way that changes resource availability (food, water, shelter, nest sites), introduced species can lead to altered native species habitat use, exposure to high-risk environmental factors, predation, or altered social dynamics that change the rate of pathogen transmission.

Mitigating threats to native species is far more complex than a theoretical elimination of a pathogen or an introduced species. Eradication of some introduced, invasive species and restoration of the former habitat is the ideal scenario in many instances, but is not feasible for all species and may not necessarily be advantageous in the context of a balanced, sustainable management strategy. Healthy domestic agricultural species can have a significant role in sustaining local economies and indirectly maintaining healthier ecosystems. Policies should be aimed at managing the domestic and peridomestic animal populations (through regulation, population control, maintenance of healthy animals, and eradication where applicable), mitigating the risk of disease transmission and, mitigating the threat of inadvertent introductions, and protecting habitats from damage by animals. In addition, despite the focus on individual species and specific diseases being introduced by them, a growing realization is that the disruption of the processes that maintain balanced, healthy ecosystem is likely to have much more profound and persistent effects on the overall maintenance of biodiversity in areas of high endemism.

This chapter has three main parts: the regulatory agencies and their jurisdiction within the Galapagos Islands, the known and possible pathogen threats to specific native taxonomic groups, and the possible action items that have been identified to continue to mitigate these risks.

10.2 Agencies and Their Responsibilities

The people of the Galapagos Islands and the Ecuadorian government have long recognized the importance of biosecurity in preserving the uniqueness of this ecological resource. Roughly 97% of the islands remain uninhabited by humans, and efforts to maintain pristine wild ecosystems are aimed at the long-term sustainability of this top ecotourism destination and national source of pride. Current regulations for maintaining biosecurity in the Galapagos Islands are under the jurisdiction of the Agency for Regulation and Control of Biosecurity and Quarantine for Galapagos, also known as "ABG" for its Spanish acronym (*A*gencia de Regulación y Control de la *B*ioseguridad y Cuarentena para *G*alápagos; bioseguridadgalapagos.gob.ec). The ABG was established in 2012 as a technical public entity under the Ministry of the Environment of Ecuador, to increase biosecurity in the Galapagos Islands, increase operational and budgetary efficiency of allocated resources, and further advance technical capacity-building efforts. The ABG has two technical Directorates: the Directorate of Normatives and Prevention, and the Directorate of Surveillance and Quality Control for Biosecurity.

The ABG plays a central, crucial role at the interface of human, animal and wildlife health. Through multiple initiatives, the ABG prioritizes disease containment and prevention, as well as population control of domestic species. Some of these initiatives include pet identification registries, animal import/export regulatory services, disease and pest monitoring (including invasive species like Giant African Snails, introduced big-headed ants and fruit flies), disease surveillance, inspections at ports of entry, and efforts to improve the general health of agricultural and domestic species. Improved farming and disease prevention, screening, and containment practices are likely to improve efficiency and reduce the numbers of animals while still meeting agricultural demands and attempting to minimize detrimental environmental effects. Activities have included advanced training on milking practices, free dog and cat spay and neuter campaigns, deployment and training of scent detection dogs for biosecurity, and disease surveillance for livestock health (including equine babesiosis, classical swine fever, foot and mouth disease, brucellosis, and other cattle infectious diseases). The ABG has been providing support to the Galapagos National Park by conducting molecular screening of captive-raised Giant tortoises in the repatriation program to detect herpesvirus and mycoplasmal pathogens. As ABG continues to grow to fulfill its mission, a key initiative will be expanding the scope of their diagnostic capabilities and providing infrastructure for disease surveillance of domestic, peridomestic, wild and feral animals.

The Galapagos still has a policy against the importation of dogs and cats, and until recently, the use of vaccines was prohibited (Levy et al. 2008). Following a technical review and risk analysis, the regulations were updated through a resolution (Resolución D-ABG-028-03-2017) in March 2017 to allow the importation of domestic dog vaccines, specifically against canine distemper virus, canine parvovirus, canine adenovirus Type II, *Leptospira spp*., and canine hepatitis. The resolution authorizes the ABG to import, control, and apply these vaccines, and the change was partly enacted to avoid the spread of canine distemper into the native wildlife. Avoiding the introduction of risky products into the Islands has been a priority for the ABG, and the agency has expanded the availability of information through online resources to increase clarity prior to arrival, and has instituted more severe penalties when the existing regulations are not followed.

The Galapagos National Park (GNP), also under the auspices of the Ministry of the Environment of Ecuador, is responsible for protecting and preserving ecological integrity and biodiversity of the terrestrial and marine ecosystems of the Galapagos Archipelago (www.galapagos.gob.ec). Under its many strategic objectives, the GNP recognizes its complementary role in protecting the Galapagos ecosystems within the human inhabited areas. The GNP also promotes an adaptive management approach for the National Park and the Marine Reserve, based on scientific knowledge to make decisions within contexts of socioeconomic and environmental conditions of the archipelago. The GNP issues scientific permits for conducting work on the islands and ensures that disease and species introductions are properly mitigated. Under its four technical directorates (Directorate of Ecosystems, Directorate of Environmental Affairs, Directorate of Environmental Education and Social Involvement, and the Directorate of Public Use), the GNP takes a multidisciplinary approach to protecting the integrity of the Galapagos ecosystems and respective ecological processes. The GNP has set expected standards of responsible behavior by scientists conducting work in the islands in the Field Guide for Research. This guide includes existing protocols to minimize the impact of scientists and visitors in the areas, with particular interest in avoiding the introduction or spread of non-native species. It includes protocols for management and research activities, including whether these occur on land or aboard a vessel, camping in uninhabited or inhabited islands, transporting living organisms, or handling scientific specimens. Failure to comply with these protocols may result in permits being revoked, scientific activities being cancelled and even legal prosecution under the Organic Law of Special Regime of the Galapagos Province, known as LOREG for its Spanish acronym (Ley Orgánica de Régimen Especial de la Provincia de Galápagos). In 2015, LOREG was updated to be able to impose more significant economic penalties if the law is broken.

Ecuador's Ministry of the Environment is responsible for managing the Fund for Control of Invasive Species in Galapagos, or FEIG for its Spanish acronym (Fondo de Control de Especies Invasoras de Galapagos). This fund was set up from private and public donations with the intent of allocating necessary resources for implementing the control of invasive species. Recent initiatives under the fund have included the control of invasive fruit flies, the African giant snail and invasive wild berries. Implementation of various initiatives under the fund may be done by a primary agency such as the ABG or the GNP, and is usually done in collaboration with each other and local municipal government entities and support from NGOs.

The Charles Darwin Foundation (CDF) is a non-profit scientific agency registered in Belgium as an International Non-Profit Organization that has been working in the Galapagos Islands since 1959 under an agreement and in partnership with Ecuadorian government agencies to provide scientific support to conserve the Galapagos Islands. As one of the most recognizable agencies with a presence on the island, the CDF is a close partner to the GNP and a highly visible entity that welcomes and educates tourists and visitors to the islands. The CDF has its own team of scientists and has worked closely with the GNP by providing scientific support, hosting scientists, and leading scientific research initiatives. In recent years, these research initiatives have been focused on three major areas: invasive species, sustainability, and conservation management.

10.3 Threats: Hosts and Pathogens of Concern

In addition to direct effects that introduced species pose to native species, such as predation, competition for resources and modification of suitable habitat, introduced species carry the risk of disease introduction. Disease introduction is the most significant threat posed by introduced species. Establishing a baseline of the endemic pathogens of native fauna through regular disease surveillance leads to understanding the degree of existing risk for an epizootic to occur. It also leads to proactive, early detection of introduced and novel pathogens before they cause widespread morbidity or mortality. Baseline disease prevalence information is crucial to make accurate epidemiological models that could inform practical wildlife management and mitigation activities. This information, which should be frequently updated in real time, should reside with local agencies and be available to the local agencies.

The status of introduced vertebrates in the Galapagos has been described by many authors and summarized in Table 10.1. It is particularly notable that the peer-reviewed literature is limited in the documentation of diseases present in most of the agricultural species. While many authors have described the infectious disease risks of chickens (Gottdenker et al. 2005; Soos et al. 2008; Deem et al. 2012), dogs, and cats (Levy et al. 2008; Gingrich et al. 2010; Diaz et al. 2016), there is limited information on what is prevalent in cattle, goats, pigs, or equids. In recent years, the ABG has been conducting active and targeted surveillance to understand the prevalence of disease in a number of these agricultural species, and by implementing strict sanitation procedures when livestock are transported between farms, they have expanded the ability to detect disease and prevent its spread. Extensive surveillance done in cattle between 2014 and 2015 failed to show any evidence of foot and mouth disease, *Brucella abortus* or bovine leucosis virus, but did show that *Anaplasma marginale*, *Neospora caninum*, and Infectious Bovine Rhinotracheitis (IBR) virus are present at a high seroprevalence (64%, 40.1%, and 45.8% respectively). In addition, bovine viral diarrhea was detected at a 6% prevalence by serological screening (Velez 2016). This active surveillance has allowed the ABG to declare the Galapagos Islands free of food and mouth disease, and efforts are ongoing to declare them free of classical swine fever.

Regardless of taxon and the diversity of known risks that they pose to endemic wildlife and ecosystems, the biggest threat resides in the large vacuum of unknown and possible risks. Policies must be comprehensive enough that they mitigate known risks and rely on best practices to compensate for theoretical but possible risks brought by any introduced species. There are some known and possible disease risks that are dictated by taxonomic susceptibility, and although this list is by no means comprehensive, it presents the diversity of disease threats to some of the

Table 10.1 Notable species introduced to the Galapagos Islands and the risks they pose to native wildlife

Species	Risk	Pathogens Documented	Distribution	Comments
Domestic poultry (chickens, turkeys, Guinea fowl, peafowl, Asian quail)	Disease introduction and maintenance	Gottdenker et al. (2005), Soos et al. (2008)	Inhabited islands	High risk of disease introduction, transmission and maintenance for all bird species
Domestic waterfowl (ducks, geese)	Disease introduction and maintenance		Santa Cruz, San Cristóbal, Isabela	Significant risk to all bird species, seabirds and aquatic birds in particular. Strains of avian influenza may establish in domestic waterfowl
Domestic pigeons (rock doves)	Disease introduction and maintenance	Harmon et al. (1987) and Padilla et al. (2004)	Eradicated from the islands (Philips et al. 2012)	All birds susceptible to shared diseases, but in particular Galápagos doves (*Zenaida galapagoensis*) due to taxonomic relationship
Cattle egrets (*Bubulcus ibis*)	Disease maintenance Predation of native species Physical damage to mangroves, excess phosphorous and nitrogen in wetlands		Can reach all islands, breeding in mangroves and migrate to feed in agricultural grazing areas	All bird species, possible zoonotic disease reservoir (Phalen et al. 2010) Some trematodes are associated with egret species and are capable of infecting multiple species if the competent hosts are present
Smooth billed Ani (*Crotophaga ani*)	May predate native invertebrates and nestling birds May have a role in seed dispersal and in particular the invasive *Rubus niveus* berry (Guerrero and Tye 2011)		Widely distributed (see Philips et al. (2012))	Role in infectious disease transmission is unknown. Known to predate finch nestlings (Connett et al. 2013)
Red-masked parakeet (*Aratinga erythrogenys*)	Disease introduction Habitat modification		Not likely to be established	Psittacines can serve as reservoirs of *Chlamydophila psittaci*, especially if they originate from captive managed flocks or individual pets without proper biosecurity

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Species	Risk	Pathogens Documented	Distribution	Comments
Domestic cats *(Felis silvestris Catus)*	Predation of native species, Disease introduction and maintenance	Levy et al. (2008) and Deem et al. (2010b)	All inhabited islands	Cats are general, indiscriminate predators capable of impacting populations of many species *Toxoplasma gondii* is a serious protozoal parasite with an exclusively feline host known to affect a multitude of species (Dubey et al. 2003, Levy et al. 2008 and Deem et al. 2010b)
Domestic dogs (*Canis lupus familiaris*)	Predation of native species Disease introduction and maintenance	Levy et al. (2008), Gingrich et al. (2010) and Diaz et al. (2016)	All inhabited islands	Dogs can predate all species, but have impacted penguins and land and marine iguana populations (Barnett and Rudd 1983, Philips et al. 2012) *Dirofilaria immitis*, canine distemper virus, canine adenovirus, and parvovirus may be common (Levy et al. 2008) and a risk to native pinnipeds. Intestinal parasites are a risk to many species (Gingrich et al. 2010)
Donkeys and horses (*Equus asinus* and *Equus caballus*)	Habitat modification (trampling, compaction) Competition for food with native herbivores (tortoises, iguanas) Overgrazing Damage to nests by trampling Viral infectious disease introduction and maintenance	Limited published accounts	Domesticated horses are found in all inhabited islands, feral donkeys are found in Santa Cruz, Isabela and San Cristóbal (Philips et al. 2012)	Tortoise, land iguana, and ground nesting bird nests can be trampled. These species compete for food resources with the native herbivores Tortoises and other reptiles, and many bird species may be susceptible to some of the viral, arthropod-vectored encephalitides of equids

Pigs (*Sus scrofa*)	Predation of native animal and plant species Habitat modification and degradation Spread of invasive plant species and seed dispersal	Limited published accounts in peer-reviewed literature, but internal monitoring is ongoing by ABG	Santa Cruz, San Cristóbal, Isabela Floreana	Predation and tramping of nests, especially chelonian eggs and ground-nesting birds is a concern. Swine have a role in the epidemiology of zoonotic strains of avian influenza virus Efforts are underway to certify the Galapagos Islands as free of classical swine fever
Cattle (*Bos taurus*)	Habitat modification (overgrazing, tramping and compaction) Damage (collapse) of bird nest burrows Seed and plant dispersal Native plant damage Competition for food with native herbivores (tortoises, iguanas)	Limited published accounts in peer-reviewed literature, but internal monitoring is ongoing by ABG (Velez 2016)	Domesticated in Santa Cruz and Floreana, feral in Isabela and San Cristóbal	Tortoise, land iguana and ground nesting bird nests can be trampled. These species compete for food resources with the native herbivores Some ectoparasites of cattle (ticks) may affect other species, and many species are vectors for specific diseases. *Rhipicephalus microplus* ticks are common on Galapagos cattle. Serology surveillance by ABG has shown a high seroprevalence for *Anaplasma marginale*, *Neospora caninum* and infectious bovine Rhinotracheitis (IBR) (Velez 2016)
Goats *(Capra hircus)*	Habitat modification (overgrazing, tramping and compaction) Facilitate invasive, alien plants Seed and plant dispersal Native plant damage and impaired regeneration by consuming seedlings Competition for food with native herbivores (tortoises, iguanas)	Limited published accounts in peer-reviewed literature	Santa Cruz San Cristóbal Isabela	The effect of high populations of feral goats on the landscape has been one of the most well-documented environmental issues in the Galapagos, and eradication efforts have been some of the most successful programs Tortoise,land iguana and ground nesting bird nests can be trampled. These species compete for food resources with the native herbivores

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Table 10.1 (continued)

Species	Risk	Pathogens Documented	Distribution	Comments
Domestic sheep (*Ovis aries*)	Similar effects to those of goats and cattle, but not a significant issue in the Galapagos Islands		Historically farmed, not common	
House mice (*Mus musculus*)	May affect native plant mortality May contribute to seabird mortality and survival through predation (Wanless et al. 2007), or through unknown mechanisms such as disease Vectors of diseases that can affect other species		Present in at least 8 islands in the archipelago (Philips et al. 2012)	The role of mice and other rodents as disease vectors to other vertebrate species, and as agents of zoonotic diseases is well documented worldwide The use of rodenticides to control mice can have an effect on non-target species
Norway rats (*Rattus norvegicus*) and black rats (*Rattus rattus*)	Rats can be predators of the eggs and hatchlings of many species, both birds and reptiles (including seabirds and tortoises) Introduced rats compete with the native rice rats and have an effect on local populations (Harris and Macdonald 2007) Rats are disease vectors to some infectious diseases of mammals		Many islands, although they have been eradicated from several islands	Rats can predate seabird species' nests (eggs and nestlings), as well as tortoises

fauna of the Galapagos Islands. Humans have been excluded from the list, as anthropogenic effects on endemic species are much bigger in scope than the intent of this chapter. However, of particular note is the ongoing global concern of antibiotic-resistant bacteria from medical and agricultural uses emerging in wild animal populations. Animals living in closer proximity to humans are likely to share bacteria of human origin, and sometimes the exposure to antibiotics does cause a shift in internal host bacterial communities. In Galapagos, bacterial isolates from land iguanas, marine iguanas, Galapagos tortoises, and seawater suggest that living in proximity to human settlements potentially has a higher exposure to human enteric bacteria (Wheeler et al. 2012).

10.3.1 Terrestrial Mammals

There are very few native terrestrial mammals in the Galapagos and these are limited to four species of rice rats and two species of bats. Introduced rats carry a number of pathogens that can be transmitted to the endemic rice rats. In addition, all species of mammals are susceptible to rabies, a lethal virus that could be potentially introduced and spread by unvaccinated dogs or cats.

10.3.2 Marine Mammals

For purposes of this chapter, the group of marine mammals includes the 25 cetacean species (whales and dolphins) that spend their lives at sea or as oceanic migrants (within the Galapagos Marine Reserve), but also the two Otariid pinniped species that spend portions of their lives living on the coast. The Galapagos sea lion (*Zalophus californianus wollebacki*) is an endemic subspecies, while the Galapagos fur seal (*Arctocephalus galapagoensis*) is an endemic species. Pinnipeds are susceptible to a number of infectious diseases carried or transmitted by domestic carnivores (dogs and cats), including but not limited to canine distemper, rabies virus, and influenza virus. In addition, certain parasitic protozoal diseases such as *Sarcocystis neurona, Toxoplasma gondii,* and *Neospora caninum* have been recognized pathogens of marine mammals worldwide, and these are often associated with contamination of waterways from domestic carnivore feces (Dubey et al. 2003). Domestic dog feces are a source for intestinal parasites that can infect other carnivores, and have been documented in the Galapagos (Gingrich et al. 2010; Diaz et al. 2016). The presence of *Toxoplasma gondii* has been recognized in the Galapagos Islands in domestic cats and some bird species (Levy et al. 2008; Deem et al. 2010a; Verant et al. 2013), and cattle are commonly seropositive to *Neospora caninum* (Velez 2016). Although current policies prohibit the importation of dogs and cats, both species could be inadvertently introduced in ships, or illegally smuggled as companions. Dogs and cats are a risk for numerous infectious diseases, and likely serve as reservoirs for these carnivore pathogens (Levy et al. 2008). The role of both dogs and cats as infectious disease reservoirs is even more significant in the absence of vaccination programs.

10.3.3 Birds

Although no bird has become extinct in the Galapagos since the arrival of humans in 1535, the risk of disease being introduced to the Galapagos avifauna is significant, and probably of higher catastrophic potential than any other taxonomic group. Of the 152 bird species recorded in the Galapagos, 61 species are considered residents, 28 are endemic species and 16 are endemic subspecies. Sources of potential disease introduction are agricultural species (in particular poultry), migratory birds, and introduced vectors of disease (such as mosquitoes). In addition, anthropogenic environmental changes could lead to modified social interactions or variable dispersal or congregations of individuals, leading to altered disease transmission dynamics. Colonial species, most of which are seabirds nesting in clusters along shorelines, are at particular risk in the event of single environmental disasters or disease outbreaks.

Many pathogens of domestic poultry have been identified in the Galapagos Islands (Gottdenker et al. 2005; Soos et al. 2008; Deem et al. 2012) and pose an immediate concern of disease transmission if biosecurity practices are not in place. Of particular concern is the potential of Newcastle disease (avian paramyxovirus-1) becoming established in endemic, susceptible species of small population sizes, such as the Galápagos penguin (*Spheniscus mendiculus*), the flightless cormorant (*Phalacrocorax harrisi*), or the lava gull (*Larus fuliginosus*) (Gottdenker et al. 2005). Backyard poultry, where low densities of birds roam in peridomestic areas, and commercial poultry farms, where chickens are confined at high densities in a single area for a limited time until they go to market, pose significant, but different, risks of disease spillover to native wildlife (Gottdenker et al. 2005; Soos et al. 2008). On one hand, backyard poultry often roam around human settlements and may have frequent direct contact with wild birds in the peridomestic environment which may increase transmission risk, but they are at lower densities, have varying age structures, and often include long-lived genetically diverse animals in their populations that have a large amount of acquired immunity to pathogens, effectively reducing infectious disease transmission, spread, and severity. However, large-scale intensive chicken farm operations, despite biosecurity measures that attempt to reduce within-flock infectious disease transmission, consist of very high densities of single-aged, short-lived, and genetically uniform animals, which can provide a dangerous amount of susceptible epidemic fuel for pathogens with high basic reproduction numbers, creating a very high concentration of pathogens that could easily spill-over into susceptible wild species by direct or indirect contact, or vector-borne transmission. Management of poultry waste from larger scale operations is a potential concern, should such waste contain infectious agents (Gottdenker et al. 2005). *Toxoplasma gondii*, a protozoan pathogen with an obligate felid host, is one pathogen with serological evidence of exposure in Galapagos aquatic birds, and carries significant potential for mass mortalities of bird species (Deem et al. 2010a).

A well documented and impactful introduction has been the parasitic *Philornis* fly. *Philornis downsi* is an obligate dipteran bird parasite accidentally introduced to the Galapagos Islands sometime in the 1960s and documented to parasitize nestlings roughly 30 years later (Causton et al. 2013; Chap. 9, this volume). Although the adult fly has a similar lifestyle to other Muscid flies, feeding on fruit or decaying vegetation, they deposit their eggs on bird nests and the larvae parasitize nestlings. Parasitism of finches by *Philornis* larvae has been a significant contributor to the decline of some populations, in particular the endangered mangrove finch (*Camarhynchus heliobates*) (Fessl and Tebbich 2002; Koop et al. 2011). Management efforts to control the fly have proven extremely challenging, in part due to gaps in knowledge in the biology of *P. downsi*, and because the fly is widespread throughout the archipelago. A recent research initiative involving the provision of permethrin-permeated nesting material may be an effective, targeted mitigation effort (Knutie et al. 2014).

Avian malaria, the disease caused in birds by Apicomplexan blood parasites, poses a significant pathogenic threat to some of the species of endemic birds in the Galapagos. Many hemoparasites are likely to have co-evolved and co-adapted with their vertebrate hosts, but the introduction of novel parasites to non-adapted species can have extreme effects in mortality and morbidity at the population level. Competent invertebrate, blood-feeding hosts are essential to allow completion of the protozoan life cycle, transmit the parasite, and cause disease. The introduction of *Culex quinquefasciatus* to the Hawaiian Islands, and its ability to serve as a competent host to *Plasmodium relictum,* an agent of avian malaria, is recognized as a significant contributor in the extinction of a large number of endemic Hawaiian bird species (van Riper et al. 1986). Both *Culex quinquefasciatus* (Whiteman et al. 2005) and *Plasmodium sp.* (Levin et al. 2009, 2013) have been identified in the Galapagos Islands, and both are likely recent arrivals. Multiple lineages of *Plasmodium sp*. have likely entered the Galapagos via migratory birds (especially bobolinks) and not established themselves, but the possibility exists that a *Plasmodium* lineage has established itself in the islands with a local host based on its detection at multiple sites throughout multiple years (Levin et al. 2013). Unlike the situation in the Hawaiian Islands, neither morbidity nor mortality of any Galapagos bird species has been attributed to *Plasmodium sp.*, although a serological survey of Galapagos penguins showed a very high prevalence of exposure between 2004 and 2009 (Palmer et al. 2013). *Plasmodium spp.* are known potential pathogens of penguins housed under human care (Fix et al. 1988; Grim et al. 2003). It has been speculated that *C. quinquefasciatus* larvae were introduced to the Galapagos Islands in standing water on transport vessels, but it is possible that additional inadvertent introductions have occurred and may continue to occur through residual standing water within compartments in airplanes, ships, or cargo (Peck et al. 1998; Whiteman et al. 2005; Bataille et al. 2009b). This freshwater-dependent mosquito is likely to be more common around human settlements where fresh water is available, but can spread rapidly during rainy seasons (Whiteman et al. 2005) or weather events by using rain puddles.

Mosquitoes such as *C. quinquefasciatus* and *Aedes taeniorhynchus* can also be a source for introducing or spreading other arthropod-borne diseases that may enter in domestic species or be present as circulating viremias in migratory birds, including West Nile Virus, Equine Eastern and Western encephalitides (Bataille et al. 2009a). Modern trade and commerce practices pose a risk for the emergence and spread of many arhboviruses (Pfeffer and Dobler 2010). The inadvertent transport of mosquitoes in airplanes has been predicted to be the most significant risk of West Nile virus introduction to the Galapagos Islands (Kilpatrick et al. 2006), and may currently be the single most significant risk for mosquito and arthropod-borne disease introduction in general (see management response in Chap. 12, this volume). Avipoxviruses are a group of avian taxa-specific viruses that can also be transmitted by blood-feeding insects, but because the transmission is by mechanical routes, the species of mosquito is less relevant. Several avian pox strains do occur in the Galapagos (Thiel et al. 2005), and although likely to be taxa-specific, distribution patterns could be affected by the presence or absence of different arthropod vectors or changes in disease transmission dynamics caused by the various domestic animal introductions.

The Galapagos penguin, with a population of roughly 2000 individuals in a relatively limited geographic distribution, has been classified as endangered by the IUCN (IUCN 2015). Historical El Nino events have had a significant impact on population numbers: from 3000 to 699 in the 1982–1983 event, and from 2252 to 779 in the 1997–1998 event (Vargas et al. 2005). Following each reduction, the population has been slow to rebound, in part due to a low reproductive rate and high juvenile mortality (Vargas et al. 2006). The role of infectious disease during these population drops is not known. During El Nino-Southern Oscillation events, changes in oceanic currents and water temperatures lead to decreased marine productivity and less prey available to penguins. A concurrent increase in rainfall leads to optimal conditions for mosquito breeding; and some mosquitos are vectors of lethal blood parasites known to affect penguins as previously mentioned.

10.3.4 Reptiles

The Galapagos tortoise (*Geochelone elephantopus*) is probably the most iconic of the Galapagos reptiles, but is by no means the only one. Land iguanas and lizards are present on the islands, and the marine iguanas are just as unique and iconic as the tortoises for which the islands are named. A long-term Galapagos tortoise repatriation program, whereby many tortoises are raised at the breeding center in Santa Cruz Island and re-introduced to their native islands, has been successful for many years. Disease has not been considered a significant factor in the Galapagos tortoises, and little documentation exists of the diseases affecting them. Anecdotal accounts of mortality from Santa Cruz-reared tortoises has alluded to tortoises that have died of pneumonia, and infections of the intestinal or respiratory systems, but the actual pathogens have not been characterized in the published literature. Shell diseases are a common presentation in many tortoise species, and although many are superficial opportunistic problems, there are instances of aggressive fungal invasion in some species (Stringer et al. 2009). Although it is assumed that these may be opportunistic infections and common in rearing situations, further investigation of these cases would be beneficial to understand the infectious disease potential as these animals are repatriated. In any captive breeding and repatriation program, there is a theoretical risk that the breeding stock itself could serve as agents to introduce, amplify, or maintain a novel pathogen into the ecosystem. This is not a very likely risk for the Galapagos tortoise at current time and based on current knowledge, although the possibility exists for tortoises to become symptomatic from mycoplasmal or herpesviral pathogens that are thought to be enzootic in many tortoise species (Martel et al. 2009). In addition, there is a risk that tortoises could be exposed to arthropod (mosquito) vectored encephalitides, since some reptile-feeding mosquitoes have been documented in the islands and mosquitoes have played a significant role in the maintenance of viral diseases once introduced and established in some reptile populations (Unlu et al. 2010). Viruses such as West Nile virus and eastern equine encephalitis can be a threat to reptile populations, and some reptiles could even serve as significant amplifier hosts to some of these viruses (Klenk et al. 2004). As previously mentioned, air traffic is currently the most likely threat to arthropod-borne disease introduction. Introduced lizards (primarily gecko species) could serve as vectors to a number of lizard-specific viruses.

Hard-bodied ticks of the *Amblyomma* genus are known to parasitize the giant tortoises and other Galapagos reptiles (lava lizards and iguanas) (Keirans et al. 1973). There is potential for ticks to move between cattle and reptiles, and *Amblyomma spp.* are the known hosts for many diseases worldwide even if none have been recognized in Galapagos.

In recent years, fungal diseases have been identified as emerging pathogens of many wild animal species (Padilla 2011). Reptiles are no exception, and while the literature is rapidly evolving on pathogenicity and transmission dynamics of many of these organisms, significant gaps exist (Paré and Sigler 2016). This lack of knowledge of possible pathogens and their transmission dynamics warrants a conservative approach to biosecurity measures. Some mycotic pathogens are opportunistic and exploit the host's compromised immune status, concurrent infections, or an ectotherm's body temperature that favors fungal growth. However, many of the recently identified pathogens appear to be primary pathogens of ectotherm species. In many cases of fungal diseases affecting wildlife, the true nature is only recognized once the disease reaches epizootic proportions or is perceived as a zoonotic threat (Padilla 2011).

A seemingly emerging disease of epizootic potential in sea turtles is systemic coccidiosis, usually attributed to *Caryospora cheloniae.* Initially recognized in marine cultured-reared green sea turtles (Leibovitz et al. 1978), the disease has been implicated in several epizootics and mass mortality events (Gordon et al. 1993;

Chapman et al. 2016). Little is known about the epidemiology of this disease, and even the infectious organism that causes it. Recent molecular diagnostic tools should help elucidate this disease, the species of coccidia that cause it, and what are relevant risk factors to understand its transmission and protective measures to avoid it (Chapman et al. 2016). Little is known on how *Caryospora cheloniae* (or any systemic coccidia) is spread in sea turtles. Similarly, chelonian intranuclear coccidiosis is also a systemic, poorly understood coccidial disease that affects terrestrial chelonians (Garner et al. 2006).

Analysis of sea turtle eggs in other parts of the world has shown evidence of exposure to polluted effluent from humans and animal waste. (Al-Bahry et al. 2009). This is a theoretical concern with turtles around the human-inhabited islands of the Galapagos, but with the long distance migration of sea turtles it is difficult to realistically quantify how unique or impactful this could be to sea turtle populations. A survey of green sea turtle mortality in Galapagos during the 2009–2010 nesting season from three nesting beaches showed a disproportionate amount of anthropogenic interactions playing a role in mortalities (Parra et al. 2011). Interaction with fisheries and boat collisions were significant.

Fibropapillomatosis is a common proliferative disease of free-ranging sea turtles that has been seen in all species except for leatherback turtles (*Dermochelys coriacea*), although it is primarily a disease associated with green sea turtles (*Chelonia mydas*). It has a global distribution, predominantly in tropical regions. A herpesvirus is involved, but the disease is likely multi-factorial and its presentation seems to vary geographically. Environmental factors (pollution, heavy metals), host immunity and local population genetics likely influence the manifestation and spread of disease. Fibropapillomatosis is most prevalent in turtles near human inhabited shorelines, around areas with high human density and areas with degraded ecosystems, including areas affected by agricultural runoff (Aguirre and Lutz 2004).

10.4 Action Plan

Introduced species and the diseases they carry will always loom as a threat to the wildlife of the Galapagos Islands, and understanding the regulatory agencies that oversee and enforce them is crucial to the implementation of action plans aimed at protecting the native wildlife in perpetuity. The success of any conservation effort resides in the power and engagement of the local authorities and citizens who want to protect their natural heritage and make it a sustainable economic resource.

A workshop held in Santa Cruz in 2015 (Workshop Summary 2015) convened a large number of stakeholders and subject matter experts to prioritize needs and develop a logistical framework to address the current challenges. The collaboration between local agencies (including the ABG, the GNP, CDF, and other partners) is crucial. Chapter 12 describes the need and framework for local collaboration in the context of conservation. External scientists must continue to collaborate and invest in the long-term sustainability of conservation initiatives through in-country capacity building.

The 2015 workshop group identified seven main priorities, of which some action plans are already being implemented.

10.4.1 Priority 1

Establish an adequately staffed, equipped, and biosecure laboratory facility that can quickly diagnose, detect, and maintain diseases in real time. Secure, sustainable, and long-term operational funding is essential for this priority to have the intended effect. This facility would be basically equipped for diagnostic services in clinical pathology and microscopy, molecular biology, parasitology, microbiology, serology assays, and general pathology. A local diagnostic lab would improve the turnaround time to get results for disease investigation and surveillance, as well as for quarantine and biosecurity maintenance. The ABG is a logical agency to take the leadership on such a diagnostic facility.

A secondary goal would be to incorporate a facility that allows for clinical management, treatment, and better understanding of disease syndromes affecting individual animals. For such a facility to be truly impactful, procedures must be in place to keep track of disease trends and diagnoses. The facility must remain true to the priority of a wildlife disease and detection facility, staffed by trained and competent veterinarians and diagnosticians, or could be at risk of becoming a permanent holding facility for individual animals with irreversible conditions that render them nonreleasable and become an undue burden on local resources.

10.4.2 Priority 2

Establish and refine wildlife health program policies and procedures. This initiative would include reviewing policies on domestic animal vaccination protocols and products used and reviewing and reinforcing policies for the prevention of entry of diseases in human-habituated islands. It would also include policies for preventing disease occurrence and altering host-parasite evolution, continued disease surveillance and developing emergency contingency plans to respond to unusual morbidity and mortality events.

Management policies in the Galapagos Islands should be continuously evaluated to critically determine if they are having the intended effect on overall health management and species conservation. A praiseworthy example is the aforementioned resolution (D-ABG-028-03-2017) signed into effect in March 2017 that allows the importation and use of domestic dog vaccines against significant canine pathogens. Prior to that, the policies prohibited all animal vaccinations in Galapagos. This policy was in place to contain the possibility of vaccine-related disease introduction from modified live strains, and may serve a diagnostic purpose in serological pathogen detection through surveillance efforts. A scientific technical review and risk analysis done in late 2016 led to a revision of the policy for domestic dogs through the newly enacted resolution, although it is still in effect for other species. As vaccine technology has advanced and safer vaccines are available, vaccines can be a barrier to prevent disease spread. In the absence of robust vaccination programs, susceptible animals that are already infected with infectious diseases may serve as a reservoir for maintaining the disease (Levy et al. 2008). The process that led to the ability to import and use canine vaccines is a model that can be used for all species: infectious disease surveillance led to a refined definition of perceived need, followed by a technical review and risk analysis, which was then put into action to halt the spread of high risk pathogens. Although it is possible that domestic dog vaccines had been used illegally in the past (Diaz et al. 2016), the regulation of vaccine products through the ABG will allow this to be a part of a comprehensive disease control, prevention, and monitoring strategy.

Currently, air travel into the Galapagos Islands must originate in either Quito or Guayaquil. These flights undergo appropriate inspection and disinfection to curb introduction of agents of concern (*see* Chap. 12, this volume). However, the bulk of cargo enters the islands by sea, and these ships undergo inconsistent methods of inspection and disinfection. Standardization of policies and continuity in how the knowledge is preserved and passed during staff changes is essential for this initiative to be fruitful. Without the needed continuity and consistency, the policies would be at risk of being exercises on paper that do not have a functional application.

Support should be in place to promote the science-based policies among the public and local residents through education and public relations campaigns. For example, a recent study has shown that despite successful dog sterilization campaigns implemented in Galapagos, the dog population in Santa Cruz island is higher than predicted, and it is believed that the local culture against surgically sterilizing dogs is a limiting factor to effectively control populations (Diaz et al. 2016). In cases such as these, enforcement of the policies could even be incentivized to promote acceptance and advance implementation.

10.4.3 Priority 3

Continue to invest in capacity building, technology advancement and continuity of knowledge and local expertise in animal health. This priority for capacity building and continuity of knowledge is crucial to everything else in any action plan. If technical expertise and knowledge leaves, the technology transfers become obsolete pieces of equipment. The scientific staff must be continually connected with scientific advances worldwide (*see* Capacity Building, Chap. 12 this volume). Technology transfer with limited transfer of expertise or continuity of expertise is a common hurdle that plagues many well-meaning but eventually unsuccessful conservation initiatives.

10.4.4 Priority 4

Establishment of a rehabilitation facility for treatment of chronically injured or diseased animals. For a rehabilitation facility to be successful the organization must have clear goals, triage, and resource prioritization decision trees, or they will be overwhelmed by the constant influx of injured or diseased individuals who could become permanent residents.

10.4.5 Priority 5

Develop a centralized data management platform that is easily accessible to all stakeholders. Access to data, in real time, is important to have the necessary objective information to implement wildlife management and policy decisions. If surveillance information is being generated through a diagnostic laboratory on site, this could simplify the number of steps and connections before the information comes back to Galapagos. There must be transparency and collaboration, and avoid the pitfalls of secrecy and individual territoriality over pet projects.

10.4.6 Priority 6

Standardize protocols to maximize the value of health-related information collected from live animals. Standardized protocols are useful for mining data and extracting epidemiological information. This is important to take full advantage of situations as they present themselves. Perhaps equally important is the continued training of on-site personnel for clinical problem-solving and health diagnostic approaches to rule in or rule out diseases of concern, and should be done in conjunction with Priority 3.

10.4.7 Priority 7

Establish a facility or relationship with an existing facility that will serve as a repository of all biological samples collected in the Galapagos Islands. Proper curation of all samples from the Galapagos should take place so that the samples are in one protected place as the property of the Ecuadorian government. If a new pathogen is detected in Galapagos, such a repository could allow agencies to "look back" and test previously collected samples to determine when and where that pathogen first showed up in historic samples.

The Galapagos Islands will always continue to be a unique biological resource and a prime ecotourism destination. The future is bright, with strong initiatives and engagement from local scientists and support from many partners. Animals—domestic, peridomestic, and wild, will continue to be present in the islands. The management of introduced species and surveillance for diseases that could be introduced are key components of protecting the Galapagos fauna in perpetuity.

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