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Review of One Health in the Galápagos Islands (Part 2): climate change, anthropogenic activities, and socioeconomic sustainability

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The Galápagos archipelago is a vast reservoir of terrestrial and marine biodiversity and is particularly susceptible to human, animal, and environmental impacts. Climate change, globalization, and the blurring of human-domestic animal-wildlife interfaces are poised to bring new threats and challenges to the region. A One Health perspective that simultaneously considers human, animal, and environmental health is imperative in assessing and mitigating the challenges facing the Galápagos Islands. Many challenges facing biodiversity in the Galápagos Islands can ultimately be linked to anthropogenic factors. In Part I of this review, we reviewed the impacts of invasive species and identified infectious diseases of importance. In Part II of this review, we discuss the impacts of climate change and ocean acidification, and highlight the effects of several direct anthropogenic activities, including tourism, overfishing, pollution, land use, and human-wildlife conflict. We also review the socioeconomic and political context of the Galápagos Islands, including current challenges in water and energy use, sanitation, and economic stability. We examine the importance of investment in local development for building resiliency and sustainability in the archipelago. Finally, we discuss the impact of the COVID-19 pandemic in the region. Throughout this two-part review, we build a cohesive picture of One Health in the Galápagos Islands by integrating past work, current needs, and emerging threats. We also consider overarching goals for conservation, ecosystem management, and socioeconomic sustainability that have been previously defined by both governmental and non-governmental stakeholders, and identify discrete, implementable, and interdisciplinary recommendations that will facilitate achievement of those goals.

KEYWORDS

Galápagos, One Health, planetary health, wildlife, conservation, endemic species, invasive species

1 Introduction

This two-part review outlines current and emerging challenges facing the Galápagos Islands and highlights the value of a One Health approach to understanding these factors and developing appropriate management strategies. In Part I, we outlined the historical context of biodiversity in the region and focused on the impact of introduced and invasive species, as well as infectious disease threats, and made suggestions for risk mitigation. We also discussed the regulatory bodies overseeing the development of ecological management strategies in the Galápagos Islands, and highlighted avenues for improvement in biosecurity measures, while emphasizing the importance of inter-sector collaboration. In Part II of this review, we demonstrate the interplay between socioeconomic stability in the archipelago and anthropogenic activities that also pose a threat to biodiversity, such as tourism, fishing, pollution, and the illegal wildlife trade. Finally, we synthesize recommendations from both parts of the review under four pillars: Education, Regulations and Infrastructure, Surveillance, and Research, with a goal of defining discrete and implementable recommendations to move towards a more sustainable future.

1.1 Socioeconomic context of the Galápagos Islands

The vast biodiversity of the Galápagos Islands has long attracted tourists. The first cruise ship visited the archipelago in 1934; by 1979, annual visitors numbered nearly 12,000. In 2019, the Galápagos National Park Directorate (GNPD) estimated 271,000 visitors (Galápagos National Park Directorate, 2019). As the primary economic industry, tourism contributes half of Galápagos Gross Domestic Product (GDP) and accounts for 71% of the job market, from guided tours, snorkeling and scuba diving, cruises, hotels, resorts, and restaurants (National Institute of Statistics and Census (INEC), 2017). From 1992 to 2007, the number of hotels and restaurants doubled and tripled, respectively (Epler, 2007). The steady rise in tourism also corresponded to a rise in immigration, with an annual growth rate approximately 4% higher than mainland Ecuador, and a population increase of over 400% between 1962 and 1990 (Bremner and Perez, 2002; Neira, 2016). Today, the Galápagos Islands are home to approximately 32,000 inhabitants (Galaípagos Government Council, 2021).

Fisheries, agricultural production, and lumber are also components of the Galápagos economic landscape. There are more than 50 species of fish of commercial interest and large overseas markets for spiny lobster and sea cucumber (Viteri et al., 2022). Challenges in fisheries management have led to exploitation of target-species, bycatch pressures on protected wildlife, and general habitat degradation, while fuel and fishing gear lead to marine pollution with downstream effects on endemic species. For example, sailfin grouper (*Mycteroperca olfax*), spiny lobsters (*Panulirus penicillatus* and *P. gracilis*) (Szuwalski et al., 2016), and brown sea cucumber (*Isostichopus fuscus*) (Wolff et al., 2012; Ramírez-González et al., 2020) populations have declined significantly (Usseglio et al., 2016; Watkins and Cruz, 2007). As of 2022, agricultural production focused mainly on coffee, vegetables, bananas, oranges, and other fruit (Ministry of Agriculture and Livestock, 2022). Depending on the island, livestock number between 500-1,500 heads of cattle, 2,500 swine, and 8-12,000 poultry (primarily broiler chickens) (Ministry of Agriculture and Livestock, 2022).

While fishing and agriculture are important for economic stability and food security, these industries have contributed to the establishment of invasive species and diseases, as well as ecosystem pollution due to unsustainable practices. In addition, current local food production does not fully meet demands, thus there is still a dependence on imported continental products (Barrera et al., 2019; Galápagos National Park Directorate (Dirección Nacional del Parque Nacional Galápagos) - GNPD (2014)). Import of raw materials is costly and local production is limited due to lack of manufacturing infrastructure (Watkins and Cruz, 2007). In addition, the extreme focus of human resources training and skill acquisition towards tourism-facing markets creates a reliance on the tourism industry to keep laborers employed, and a corresponding dearth in income if tourism were to halt, such as at the start of the Coronavirus disease of 2019 (COVID-19) pandemic (Chaves et al., 2023). Conversely, the lack of specialized training for Galápagos residents leaves gaps in expertise needed for environmentally-focused positions, including biosecurity and epidemiological research. The provision of public services, including sanitation, water sustainability, education, and healthcare, as well as enforcement of biosecurity practices and conservation measures, falls primarily upon local institutions that may lack sufficient funding and personnel to fully carry out these responsibilities. The Galápagos Islands therefore share with other oceanic islands several key barriers to long-term sustainability (Watkins and Cruz, 2007).

1.2 Political context of the Galápagos Islands

The Galápagos Islands are considered a province of Ecuador, yet physical distance and unique needs distinguish the archipelago from the mainland. As a result, the governance of the Galápagos Islands has long involved a delicate balance between national and regional authorities (Galaípagos Government Council, 2021). Since 1998, the Galápagos Islands have been under the governance of a Special Regime, with a degree of political and financial autonomy and public policies developed through a council with input from representatives of central and municipal governments (Galaípagos Government Council, 2021). Policymaking is also informed by input from international partners. Non-governmental organizations (NGOs) and research groups, with collaborations across borders and various sectors, have been critical to the protection of wildlife and establishment of sustainable industries in the Galápagos Islands.

The Charles Darwin Foundation (CDF), for instance, was founded in 1959 to identify and mitigate threats to biodiversity through research and conservation, with such successes as the Breeding and Repatriation Program for Giant Tortoises, which has resulted in restoration of over 7,000 juvenile tortoises to their islands of origin, and Project Isabela, which resulted in effective population control of feral goats (Galápagos Conservancy, 2023b). Currently, major projects focus on invasive species, such as the avian vampire fly (*Philornis downsi*), which poses a major threat to the endangered mangrove finch (*Camarhynchus heliobates*), and the blackberry shrub (*Rubus niveus*), which threatens endemic *Scalesia* forests (Charles Darwin Foundation, 2023). The Galápagos Whale Shark Project has been instrumental in documenting migration patterns of endangered whale sharks (*Rhincodon typus*), characterizing the unique phenomenon that nearly all whale sharks in Galápagos waters are female (Hearn et al., 2016). NGOs provide funding and personnel to augment the efforts of federal and local authorities, ultimately improving implementation, monitoring, and enforcement of existing regulations. NGOs also support research that informs development of effective policies, and fund conservation programs dedicated to assessing and addressing the needs of threatened species.

Nonetheless, some historical conservation efforts have failed to consider, or stood directly at odds with, local interests (González et al., 2008). For example, intentionally limiting the development of local infrastructure and public services was once proposed as a viable method of combating the rise in immigration to the Galápagos Islands (González et al., 2008; Hennessy, 2018). Wrote Hennessy (2018) in her analysis of the neocolonial history of the archipelago: "an oft-repeated refrain was that the problems of the Galaípagos stemmed from the 'three percent' of the islands where people live. … A sense that there existed a *human* crisis in a place of nature was pervasive … This way of framing the islands' problems has remained common sense despite policy-setters' recognition of the need to include local populations in conservation – something that speaks to the hegemony of visions of the islands as a natural laboratory where the only people who truly belong are scientists and conservationists." These false dichotomies serve only to disparage and alienate stakeholders that must play a key role in conservation. While it cannot be ignored that most threats are anthropogenic in nature, the human-driven pressures on the Galápagos Islands cannot be solely and simplistically ascribed to resident communities. Many of these pressures are instead derived from, or severely exacerbated by, globalization and industrialization, climate change, tourism, and illegal activities. In addition, historical failures to invest in public infrastructure have led to deficits in public education, healthcare, water sanitation, and agricultural management. Viewed through this lens, Galápagos residents have not been given sufficient tools to offset the impacts of human settlements on surrounding ecosystems, and must further contend with the downstream effects of anthropogenic activities of external origin. Wrote González et al. (2008), "this controversy between an isolated (claimed by conservation advocates) vs. an increasingly open (demanded by residents and local authorities) archipelago lies at the base of most conflicts in Galápagos." Throughout this review, we will provide several examples of historical conflicts between and within these sectors.

Fortunately, recent developments in management have incorporated more balance between conservation and development, recognizing the need to stimulate local discussions for the development of sustainable socioeconomic practices (González et al., 2008; Garcia Ferrari et al., 2021). The founding of the Agency for the Regulation and Control of Biosecurity and Quarantine for Galápagos (ABG) in 2012 was instrumental in centralizing management power and building local resources for preventing and controlling biological threats. ABG laboratories and scientists are thus able to focus on studying threats immediately pertinent to the region. In 2022, the CDF expanded their program of travelling libraries to enhance information access within schools, and high-speed internet connectivity reached the archipelago later that year. Investing in local infrastructure and encouraging buy-in from local stakeholders are critical steps in developing resilience across sectors and building a shared vision for the future (González et al., 2008; Garcia Ferrari et al., 2021; Burbano et al., 2022). Incorporating community perspectives has been shown to improve both ecological and social outcomes of protected areas (Intergovernmental Platform on Biodiversity and Ecosystem Services, 2023). Ultimately, regulations that benefit conservation must still demonstrate that local sustainability is a priority.

The Galápagos 2030 Strategic Plan was released by the Galápagos Government Council in 2021, with a strong emphasis on investing in communities to simultaneously achieve progress in conservation (Galaípagos Government Council, 2021). The plan integrated input from various sectors, including Galápagos citizens and public and private organizations. The plan is built upon five pillars, governance, community, environment, habitat, and economy, and outlines goals that include 1) achieving accessible and high-quality education and healthcare for all; 2) committing to responsible and sustainable natural resource use and environmental protection; 3) achieving a stable and diversified economy to promote economic resilience; 4) investing in agricultural production to promote food security; 5) establishing strong political autonomy; and 6) improving public infrastructure to support local communities, including efficient cargo transport, waste management, water and energy systems, and digital connectivity. For this vision to become a reality, we must incorporate lessons from the historical narrative and implement previously documented avenues for improvement.

It is also encouraging that international partners are increasingly recognizing the importance of a co-management approach. In June 2023, for instance, the United States Agency for International Development (USAID) announced 9.7 million United States dollars (USD) in aid to combat illegal fishing of sharks and rays in Ecuadorean waters through the *Habla Tiburon* project, with a commitment to empower local stakeholders during collaborative development of a fisheries management plan with the Government of Ecuador (USAID, 2023).

1.3 Unique climate of the Galápagos Islands

Part of the biodiversity of the Galápagos Islands is due to its unique location at the intersection of several major ocean currents and wind paths, resulting in a more seasonal climate compared to other equatorial islands (Trueman and d'Ozouville, 2010). Galápagos penguins (*Spheniscus mendiculus*), for instance, are the only species of penguin living in the tropics, owing to cold air and water temperatures resulting from deep ocean upwellings. The archipelago can thus inform our understanding of ecosystem resilience in the context of climate change (Salinas-de-León et al., 2020).

Vegetation composition in the Galápagos Islands is influenced by the warm, dry climate and presence of volcanic sediment. Western islands have more recent volcanic origins and thus greater lava cover and lower deciduous vegetation (Moity et al., 2019). Galápagos mangrove forests can grow directly on lava rock, thus stabilizing the substrate, providing a foundation for subsequent plant colonization (Moity et al., 2019). Due to their high salt tolerance and ability to filter salt through their root system (Kim et al., 2016), mangrove forests also act as a transition zone between marine and terrestrial environments (Palit et al., 2022) and are thus critical to coastal ecosystems as nutrient reservoirs, substrate anchors, and habitats for endemic species, including the endangered mangrove finch (*Camarhynchus heliobates*). Mangrove forests are also remarkably resilient in the face of environmental fluctuations (Alongi, 2015).

The Inter-Tropical Convergence Zone (ITCZ) is an air column at the convergence of northern and southern trade winds, impacting rainfall and temperature along its path. When the ITCZ migrates south over the Galápagos Islands, it brings warm, humid air and defines the climate of the hot season. During the cool season, the ITCZ resides north of the archipelago (Trueman and d'Ozouville, 2010). Equatorial trade winds also promote upwelling of cool ocean waters (Trueman and d'Ozouville, 2010). Annual rainfall can be significantly impacted by the eastern Pacific Southern Oscillation, characterized by a warm and cool phase. In the Galápagos Islands, El Niño Southern Oscillation (ENSO) events bring an influx of warm water and dampen or eliminate cold water upwellings (Firing et al., 1983), increasing air temperatures and rainfall, and prolonging the hot season. On the contrary, La Niña events are associated with cooler and dryer air (Trueman and d'Ozouville, 2010). The Equatorial Undercurrent (EUC) is a fast-flowing current that carries cold, nutrient-rich water to the western coast of the archipelago (Karnauskas, 2022; Karnauskas and Giglio, 2022). The interplay between these water and wind currents provides the context for examining the effects of climate change on the region.

2 Threats to Galápagos biodiversity

2.1 Climate change and weather events

A 2013 report by the Intergovernmental Panel on Climate Change (IPCC) concluded that nearly all long-term global warming since 1850 has resulted from human activities (Stocker et al., 2013). Given the delicate balance of climate mediated by ocean currents and winds, the Galápagos Islands are expected to be particularly susceptible to climate change and alterations in ENSO event frequency and amplitude (Dueñas et al., 2021). In 2011, Banks et al. predicted an increase in background air and water temperatures, a decrease in cold upwelling water, and intensification of both El Niño and La Niña events (Banks et al., 2011). From 1981 to 2017, land surface temperatures increased by approximately 0.6°C in the lowlands and 0.21°C in the highlands, with a 45% reduction in humidity (Paltán et al., 2021). Between 2002 and 2018, sea surface temperatures in the Galápagos Marine Reserve (GMR) increased by 1.2°C overall; however, by region, western and southern regions experienced cooling, while northern and eastern regions experienced warming (Paltán et al., 2021). The cool upwelling of the EUC at the western coast of the Galápagos Islands appears capable of offsetting a proportion ocean warming, and its strength has been predicted to increase as the current becomes more aligned with western shores (Karnauskas, 2022; Karnauskas and Giglio, 2022; Liu et al., 2013). However, this should not be mistaken as an indicator that Galápagos ecosystems are not affected by climate change. In fact, climate changes may have diverse impacts within and between different Galápagos ecosystems.

A recent study suggested that El Niño events may be detrimental to marine species while improving the productivity of terrestrial species (Dueñas et al., 2021). The increase in strength and frequency of ENSO events, in combination with background warming, could pose a significant challenge that alters marine organisms' susceptibility to morbidity and mortality. Following the severe ENSO of 1982-83, for instance, shallow reef habitats were dramatically altered, with overgrowth of crustose coralline algae and decline in algal and coral biodiversity, further compounded by urchin grazing resulting in barren reefs and habitat loss (Edgar et al., 2010). Coral reef communities and macroalgae-dominated areas are heavily dependent on cold water upwellings (Banks et al., 2011). ENSO-associated warming has been implicated in infectious disease outbreaks leading to population declines in ring-tailed damselfish (*Stegastes beebei*) and king angelfish (*Holacanthus passer*) (Lamb et al., 2018). The severity of ENSO events also correlates with mortality and displacement in Galápagos fur seals, Galápagos sea lions, and Galápagos penguins (Boersma, 1998; Trillmich and Limberger, 1985; Páez-Rosas et al., 2021; Denkinger et al., 2014; Salazar and Denkinger, 2010). Conversely, Karnauskas and Giglio (2022) warned that the stronger EUC combined with La Niña events could cause sudden cooling that could shock corals and other marine life.

Galápagos coastlines are important breeding and nesting sites for sea turtles, flightless cormorants, marine iguanas, and sea lions. Alterations in coastal shape or composition may impact site suitability, and thus population health, of these endemic species. In March of 2011, a tsunami originating off the coast of Japan struck the Galápagos Islands, causing floods 3-4 meters above the tideline (Lynett et al., 2013). Structural damage to boats, moorings, and beachfront buildings was documented on multiple islands. The southwest coast of San Cristóbal Island, a key marine iguana nesting site, was particularly affected (United Nations Educational, Scientific and Cultural Organization - UNESCO, 2011a). Nest destruction was also present at flightless cormorant nesting sites on Fernandina Island, although mortality in adults was low and successful nesting was subsequently observed (UNESCO, 2011b). Future alterations in the composition of sandy beaches have also been predicted secondary to rising sea levels and increased tourism (Banks et al., 2011).

In terrestrial ecosystems, variable weather patterns may also contribute to the survival of invasive species over native or endemic flora and fauna (Banks et al., 2011). Trueman and d'Ozouville

(2010) posited that the dry lowlands were vulnerable to a warmer and wetter climate, which would favor invasive species and further threaten arid-adapted endemic species. Warming temperatures typically promote vegetation growth (Charney et al., 2021), which could support larger populations of tortoises and increase fitness of juveniles and adults. However, changes in rainfall patterns would likely simultaneously affect the composition of vegetation, in turn altering the relative fitness of different species within that ecosystem. Rainfall is also the primary driver of soil organic carbon accumulation, with altitude and wind direction being key contributing factors (Rial et al., 2017).

Tortoises migrate annually in anticipation of seasonal changes. Seeds consumed in one location can be dispersed through dung along established migratory routes. Ellis-Soto et al. (2017) concluded that tortoise migration would drive expansion of invasive guava into the lowlands, leading to detrimental effects on native plants. In addition, if sudden or drastic weather events become more common, tortoises may not be able to rapidly migrate in response, leading to morbidity or mortality. Overall, climate change-derived ecosystem alterations and more acute fluctuations in weather patterns are likely to lead to ecosystem instability, with severe impacts on delicate endemic wildlife populations.

2.2 Balancing tourism and biodiversity in the Galápagos Islands

Charles Darwin himself commented on the remarkable fearlessness of Galápagos native fauna: "Extreme tameness … is common … a gun here is superfluous; for with the muzzle I pushed a hawk off the branch of a tree" (Darwin & Kebler, 1859). Today, Galápagos wildlife are still highly tolerant of human presence (Figure 1), with sea lions and birds commonly congregating at tourist areas on beaches, ports, and docks. While this fearlessness offers tourists a uniquely close view of wildlife, it also poses opportunities for human-wildlife-domestic animal interactions, with associated risks from chronic stress, physical injury, foreign material ingestion, inappropriate diet, or disease transmission.

The Galápagos National Park (GNP) requires that tourists maintain a 6-foot distance from wildlife (Galápagos Conservancy, 2023a). Feeding of wildlife, flash photography, and littering are prohibited. These restrictions are enforced by local authorities and reinforced by tour guides and residents. However, enforcement can be challenging in the face of expanding tourism, with faster growth in tourism than in enforcement personnel, diminishing mindfulness of environmental stewardship among tourists, and difficulty of regulating pollution and wildlife interactions during tourist activities at coastal and marine areas, such as diving, snorkeling, boating, or beach-going (Watkins and Cruz, 2007).

Tourists elicit a wide range of responses from Galápagos wildlife, from fear to ambivalence to positive interest. Burger and Gochfeld (1993) documented that three species of boobies avoided nesting in proximity to tourist trails and performed more vigilance behaviors, such as calls, turns, and walking or flying away, when tourists passed. Some studies have also found that Galápagos wildlife may be tolerant of human presence. An evaluation of corticosterone levels in marine iguanas at tourism sites showed no evidence of chronic stress (Romero and Wikelski, 2002). Galápagos sea lions generally tolerate human activities and juveniles are often curious and playful towards humans. However,

FIGURE 1
Galápagos sea lions (*Zalophus wollebaeki*) resting on beachside benches in a tourist area of Isabela Island in the Galápagos Islands, Ecuador.

there may be limits to these behaviors, with Galápagos sea lions fleeing once humans were within 4 meters (Denkinger et al., 2015). Walsh et al. (2020) observed that Galápagos sea lions on more disturbed beaches exhibited less aggressive behavior towards humans compared to sea lions in more remote areas, though individual animal tolerances and life stage may impact behavior and habitat choice. Even tourist interactions that do not serve as behavioral stressors can confer potentially detrimental effects on wildlife health. Knutie et al. (2019) demonstrated that the gut microbiota of Darwin's finches was affected by human presence via consumption of processed foods. Deviation from their natural diet could alter the microbiota, with detrimental effects on gut health and egg-laying performance, as demonstrated in other avian species (Diaz Carrasco et al., 2019; Sun et al., 2022).

Tourism is responsible for rapid economic growth, with a 78% increase in GDP from 1999 to 2005 (Taylor et al., 2009; Watkins and Cruz, 2007). However, the extreme reliance on tourism for economic stability is juxtaposed against the potential threats that tourism confers on ecosystem and wildlife sustainability. The GNPD has faced local pressure to increase the number of permits issued to local guides to bring tourists into protected areas, in the interest of improving local revenue streams (Watkins and Cruz, 2007). However, this model would most likely result in short-term gains without long-term sustainability. The current rate of tourism growth has the potential to outpace existing natural resources. In a socioeconomic assessment for the CDF, Watkins and Cruz (2007) wrote: "To date, development in Galápagos has been based on a "frontier mentality" with a focus on market-driven development and minimal consideration to equity and long-term sustainable development. This is reflected in businesses that have experienced periods of rapid growth and prosperity followed by collapse. Such was the case with the exploitation of fur seals and the Galápagos-based whaling industry, as well as contemporary examples in fisheries. We now see a similar pattern with the development of tourism."

A recent meta-analysis of the global effects of tourists on wildlife assessed that negative impacts are often over-reported and that the benefits of tourism (e.g. bringing in revenue that ultimately supports long-term conservation and biodiversity preservation efforts) may outweigh transient negative impacts (Bateman and Fleming, 2017). This argument for ecotourism relies on charismatic ambassador species to inspire visitors to donate towards conservation and raise awareness at a global level, beyond what can be achieved with local measures alone. Previously, tourism in the Galápagos Islands focused on activities that could be experienced nowhere else and highlighted the unique biodiversity of the region, thus intrinsically linking tourism to a need for conservation. However, more recent expansion of the tourism industry to include resort-like activities such as large cruises, kayaking, parachuting, and water sports is concerning for opportunistic economic expansion with little long-term benefit to conservation (Watkins and Cruz, 2007). It is therefore necessary to rethink the role of tourism, acknowledge its rapid consumption of resources and its potential downstream effects, and devise strategies to diversify the economy for a sustainable future (Burbano et al., 2022; (Development Bank for Latin America and the Caribbean, 2022). In addition, the development of a sustainable model for tourism requires incorporation of local perspectives to develop a shared vision, both to effect change and maintain long-term progress (Burbano et al., 2022). Investment in basic services for local communities, such as healthcare, education, and water sanitation, are also key (Burbano et al., 2022).

Aside from the COVID-19 pandemic, the Ecuadorian government had not historically placed limits on the number of tourists visiting the Galápagos Islands. However, several systems effectively regulated tourism levels, with the goal of preventing ecosystem resource exploitation. All visitors to protected areas must be accompanied by tour guides, and the admission of groups to these sites is regulated by a visitor management system (SIMAVIS) overseen by the GNP (Reck et al., 2010; Cajiao et al., 2020). Developed in 2008, SIMAVIS tracks the visitation schedule and the acceptable number of visitors per site. Marine and terrestrial tourism are also monitored through a collaborative approach, integrating input from GNPD staff, research groups, and tour guides; this information is used to periodically revise the acceptable number of visitors per site (Reck et al., 2010; Cajiao et al., 2020). These systems have been instrumental in limiting the potentially detrimental effects of tourism on protected areas. However, efficient tourism monitoring has been hindered by logistical and financial constraints (Cajiao et al., 2020). Pizzitutti et al. (2016) predicted that existing visitation sites would become saturated with visitors between 2017 and 2020, and subsequently would become overcrowded. While those models did not account for the interruption in tourist activity due to the COVID-19 pandemic, visitation sites nonetheless cannot sustain unrestricted tourism growth. In late 2022, the UNESCO World Heritage Committee encouraged the Ecuadorian government to "develop and implement a clear tourism strategy that ensures that suitable measures are sustained in the long term as permanent regulations, with a clear action plan with urgent measures to achieve the zero growth model, including maintaining the moratorium on construction of new tourism projects and the limits on the number of flights," (UNESCO and World Heritage Committee, 2022).

Several recent innovations in tourism management have been implemented in the archipelago. SIMAVIS underwent comprehensive revision in 2017, with improvements in data collection, mobilization of tour guides and other stakeholders to enhance monitoring capacity, and revision of protocols to improve implementation and enforcement, thus improving efficacy and efficiency (Cajiao et al., 2020). In 2017, the online Galápagos Guide Monitoring Network (GGMN) was established as a centralized method for tour guides to record observations regarding potential conservation threats (Cajiao et al., 2020), greatly augmenting monitoring efficiency, with a ten-fold increase in number of reporting tour guides and a 25-fold increase in recorded observations from 2015-2018 (Cajiao et al., 2020). In addition, the DiveStat program was implemented in 2015 to monitor divers and underwater activities in the GMR (Cajiao et al., 2020). These efforts are aimed at early detection of potential conservation challenges.

2.3 Pressures originating in the marine environment

2.3.1 Ocean acidification

Galápagos waters are naturally acidified and nutrient-rich due to upwelling from deep ocean currents (Manzello, 2010). Anthropogenic increases in environmental carbon dioxide will lead to ocean acidification throughout the tropics in the following decades (Manzello et al., 2014). Corals are particularly susceptible to acidification, with impacts on skeletal density (Mollica et al., 2018), growth, and diversity (Thompson et al., 2022). Manzello et al. (2014) observed that corals struggled to recover from stressful events in the face of acidified and nutrient-dense waters. In addition, corals show limited ability to adapt to acidification over time (Thompson et al., 2022). Galápagos waters thus provide a model for studying the effects of global warming, eutrophication, and ocean acidification on coral reefs (Manzello et al., 2014). The GNPD has established an underwater coral nursery to facilitate monitoring of coral health and contribute to coral restoration efforts on islands affected by coral loss. Ocean acidification also has impacts on fish (Chung et al., 2014), marine microbial communities (Guevara, 2015), invertebrates (Chan et al., 2011) and phytoplankton (Litchendorf, 2006).

Galápagos mangroves are estimated to store over 778,000 tons of inorganic carbon (Tanner et al., 2019). This carbon can be utilized to buffer coastal waters, thus mitigating ocean acidification (Sippo et al., 2016). Mangrove deforestation has been estimated at 1-2% per year; if this trend continues, mangrove forests may disappear within the century (Alongi, 2002). While mangroves can withstand increased humidity and rainfall, they are predicted to decline in areas where climate change results in a more arid environment (Alongi, 2015).

2.3.2 Overfishing, poaching, and bycatch

Fishing is a major contributor to the Galápagos economic landscape. Fisheries can be broadly classified as benthic or demersal-pelagic (Castrejón, 2011). Benthic invertebrates include sea cucumbers (pepino del mar) and spiny lobsters (langosta espinosa), which generate a large proportion of revenue, as well as species that are typically incidental catches, such as slipper lobsters (langostino) (*Scyllarides astori*), chitons (canchalangua) (*Chiton goodallii* and *Chiton sulcatus*), octopus (pulpo) (*Octopus oculifer*), and snails (churo) (*Hexaples princeps* and *Pleuroploca princeps*) (Castrejón, 2011). Demersal-pelagic fish include approximately 68 species; important members have been outlined by Castrejón (2011). Of the demersal fish, the sailfin grouper (bacalao) is the primary fishing target; other important members include other species of grouper (*Epinephelus* spp.), ocean whitefish (blanquillo) (*Caulolatilus princeps*), and the endemic white-spotted sand bass (camotillo) (*Paralabrax albomaculatus*). Coastal pelagic fish include the wahoo (*Acanthocybium solandri*), Thoburn's mullet (*Mugil thoburni*), and the endemic Galápagos mullet (*M. galapagensis*). Deep sea fishing operations typically target large pelagic fish, such as yellow tuna (*Thunnus albacares*), Bigeye tuna (*Thunnus obesus*), swordfish (*Xiphias gladius*), and mahi-mahi (*Coryphaena hippurus*) (Castrejón, 2011).

In many cases, the fishing industry continues to be at-odds with conservation efforts, and overexploitation of marine resources represents a significant pressure on wildlife populations in the region. Illegal, unreported, and unregulated (IUU) fishing is a major threat to marine ecosystems, food security, and economic stability worldwide. Despite the efforts of local authorities, residents, and conservationists, the illegal wildlife trade still persists in the region (Galápagos Conservancy, 2021; Frazier, 2021). Illegal fishing is a major threat to endemic Galápagos species, perpetrated by international commercial fleets, illegal sportfishing operations, and even local fisheries. Illegal fishing includes poaching of protected species or fishing of commercial species in violation of regulations on fishing season, quotas, or life stage. Schiller et al. (2013) reported that between 1994 and 1999, 3,000 tons of sea cucumbers (*Isostichopus fuscus*) were caught illegally in Galápagos waters. In 2017, thousands of dead sharks were intercepted by the Ecuadorian Navy and Galápagos National Park (Bale, 2017). Unregulated fishing refers to fishing of stocks that are not covered under explicit regulations or when occurring by foreign vessels in areas managed by a regional fisheries management organization (RFMO), an international consortium of countries that collaboratively manages fishing stocks. In 2023, to mitigate IUU fishing, multinational cooperation via the United Nations produced measures for the preservation of biodiversity in waters outside of national borders, such as much of the ocean surrounding the Galápagos Islands, and development of procedures for the boarding and inspection of vessels in the South Pacific Ocean (United Nations General Assembly, 2023; South Pacific Regional Fisheries Management Organisation, 2023).

While the preservation of aquatic biodiversity confers long-term economic benefits, these are largely overlooked by poachers in the interest of short-term profits. For example, the northern Islands of Darwin and Wolf are home to the largest reef fish biomass ever recorded, comprised primarily of sharks (Salinas-de-León et al., 2016). The tourism value of a single live shark throughout its lifetime in the Galápagos Islands has been estimated at 5.4 million USD (Lynham et al., 2015). Nevertheless, poaching and bycatch pressure are ongoing and significant threats to marine life in the GMR. From 2001-2007, Ecuadorian authorities seized 29 sharks caught within the GMR (Carr et al., 2013). In addition, commercial fishing ships still often operate at GMR boundaries, waiting for whale sharks (*Rhincodon typus*) and scalloped hammerhead sharks (*Sphyrna lewini*) to exit protected areas (Alava and Paladines, 2017; United Nations, 1982).

We define overfishing as legal fishing activities that are still ultimately unsustainable, impacting the resilience and biodiversity of marine ecosystems. These impacts have been documented in many Galápagos species, including sailfin grouper (Usseglio et al., 2016), brown sea cucumbers (Wolff et al., 2012; Ramírez-González et al., 2020), spiny lobsters (Szuwalski et al., 2016), and slipper lobsters (Hearn, 2006; Castrejón, 2011). Prior to 1998, less than 1% of Galápagos waters were protected from fishing. The 1990s saw a rapid rise in artisanal fishing, coinciding with growth of the sea cucumber fishery and expansion of tourism, both stimulating immigration from mainland Ecuador (González et al., 2008; Castrejón and Charles, 2013; Bremner and Perez, 2002). Over 5 million sea cucumbers were harvested over a 3-month timespan in 1994 (Bremner and Perez, 2002). The consequent increase in pressure on marine resources led to accelerated ecosystem degradation. In response, the Special Law for Galápagos was established in 1998, designating 133,000 square-kilometers of marine, coastal, and inland waters as the GMR and prohibiting industrial fishing, while still allowing artisanal and theoretically "small-scale" fishing.

To regulate fisheries, the GMR Management Plan (GMRMP) was implemented in 1999. The GMRMP was designed as an ecosystem-based spatial management (EBSM) plan (Castrejón and Charles, 2013), which accounts for the effects of fishing on the entire marine habitat, including both target and off-target species, and the impacts of other anthropogenic activities such as tourism, marine transport, and energy use (Castrejón and Charles, 2013). EBSM strategies have been effective at promoting ecosystem resiliency and economic sustainability in other regions, such as the Great Barrier Reef (Day, 2008). However, EBSM in the GMRMP faced several challenges, which will be discussed in Section 2.4.5.

Although densities of chitons have declined in coastal fishing areas and a legal minimum harvest size has been proposed (Herrera et al., 2003), there are currently no regulations on the seasonality or capture size for chitons, octopus, or snails (Castrejón, 2011; Riofrío-Lazo et al., 2021). Further research on the impacts of fishing on these less studied benthic invertebrates is warranted.

By implementing more stringent limits on fishing, we can expect to increase commercial stocks, protect marine ecosystems by reducing trophic cascades and habitat degradation, and decrease pollution and carbon emissions from fishing vessels (Sumaila and Tai, 2020). In addition, an increase in fish biomass would increase blue carbon sequestration within marine life (Sumaila and Tai, 2020). A collaborative approach to fisheries management is necessary to effect lasting change in Galápagos waters (Castrejón et al., 2013; Usseglio et al., 2016). Appropriately balancing participatory management from local stakeholders with top-down reform, however, is challenging.

In a recent study, computational modeling was used to evaluate the impact of fishing on ecosystem stability in the southeastern GMR, and concluded that overall, current fishing practices are sustainable and that ecosystem is resilient (Riofrío-Lazo et al., 2021). In that study, the authors also noted that ecosystem balance was promoted by marine mammals, sharks, and certain birds and fish, including the sailfin grouper, suggesting that this latter fish of commercial interest may merit more protection as an ecosystem stabilizer. While these findings are encouraging, the authors acknowledge the inherent limitations of modeling a system using incomplete data on illegal fishing and bycatch (Riofrío-Lazo et al., 2021). Continued reassessment of both target and non-target species in commercial fisheries is necessary to ensure that fisheries management plans in the GMR operate sustainably, particularly while the ecosystem remains under threat from other concurrent marine pressures, such as illegal fishing, marine pollution, and climate change.

2.3.3 Marine pollution

Contamination with plastics, persistent organic pollutants, and heavy metals are concerns stemming from anthropogenic activities and disturbances. In several studies, beach plastics were most abundant on the windward eastern coasts of the Galápagos Islands (Jones et al., 2021; Muñoz-Pérez et al., 2023), although Galápagos beaches had lower levels of plastic debris than Ecuador beaches (Mestanza et al., 2019). Plastic pollution affects the ecophysiology and health of a wide variety of species (Alava et al., 2023). Through citizen science efforts, Muñoz-Pérez et al. (2023) reported plastics pollution in 52 animal species on the Galápagos Islands, including mammals, birds, reptiles, fish, and invertebrates. Macroplastic contamination of the environment can lead to morbidity and mortality in wildlife via ingestion, leading to impaction, gastrointestinal disease, or starvation, or entanglement with subsequent constricting injuries or drowning (Muñoz-Pérez et al., 2023). These impacts have been documented with particularly high risk in green sea turtles (*Chelonia mydas*), marine iguanas (*Amblyrhynchus cristatus*), giant tortoises (*Chelonoidis* spp.), Galápagos sea lions, medium-billed ground finches (*Geospiza fortis*), whale sharks (*Rhincodon typus*), spine-tailed mobulas (*Mobula japonica*), and black-striped salemas (*Xenocys jessiae*) (Muñoz-Pérez et al., 2023).

Plastic pieces less than 5 mm in diameter are considered microplastics. Microplastics originate from the breakdown of beach litter, synthetic clothing, plastic films from packaging, and microbeads from toothpastes and body washes. Microplastics have been identified in multiple Galápagos beach sites (Jones et al., 2021) and were ubiquitous in seawater (Alfaro-Núñez et al., 2021). Microplastics have also been identified in invertebrates (Jones et al., 2021) and hundreds of marine organisms commonly consumed by humans (Alfaro-Núñez et al., 2021), as well as Galápagos penguin guano (McMullen, 2023). Microplastics can result in intestinal impaction in birds (Carlin et al., 2020; Wang et al., 2021) and alter gut microbial composition (Fackelmann et al., 2023). Microplastics also absorb polycyclic aromatic hydrocarbons (PAHs), thus facilitating their ingestion and bioaccumulation (Rochman, 2015). Microplastics and marine debris at turtle nesting sites may result in obstruction, toxin exposure, and affect temperatures of nesting sites, a determining factor for sex in some species (Beckwith and Fuentes, 2018; Garrison and Fuentes, 2019). Microplastics also have the potential to promote biofilm formation and select for different populations of microorganisms (Qiang et al., 2021), posing a risk to the balance of aquatic and coastal ecosystems and potentially serving as an avenue for pathogen acquisition. In the interest of combatting plastics pollution, the Galápagos Special Regime Government Council (Consejo de Gobierno de Régimen Especial de Galápagos – CGREG) enacted Resolution 05-CGREG-2015 in 2018 to restrict the consumption of single-use plastics in the archipelago (CGREG, 2015, CGREG, 2018). Nonetheless, many products can still serve as sources of microplastics pollution.

The use of Galápagos waterways for fuel and oil transportation also confers a risk for wildlife. In 2001, the oil tanker *Jessica* ran aground on a reef at San Cristóbal Island (Sanderson et al., 2001). The resulting spill of nearly 800,000 gallons of oil led to a 62% mortality in marine iguanas over the following year (Wikelski et al., 2002). For seabirds, oil results in feather matting and loss of waterproofing, resulting in hypothermia and impairing buoyancy. Sea lions are similarly at risk, with conjunctivitis, burns, and death documented in association with exposure to oil (Salazar, 2003). Inhalation of oil particles also results in respiratory distress and can lead to long-term effects such as diminished reproductive success. Smaller spills were recorded in 2019 on San Cristóbal Island (UNESCO, 2019) and 2022 on Santa Cruz Island (Meyer, 2022); in both cases, rapid cleanup measures occurred in collaboration with authorities, conservationists, and volunteers, with the GNPD ultimately reporting no lasting effects from these two incidents.

Accumulation of heavy metals also poses a threat to human and animal health. Classically, heavy metals accumulate within biological systems and reach higher concentrations among species at the top of the food chain. Franco-Fuentes et al. (2021) documented high concentrations of heavy metals in demersal and pelagic fish in the Galápagos Islands. Lead levels in Galápagos birds vary by species and are higher than those in birds from other oceanic islands (Jiménez et al., 2020). The main natural sources of heavy metals are volcanic activity and the erosion of rock formations (Tchounwou et al., 2012). Upwelling currents can also affect heavy metal accumulation (Franco-Fuentes et al., 2021; Jiménez et al., 2020). El Niño events can also cause nutritional stress and increases vulnerability to pollutants (Alava et al., 2023). No clear association between human activities and heavy metal concentrations in Galápagos birds has been determined (Jiménez et al., 2020; Jiménez-Uzcátegui et al., 2017). However, Dinter et al. (2021) reported high levels of cadmium, cobalt, chromium, copper, nickel, and zinc in agricultural topsoil in the Galápagos, most likely due to agrochemical use (Dinter et al., 2021), which could lead to environmental contamination and runoff. Other potential anthropogenic sources of heavy metals include the use of lead shot or fishing line sinkers; byproducts of coal-burning plants and gas combustion; and corrosion of water or sewage pipes (Tchounwou et al., 2012). Runoff from metal foundries, mines, refineries, and chemical plants are significant contributors in other regions, (Tchounwou et al., 2012), but are less likely play a role in the Galápagos Islands.

2.3.4 Traumatic injury to wildlife in the marine environment

A variety of human activities can result in accidental traumatic injury to wildlife. In the marine environment, bycatch, fishing gear entanglement or ingestion, and propeller injuries and other vessel strikes may occur (García-Parra and Tapia, 2014). Macroplastic ingestion or entanglement is also a major concern, as discussed in Section 2.4.3.

Galápagos waters are traversed by a variety of vessels, including commercial and small-scale fishing boats, ferries between islands, tour boats, and dive boats. Vessel collisions with marine mammals and fish are a major concern worldwide, with the potential to cause trauma or death to the animal, injury to passengers, and damage to the boat itself (Schoeman et al., 2020). Boat strikes are a documented risk to sea turtles in the GMR, affecting both nesting and foraging sites (Denkinger et al., 2013). Fast boat speeds increase the risk of collision and incidence of mortality in sea turtles, therefore speed limits and "go-slow zones" and area closures have been suggested as key management points (Denkinger et al., 2013; Fuentes et al., 2021). Boat propeller injuries have also been documented in Galápagos sea lions (Denkinger et al., 2015), a social species that frequents coastal areas and beaches of inhabited islands. Vessel collisions also affect whale sharks, who frequent shallower waters and whose movements frequently overlap with large vessel traffic (Womersley et al., 2022). The Galápagos Islands are an important waypoint for seasonal migration of pregnant female whale sharks (Hearn et al., 2016); injury to these individuals thus has further downstream population impacts.

2.3.5 Challenges and solutions for management of the marine environment

Marine zoning in the GMR was meant to allow sustainable economic activities in designated areas while maintaining protected regions for the recovery and preservation of threatened species, thus decreasing conflict and competition between different sectors (Review: Castrejón and Charles, 2013; Galápagos National Park Directorate, 1998; Edgar et al., 2008). Deep waters were designated as "multiple use zones," for fishing, tourism, and other GNP-approved activities, while "limited use zones" near coastal areas were subdivided for conservation, tourism, and fishing (Review: Castrejón and Charles, 2013). The GMRMP resulted in an increase in large grouper, white-spotted sand bass, and Galápagos grunts (*Orthopristis forbesi*) in no-take zones compared to fishing areas (Banks, 2007). Nonetheless, Pontón-Cevallos et al. (2020) predicted that establishment of additional no-take zones and protection of grouper nurseries in mangroves would still be necessary to prevent population collapse of this species.

Ultimately, the success of the GMRMP zoning strategy was hindered by several factors. The co-management strategy was intended to promote local stakeholders advocacy and participation (Castrejón and Charles, 2013; Edgar et al., 2004). However, special interest lobbying during the delineation of no-take zones resulted in *de facto* prioritization of economic activities over environmental interests (Castrejón and Charles, 2013). For instance, sea cucumber fishermen advocated for no-take zones in areas with already low sea cucumber density, while tour guides lobbied to continue operating in areas with large populations of endangered sharks (Edgar et al., 2004). Between 2000-2001, sea cucumber density was three-fold higher in fishing areas and shark density was five-fold higher in tourist areas, compared to corresponding no-take zones (Edgar et al., 2004).

In addition, because the GMR is spatially heterogeneous with regards to population density and species composition, implementation of a total allowable catch (TAC) quota may be ineffective at preventing overexploitation (Castrejón and Charles, 2013). For example, sea cucumber reproduction requires high population density, thus depletion of one high-density area has higher population-level impacts compared to collecting from multiple less dense regions, even if total numbers fall within TAC quotas. Seasonal fishing limitations, therefore, may provide benefits over TAC for certain species (Castrejón and Charles, 2013). In the past three decades, several periods of quota-regulated sea cucumber fishing have alternated with harvest moratoriums, attempting to satisfy the fishing industry while mitigating population-level impacts (Bremner and Perez, 2002; Ramírez-González et al., 2020). Nonetheless, current strategies appear to be insufficient at preventing sea cucumber overexploitation (Ramírez-González et al., 2020).

Education of local stakeholders is key to achieving buy-in and adherence to regulations, including reporting of observed illegal activities by fishermen in the field. Artisanal fishermen hold most of the fishing permits for the GMR, and thus should be key targets for education. For instance, fishermen seeking rapid economic benefits of harvesting sea cucumbers from high-density areas may initially disagree with zoning regulations, but increased education could lead to recognition that short-term gains may imperil the entire industry and ultimately threaten long-term economic sustainability. In addition, fishermen that buy into fishing regulations may be more likely to report observations of illegal activities.

While GMRMP zones were approved in 2000, it took another six years for physical demarcation of boundaries, further complicating enforcement and adherence to no-take zones (Castrejón and Charles, 2013) and boundaries have yet to be clearly demarcated by the Global Positioning System (GPS). Similarly, in 2004, the Eastern Tropical Pacific Marine Corridor (CMAR) was established as a protected region between Costa Rica, Panama, Colombia, and Ecuador (Enright et al., 2021). This corridor is home to many endemic species and serves as a migratory route for rays, sea turtles, sharks, and whales. However, as of 2021, the exact geographic boundaries of the CMAR had yet to be delineated (Enright et al., 2021). These disconnects between protected area designation and implementation hinder both application and enforcement.

Castrejón and Charles (2013) detailed recommendations for improvements to the zoning strategy for the GMRMP, including integrating input of local stakeholders, regional and federal authorities, and independent experts; considering the enforcement capabilities of local institutions on no-take zones; and incorporating economic incentives, restrictions on fishing gear, and seasonal fishing quotas. Moreover, a monitoring plan is essential to re-assess and revise management strategies. In 2014, the GNPD began a re-zoning project, which included a period for input from local stakeholders (Viteri et al., 2020). However, in 2016, a presidential decree designated a subset of the GMR around Darwin and Wolf islands as a marine sanctuary, off-limits to all fishing activities. This unilateral decision was seen by some to undermine the prior two years of re-zoning negotiations (Viteri et al., 2020). In 2022, another presidential decree further expanded the GMR by 60,000 square kilometers, creating the Hermandad Marine Reserve (HMR) – a wildlife migratory corridor across Ecuadorian, Costa Rican, Panamanian, and Colombian waters that prohibits all extractive activities (Galápagos Conservation Trust, 2022). White et al. (2023) documented an 88% decrease in fishing within the HMR within the year following its implementation. However, it remains to be determined whether the GMR can be appropriate patrolled to enforce these protections long term. These zones of protection are indicated in Figure 2.

Climate change and industrial fishing remain key threats to the marine environment. The challenges faced in enforcement of the GMRMP should serve as lessons towards future development plans for the CMAR and HMR. Appropriate management of fisheries has the potential to reduce illegal fishing and bycatch of protected species. Regulation of tourism in the GMR and implementation of go-slow zones or protected ocean corridors would also reduce propeller injuries and marine pollution. There continues to be a disconnect between federal and regional authorities with regards to a co-management versus top-down approach for protected areas. Sufficient personnel, regulatory oversight from local authorities, appropriate penalties for infractions, and local stakeholder buy-in are all required for boundaries drawn on paper to have practical and long-lasting positive impacts for marine protection.

2.4 Threats to the terrestrial environment

2.4.1 Land use, development, and agriculture

Land areas outside of the GNP are designated for human use as either urban or rural zones. The rural zone includes 250.5 square kilometers of land, 76% of which are agricultural production units (APUs) on Santa Cruz (47%), San Cristóbal (34%), Isabela (17%) and Floreana (2%) Islands. APU composition includes pastures (58%), non-invasive forests (22%), invasive vegetation cover (5%), permanent crops (8%), fallow land (4%), and transient crops (1%). Geenhouses, sheds, and corrals comprise another 2%. The remaining 24% of the rural zone is non-agricultural, including forests, areas taken over by introduced species, or residential areas (CGREG, 2016).

Agricultural land is inevitably subject to changes in vegetation composition and density, with downstream ecosystem impacts. Land bird diversity in the Santa Cruz Island agricultural zone (SCIAZ) was significantly lower in pastures compared to forests, although forest patches and corridors ameliorated the negative impacts of farmland (Geladi et al., 2021). The SCIAZ is surrounded entirely by protected areas and intersects with giant tortoise migratory routes, providing a setting for potential human-wildlife interactions or conflict (Benitez-Capistros et al., 2018). Pike et al. (2022a) found that over two-thirds of tortoises spend a mean of 150 days in the SCIAZ before returning to the GNP. Farmers that reported tortoise-associated damage to crops or property were also more likely to report implementing fencing and/or taking physical actions against tortoises (such as harassing, displacing, or upending) (Benitez-Capistros et al., 2018). Various strategies have been suggested to mitigate human-wildlife conflict, extrapolated from cases in other regions (Benitez-Capistros et al., 2019). Providing farmers with economic compensation to account for damage caused by wildlife can inadvertently promote expansion of agricultural areas and livestock grazing with negative downstream ecosystem effects (Benitez-Capistros et al., 2019). Strategies to reduce crop and property damage, such as creation of wildlife corridors that maintain habitat connectivity, may be more viable long-term solutions (Benitez-Capistros et al., 2019). Regardless, communication and cooperation between various stakeholders is critical to develop viable long-term solutions.

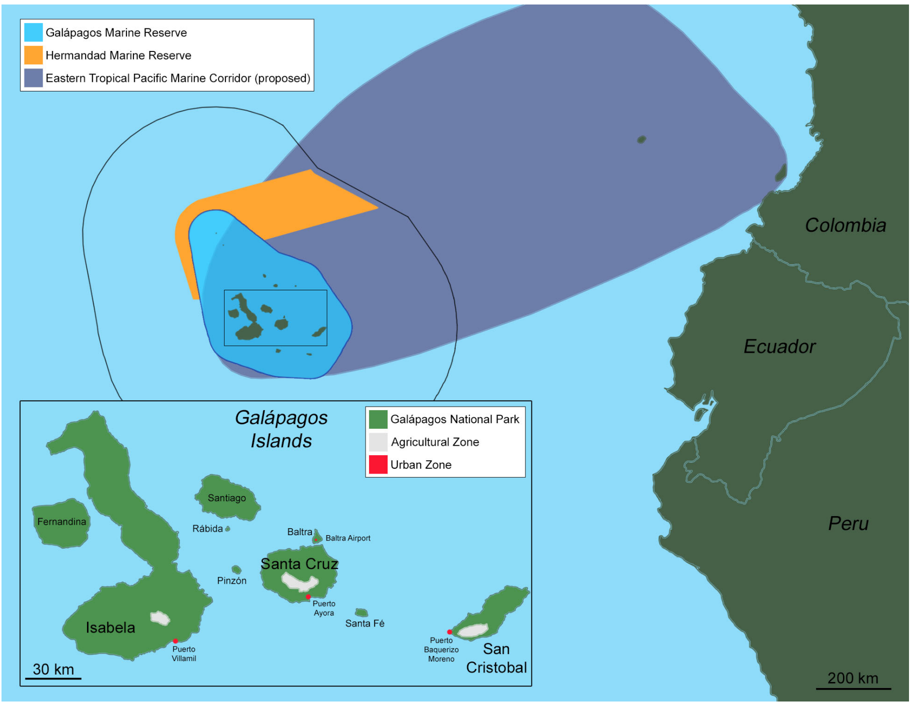

FIGURE 2
Map demonstrating key boundaries surrounding the Galápagos Islands. The Galápagos Marine Reserve (GMR) is indicated in light blue, the Hermandad Marine Reserve is indicated in orange, and the insular exclusive economic zone is indicated with a black outline (White et al., 2023). The proposed boundaries of the Eastern Tropical Pacific Marine Corridor (CMAR) are shown in purple; the official boundaries have yet to be defined (Enright et al., 2021). Most of the land mass of the archipelago is protected as the Galápagos National Park (GNP), while the agricultural and urban zones are designated in gray and red, respectively (González et al., 2008).

Pike et al. (2022a) documented that tortoise density on Santa Cruz Island was lowest in abandoned farmland and highest in tourist areas. Agricultural land abandonment, leading to uncontrolled proliferation of invasive plants, is a major challenge for terrestrial ecosystems and neighboring farms (Benitez-Capistros et al., 2014; Watson et al., 2010). 84% of Galápagos farmers that reported abandoning their property did so due to invasive species impacting production (Brewington, 2011). Abundant ground cover, short vegetation, few shrubs, and presence of ponds were all positively correlated with giant tortoise presence. These habitat features could be utilized to support tortoise conservation on farms, or to create preferred corridors that circumvent farmland to mitigate crop destruction (Pike et al., 2022a, Pike et al., 2022b). Interestingly, tortoises preferred pasture over native vegetation, and most fences in the studied areas did not significantly limit tortoise movement (Pike et al., 2022c); these findings are not necessarily intuitive, highlighting the importance of research to inform conservation recommendations.

Development of the agricultural and livestock sector is complex and controversial, as it requires changes in land use. This sector faces various obstacles, including scarce or unreliable water resources, ineffective irrigation, stony soils, and lack of labor. From the perspective of sustainable development, increasing local food production would promote food security while reducing impacts associated with imports, such as introduced species and fuel use. However, agriculture can negatively impact ecosystem health through unsustainable land/water use, monoculture cultivation, environmental pollution, land abandonment, and run-off. Since the ecosystem is the main attraction and capital of the archipelago, natural resource preservation is essential from both economic and conservation standpoints. Agroproductive development would thus require a participatory approach in management with integration of multisectoral viewpoints and long-term planning to balance these concerns (Khatun, 2018). Development also relies on external economic factors (Burbano et al., 2022). Among Galápagos farmers, a shortage of hired help was a major concern, with most immigrants more interested in the tourism sector (O'Connor, 2014; Brewington, 2011; Lu et al., 2013). Economic diversification to avoid excessive dependence on tourism would thus also benefit agroproductive development. Restoration actions following ecosystem deterioration require investments hundreds of times larger than those for protection (Khatun, 2018), highlighting the importance of prospectively balancing agroproductive and conservation interests before implementing developmental plans.

2.4.2 Organic pesticide use

Organic pesticides used to prevent crop destruction by invertebrates or invasive plants can improve agroproduction, but also result in environmental pollution, off-target killing of endemic pollinators, and neurologic, carcinogenic, or endocrine impacts on vertebrates. 100% of surveyed highland farmers on Santa Cruz Island reported concern over invasive species, and 67% reported using pesticides (O'Connor, 2014). The majority (85%) sold crops primarily to local markets. Higher rates of pesticide use were associated with education below the secondary level, as well as with larger property size, regardless of education level (O'Connor, 2014).

Although Dichlorodiphenyltrichloroethane (DDT) and other World Health Organization (WHO)-designated Class IA and IB pesticides have been prohibited in the Galápagos Islands since 2010, their use may have continued due to illegal import or use of residual stocks (O'Connor, 2014). Most farmers purchase pesticides from local shops, with only 7.5% using imported products. Ecuador's Agriculture Quality Assurance Agency (La Agencia de Regulación y Control Fito y Zoosanitario (AGROCALIDAD)) monitors vendors to enforce regulations on chemical use, but some shops still carry prohibited pesticides and medications. Farmers have also been documented to inquire about prohibited pesticides at shops, presumably due to past positive experiences (O'Connor, 2014).

The residues of sixteen pesticides, including three persistent organic pollutants (POPs), were detected in coastal waters bordering urban areas of Santa Cruz and Isabela Island (Riascos-Flores et al., 2021). POPs such as DDT have also been identified in Galápagos sea lion pups, increasing over time and reaching clinically significant concentrations, indicating that relay toxicosis and biological accumulation are relevant outcomes of pesticide use in this region (Alava and Gobas, 2012; Alava and Ross, 2018; Alava et al., 2011). Due to persistent use of DDT worldwide, it is possible that atmospheric and oceanic currents lead to DDT residues in the Galápagos Islands, although to the authors' knowledge, no studies have evaluated this possibility. Galápagos seabirds have been found to have lower levels of POPs in uropygial gland secretions compared to birds from other areas; upwelling waters may decrease local POP concentrations in seabirds foraging areas (Yamashita et al., 2021).

Addressing the overuse of pesticides is a complex challenge that requires creative approaches. Historically low-income regions that undergo rapid economic growth lack management or regulatory infrastructure to mitigate accelerated habitat degradation associated with rapid increases in pesticide use, as in a case study in Thailand (Praneetvatakul et al., 2013). Prior work has suggested that conservation education leads to more environmentally conscious decision-making among farmers (Glynn et al., 1995; Napier et al., 1986; Lynne et al., 1988). It is crucial to enhance education for farmers on the importance of identifying and avoiding prohibited pesticides, increase access to biologically sustainable products, and provide training on sustainable farming techniques to demonstrate that farmers can improve production and combat invasive species without the use of illegal products. O'Connor-Robinson et al. (2018) additionally suggested that farmers could be incentivized to participate in organic farming through a "participatory guarantee system," in which farms with an organic certification can access specific markets. However, with the exception of coffee, most Galápagos agricultural products lack large export markets (O'Connor, 2014); therefore, incentivizing organic production would most likely require targeting tourism markets, further centralizing economic interests. Development of local infrastructure to address waste and runoff is also necessary as a complementary approach to limiting the impact of POPs.

2.4.3 Human-wildlife conflict, trauma, and illegal wildlife trade

Historical exploitation of giant tortoises by whalers and mariners led to precipitous population decline. Poaching of wildlife for meat, trophies, traditional medicine, and sale at wet markets unfortunately remain major problems for Galápagos wildlife, particularly for long-lived and slowly reproducing species such as giant tortoises (Márquez et al., 2007). From 1995 to 2004, field personnel on Isabela and San Cristóbal Islands recorded observations of 190 giant tortoise carcasses (Márquez et al., 2007), presumably killed for meat.

Due to the ongoing threat of poaching and wildlife trafficking, the GNPD started a program in 2014 aimed at identifying trafficking networks (Auliya et al., 2016). Unfortunately, identifying and sentencing wildlife smugglers still poses a significant challenge, and poaching continues to occur. On Isabela Island, 4 giant tortoises were killed in 2021 and another 15 were killed in 2022 (Galápagos Conservancy, 2022). In March 2021, 185 live juvenile giant tortoises were recovered from traffickers attempting to transport them in suitcases out of Baltra Airport (Jones, 2021). Iguanas have also been targets of smuggling (Auliya et al., 2016; Gentile et al., 2013). On June 25, 2022, the Ecuadorian Navy seized two vessels carrying 5 live golden land iguanas and 84 juvenile San Cristóbal giant tortoises (State Attorney General's Office, 2022). Because of the high demand for these species in Europe, Asia, and the United States, the black market prices of golden land iguanas is up to 20,000 USD (State Attorney General's Office, 2022) while giant tortoise juveniles and adults can garner 5,000 USD and 60,000 USD, respectively (Pacífico Libre, 2021).

In addition, even when traffickers intend to keep wildlife alive for sale, morbidity and mortality still occur (State Attorney General's Office, 2022) and animals recovered from poachers may not survive to be released. Furthermore, marine iguanas and giant tortoises have genetically distinct subspecies based on their island of origin, and thus live animals recovered from poachers must also be returned to the correct location. Genetic repositories are crucial in enabling wildlife forensic scientists to determine the origins of animals reclaimed from traffickers (Quinzin et al., 2023; Auliya et al., 2016).

Trauma is also key cause of wildlife mortality in the Galápagos Islands and can occur due to interactions between endemic wildlife and domestic animals or invasive species, or secondary to human activities (Kruuk and Snell, 1981; Gottdenker et al., 2008). Populations of endemic rodents in the Galápagos Islands were decimated following introduction of the invasive black rat (*Rattus rattus*), brown rat (*R. norvegicus*), and house mouse (*Mus musculus*) (Dowler et al., 2000). Rodent predation of eggs and chicks is a documented driver of population decline in the endangered Galápagos petrel (*Pterodroma phaeopygia*) (Cruz and Cruz, 1987a, Cruz and Cruz, 1987b; Riofrío-Lazo and Páez-Rosas, 2015). Domestic cats have a major impact on wildlife worldwide, with predation directly affecting population mass and fecundity, and resource competition and disease transmission posing further threats (Medina et al., 2013; Trouwborst et al., 2020). In the Galápagos Islands, cats have been documented to consume lava lizards, iguanas, and birds (Carrión and Valle, 2018). Similarly, populations of giant tortoises, land iguanas, Galápagos sea lion, Galápagos fur seal, and several bird species have been negatively impacted by nest predation from domestic dogs (Barnett and Rudd, 1983; Kruuk and Snell, 1981). The giant tortoise is particularly vulnerable to the effects of nest predation due to their small clutch sizes.

Accidental vehicular trauma has been reported to affect land iguanas (García-Parra and Tapia, 2014), giant tortoises (García-Parra and Tapia, 2014), lava lizards (*Microlophus* spp.) (Tanner and Perry, 2007; Medrano-Vizcaíno et al., 2023), and birds (Medrano-Vizcaíno et al., 2023; García-Carrasco et al., 2020) in the Galápagos Islands. Tanner and Perry (2007) analyzed the incidence of dead lava lizards on roads on Santa Cruz Island and found that vehicular trauma disproportionately affected juvenile and adult male lizards. Further, they documented a higher proportion of fatalities in proximity to a particular long, straight road, where speeding was common, and recommended that barriers and underpasses should be considered as a management strategy.

In addition, intentional injuries can be caused by humans during human-wildlife conflict (García-Parra and Tapia, 2014). In 2008, 53 Galápagos sea lion carcasses were found on Pinta Island with skull trauma (Soto, 2008). Denkinger et al. (2015) observed injured and dead sea lions at Wreck Bay on San Cristóbal Island, and reported that 5% of sea lion deaths and 65% of non-lethal injuries were human-caused. Of human-caused injuries, 43% were due to lacerations or blows, 40% to entanglement in plastic or debris, 14% to propeller injuries, and 8% to fishing gear. Causes of human-wildlife conflict are complex and multifactorial, including unintentional injuries as wildlife interact with manmade constructs, such as fences; intentional illegal harvest of animal parts (such as turtle shells, shark fins, or sea lion penises) for sale on the black market; and perception of wildlife as a nuisance due to their interaction with farmland or livestock. Injuries that result from these interactions may be difficult to identify, particularly if they do not lead to death; in addition, active human-wildlife conflict may not be observed, particularly in remote areas. Mitigation of these conflicts thus requires determining and addressing the underlying cause of the conflict, as discussed throughout this review.

2.5 Sustainability of human settlements

In this review, we have highlighted the importance of investing in sustainable local infrastructure in the Galápagos Islands. Many anthropogenic pressures threatening biodiversity can be mitigated through improvements in public services that appropriately support local communities.

2.5.1 Economic sustainability and poverty

From 2011 to 2012, the monthly average income of a Galápagos resident was $1,901 USD, while the monthly expenditure was $1,522 USD (National Institute of Statistics and Census (INEC), 2017). For comparison, the average monthly family income of an Ecuadorian household was $735.47 in 2019 and $746.67 in 2021 (Macías et al., 2022). The higher average income in the Galápagos Islands is somewhat offset by a higher basic cost of living; the "Basic Food Basket" is 80% more expensive in the archipelago compared to the mainland (National Institute of Statistics and Census (INEC), 2017). Because Galápagos food production is not self-sustaining, there is still heavy reliance on imported products. As of 2016, 4,000-5,000 tons of goods per month were imported from mainland Ecuador, including 38% of fresh fruits and vegetables and most dry food products, bringing the total proportion of imported supplies close to 70-75% (Viteri and Vergara, 2017; Pizzitutti et al., 2016; Sampedro et al., 2020). With rising demand for consumer goods, imports are likely to increase, necessitating corresponding expansion of ports (Pizzitutti et al., 2016). Without changes in food policy, Sampedro et al. (2020) predicted that imports would increase to 95% by 2037. In 2014, the profit margin of intermediaries in the Galápagos Islands was estimated to reach 30%, further contributing to the high cost of living (Llive-Cóndor, 2017). Reliance on imported products therefore influences economic resilience and contributes to ecosystem deterioration, given the relationship between cargo shipping, invasive species, and fossil fuel use.

Tourism is the most rapidly growing industry in the Galápagos Islands, encompassing an estimated 51% of the economic landscape in 2007 (Watkins and Cruz, 2007) and 80% as of 2016 (Pizzitutti et al., 2016). The Central Bank of Ecuador estimated that tourism is responsible for 64% of gross value added (Galaípagos Government Council, 2021). Nonetheless, prior studies have estimated that only 7.6-15.5% of revenue generated from tourism directly reaches Galápagos residents, with most revenue absorbed by companies based on mainland Ecuador (de Miras, 1995; Taylor et al., 2009; Watkins and Cruz, 2007). However, Taylor et al. (2003) highlighted the importance of considering not only the direct effects of tourist expenditures, such as revenue generated by hotels, eateries, and travel agencies, but also the indirect effects of tourism. For instance, tourism stimulates production from the fishing, agriculture, livestock, forestry, and drinking water industries, although these sectors do not typically sell products directly to tourists but rather to intermediaries (Taylor et al., 2003). The increased demand for production from these sectors translates to increased income for residents (Taylor et al., 2003). The widening wage gap between the Galápagos Islands and mainland Ecuador could further increase the attractiveness of migration to the archipelago (Taylor et al., 2003).

2.5.2 Education

Addressing deficits in the Galápagos educational system was a key goal cited by UNESCO in 2007 and factored into the decision to include the Galápagos Islands in the List of World Heritage in Danger (UNESCO, 2007). UNESCO called for training and assessment of students and teachers, curriculum reform to incorporate environmental management, and improved vocational training and funding to empower residents to meet local professional needs. Fifteen years later, the Galápagos public education system is still lacking in several areas, including curricular deficiencies, inadequate facilities and infrastructure, poor access to print and digital resources, and outdated teaching practices that favor rote memorization rather than active learning. Cotner and

Moore (2018) documented that biology teachers lack expertise to adequately teach the core principles of Darwinian evolution. In addition, many Galápagos residents lack sufficient understanding of sustainable practices necessary for natural resource stewardship. Improvement in the quality of primary and secondary education would increase conservation awareness in the next generation (Jones, 2013). In addition, increased bilingual education and improvement in special needs programs is necessary. Access to education for all Galápagos residents remains one of the key goals of the 2023 Vision. In January of 2023, the Galápagos Conservancy's Education for Sustainability Program, a collaborative effort with international, national, and regional stakeholders, made headway towards a new curriculum for Galápagos students that incorporates principles of environmental sustainability.

The public school system also lacks information access due to a deficit of public libraries and limited internet connectivity. The COVID-19 pandemic further highlighted issues in education access, with 33% of students having insufficient internet connectivity to attend virtual classes (Galaípagos Government Council, 2021). The CDF initiated a traveling library program in 2019 to deliver books to schools, naturalist guides, and GNP employees (Charles Darwin Foundation, 2023, Charles Darwin Foundation, 2020). Until 2022, satellite internet connectivity was expensive and slow, with limited utility for education (Urquizo et al., 2019). High-speed internet was implemented in 2022, but is not yet available in all sites. In 2019, Urquizo et al. (2019) developed a community intranet system to increase local connectivity between schools on San Cristóbal Island (Urquizo et al., 2019). In addition, the CDF hosts a digital platform for information access, Galapagueana, that provides access to a subset of library archives. However, many older scientific publications of regional research are still only accessible in print, hindering access to the wider scientific community.

Educational opportunities for Galápagos residents must also be developed. Professional training, particularly in vocations focused on the environment, science, and research, would better equip residents to meet the needs of industries in the archipelago, allowing more economic revenue to be conserved locally. In addition, continuing education (CE) programs should be encouraged for residents with tourist-facing professions. For example, in a survey of GNP naturalist guides, most accepted the concept of evolution but expressed interest in learning more (Cotner et al., 2017). Because tourists visiting protected areas must be accompanied by a guide, guides can disseminate knowledge to tourists, encouraging conservation-minded decisions and compliance with regulations. In addition, guides are an important source of monitoring of tourist activity.

2.5.3 Energy use

Access to clean and affordable energy is crucial for sustainability development and is linked to many other areas of human development (WHO, 2022). The Energy Balance of the Province of Galápagos, prepared by the Geological and Energy Research Institute (IIGE), provides an overview of energy use and production. As of 2018, approximately 90% of energy consumed in the Galápagos Islands was imported, primarily as petroleum derivatives (IIGE, 2018). The archipelago is thus still heavily reliant on fossil fuel consumption. In 2018, the transportation sector was responsible for 84% of energy consumption overall, including 99% of diesel and 100% of gasoline (IIGE, 2018). The remaining energy consumption was divided between residential (8%), public service (5%), construction (3%), and industry (<1%) uses (IIGE, 2018). The residential sector was responsible for the greatest consumption of liquid gas (82%) (IIGE, 2018). Of the 160,900 tons of greenhouse gas emissions produced in the Galápagos Islands in 2018, diesel was responsible for 74% and gasoline for 22% (IIGE, 2018).

In 2022, according to the Agency for the Regulation and Control of Non-Renewable Energy and Natural Resources (ARC), more than 13,000 clients were registered with the Gálapagos electric company (Agency for the Regulation and Control of Non-Renewable Energy and Natural Resources (ARC), 2022), representing nearly 99.7% coverage of the public network (National Institute of Statistics and Census (INEC), 2015). Santa Cruz Island utilizes 60.7% of the electrical energy supply, followed by San Cristóbal (30%), Isabela (8.7%), and Floreana (0.6%) (IIGE, 2018). The public sector (43%) and residential sector (39%) account for most of the electric use (IIGE, 2018).

Pizzitutti et al. (2016) predicted that to meet rising demand for energy due to population growth and increased use of air conditioning, electrical appliances, and personal electronic devices, installation of more diesel-powered generators and importation of fossil fuels will likely occur. As previously highlighted in this review, the risk of marine pollution due to fuel and oil spillage is a major risk to the region. Research on the replacement of fossil fuels is thus a high priority for the region.

Of the energy produced locally, 84% is of thermal origin, 12% wind, and 4% solar (IIGE, 2018). There are currently two wind turbine plants in the Galápagos Islands, and solar panel installation is increasing (Pizzitutti et al., 2016). From 2013 to 2018, solar energy production steadily increased, accounting for approximately 30% of primary energy produced in in 2018 (IIGE, 2018). However, neither wind nor solar are yet viable alternatives to diesel in terms of fully meeting energy needs (Pizzitutti et al., 2016). Without implementation of new renewable energy resources, the proportion of clean energy in the archipelago may drop to only 5% of total energy by 2033 (Pizzitutti et al., 2016).

Llerena-Pizarro et al. (2019) proposed a hybrid solar/biogas energy generation system, with the goal of improving energy efficiency, diversifying the energy matrix and promoting sustainable local development. Based on a computer model, Arévalo et al. (2022) proposed that the archipelago had the potential to fully convert to renewable energy systems by 2031, through a combination of photovoltaic, wind, hydroelectric, and battery systems, with diesel utilized solely for backup generators. Further research into these alternative energy systems is crucial.

2.5.4 Sanitation and water sustainability

A major milestone of sustainable development outlined by the WHO is water availability and its sustainable management, which implies safe drinking water, water resource development, wastewater management, and protection of aquatic biological resources (WHO, 2022). Poor water quality is a threat to public health, associated with respiratory and gastrointestinal disease (Liu and d'Ozouville, 2011), and poses barriers to agriculture, economic sustainability, and aquatic ecosystem health. Human and animal water and waste management are inextricably intertwined; mismanagement of sewage or failure to appropriately treat drinking water contributes to infectious disease outbreaks across species boundaries.

The municipal water and irrigation supply in the main urban areas of the Galápagos Islands are provided primarily via aquifers, cisterns, or rooftop tanks (Mateus et al., 2020, Mateus et al., 2019). Aquifers contain primarily brackish water derived from seawater invasion. A desalinization plant has been present on Isabela Island since 2014, but does not function optimally. There are two drinking water plants on San Cristóbal Island. Municipal water on Santa Cruz Island is primarily untreated brackish water, considered non-potable by national and international standards (Reyes et al., 2015). Gerhard et al. (2017) reported that 90% of point-of-use water access sites on Santa Cruz Island had high levels of microbial contamination. In a survey of 453 households on Santa Cruz Island, 0% of respondents reported drinking water directly from the tap, while 13.1% of households treated tap water before consumption, and 90.1% purchased carboys of drinking water (Vásquez et al., 2021). In some cases, residents use cisterns or roof tanks to store treated drinking water (Grube et al., 2020). Overall, potable water supplies are derived predominantly from bottled water (Reyes et al., 2015; Houck, 2017). However, municipal water is commonly used for household washing and food preparation, resulting in exposure to fecal coliforms and development of waterborne gastrointestinal illnesses (Houck, 2017).

An official report on wastewater management in the archipelago states that the three municipalities utilize public sewerage systems (National Institute of Statistics and Census (INEC), 2017). However, Mateus et al. (2020) reported that on Santa Cruz Island, 97.2% of households use septic tanks, and just 1.9% utilize public sewerage. Thus, in practice, there is virtually no functional sewerage network. So far, evidence suggests that inefficient budget management inhibits the development of sanitary systems and implies a lack of transparency, misallocation of funding, disregard of research data, and lack of prioritization, coordination, and local participation (Mateus et al., 2020). Insufficient and ineffective wastewater treatment plants contribute to poor water quality and groundwater contamination, which can then flow into coastal waters.

Human activities are responsible for contamination of both ground and coastal water in the Galápagos Islands (Liu and d'Ozouville, 2011; Walsh et al., 2010; Overbey et al., 2015; Mateus et al., 2019), with malfunctioning septic tanks implicated as a major contributor (Liu and d'Ozouville, 2011). Fecal contamination of coastal areas led to regulations on recreational activities (Stumpf et al., 2013). Population growth also contributes to water contamination, as the basal aquifer on Santa Cruz Island is located beneath dense urban areas (López and Rueda, 2010). Interestingly, population changes were more strongly correlated with changes in water quality at coastal than inland sites (Mateus et al., 2019). Coastal waters are additionally contaminated by fuel from marine vessels (Walsh et al., 2010).

There have been multiple documented breaches in sanitation with regards to livestock management – particularly swine and poultry – posing risks to human and wildlife populations, including infectious diseases and antimicrobial resistance (AMR). At the national level, the Organic Health Law prohibits the use of rivers, canals, lagoons, lakes, seas, and other natural aquatic sites for discharge of sewage or wastewater produced from animal husbandry or agricultural activities, without proper treatment (Secretariat of Water (SENAGUA) and Agency for Water Regulation and Control (ARCA), 2016). While the Santa Cruz municipality treats effluents from food processing, manufacturing plants, and a hotel using artificial wetland systems, these actions are not generalized to all sources of wastewater, and waste-water treatment plants (WWTPs) have limitations (Liu and d'Ozouville, 2011). Animal waste consisting of manure or viscera is sometimes directly discharged from farms, leading to soil and groundwater contamination (Chiriboga et al., 2006). New data from Ecuador's National Agricultural Register (Registro Nacional Agropecuario (RENAGRO)) indicates that 45.2% of animal waste is untreated and 47.4% is used as fertilizer, while agricultural residues are mostly incorporated into the soil (57.5%) (Ministry of Agriculture and Livestock, 2022). While there are mandatory biosecurity protocols for livestock farms, their implementation is minor (Puente-Rodríguez et al., 2019). Pathogen introduction via imported feed is also a potential threat, although this has not been definitively documented in the region. The Management Framework for the Program about Climate Change in Galápagos determined that safeguards/investments should be established for environmental problems related to livestock waste, agroprocessing plants, and the coffee industry (Development Bank for Latin America and the Caribbean, 2022). Adequate sanitary conditions and disease prevention go hand in hand with both ecosystem and economic sustainability (Chiriboga et al., 2006).

Several efforts to improve water quality in the Galápagos Islands have been implemented in the last decade. Drinking water treatment plants were associated with a significant decrease in coliform contamination on San Cristóbal Island compared to pre-treatment levels; however, coliforms were still identified in 66% of points of use (Gerhard et al., 2017). In that study, researchers found that *E. coli* contamination of drinking water did not appear to be associated with human waste contamination, but was likely linked to environmental sources (Gerhard et al., 2017). In 2021, fog catchers were installed on Isabela Island as part of the "Harvesting Water" project, with the goal of establishing a fresh water supply and contributing to sustainable agriculture (Charles Darwin Foundation, 2021). Filtration technologies have been implemented to re-use treated wastewater (Galápagos Conservation Trust, 2021). Groasis Waterboxx®, a water-saving technology, has been implemented on several islands to augment irrigation practices for growth of several crops (Jaramillo Díaz et al., 2022).

3 Complex impact of the COVID-19 pandemic

In this section, we discuss the impact of the COVID-19 pandemic on socioeconomic, public health, and wildlife health in the Galápagos Islands. Mainland Ecuador and the Galápagos

Islands have public health systems comparable to those of other low- to middle-income countries, yet the epidemiology of the COVID-19 pandemic was strikingly different between these locations. The first recorded case of Severe Acute Respiratory Syndrome – Coronavirus 2 (SARS-CoV-2) in Ecuador occurred on February 29, 2020 (Vallejo-Janeta et al., 2023). Due to a combination of factors, including lack of emergency preparedness, diagnostic capacities, poor protective equipment, early detection and contact tracing strategies, COVID-19 rapidly overwhelmed the public healthcare system and caused a humanitarian crisis in Ecuador (Alava and Guevara, 2021). Compared to other countries, Ecuador had one of the highest excess death rates during the pandemic; indigenous populations were also disproportionately affected (Cuéllar et al., 2021). In contrast, efficient control and eradication of COVID-19 in the Galápagos Islands was made possible by several measures. To support the public healthcare system during the pandemic, both public and private funds were provided from national and international sources (Galaípagos Government Council, 2021). Since most of the archipelago is designated as a protected area, communities tend to be densely concentrated, increasing the spread of infection. The remote location also limits access to specialized healthcare facilities and diagnostics. Lockdown, isolation, and on-site testing were thus key priorities for efficient control of COVID-19 in the Galápagos Islands. Within six weeks of the first identification of SARS-CoV-2 in the Galápagos Islands in March 2020, an on-site SARS-CoV-2 testing laboratory staffed by ABG personnel was established through multi-institutional collaborations (Vallejo-Janeta et al., 2023). ABG typically carries out a variety of disease surveillance and prevention measures; during the pandemic, these efforts pivoted to primarily focus on COVID-19 molecular diagnostics. Conversely, only three laboratories in mainland Ecuador were carrying out COVID-19 testing in the early days of the pandemic, and thus lacked the capacity to meet testing needs for a population of 17 million individuals (Vallejo-Janeta et al., 2023). These differences further highlight the importance of considering the Galápagos Islands as a distinct entity with unique needs, and for developing public health management strategies on a regional basis.

At the start of the COVID-19 pandemic in February 2020, a moratorium on visitation to the Galápagos Islands was instituted. These efforts, alongside surveillance and isolation procedures for residents, were key in limiting the spread of SARS-CoV-2. However, the pandemic was associated with severe economic impacts. Despite decades of calling for economic diversification in the region, the Galápagos economy remains highly dependent on tourism. The effects of halting tourism were widespread: operators of hotels, restaurants, shops, and other tourist-facing professions found themselves without employment or facing a sharp drop in customers. As a result of border closures, fishing exports declined and prices of fish, such as tuna and lobster, declined up to 43.0% (Viteri et al., 2022). In June 2020, tourism was allowed to resume at a reduced level; that year, tourism was 73% lower than the 271,000 visitors of 2019 (Burbano et al., 2022). Pandemic-associated economic losses in the Galápagos Islands have yet to be fully quantified.

The Galápagos Islands nonetheless demonstrated a degree of economic resiliency at the peak of the pandemic. Fisheries underwent adaptive shifts in the food supply chain in the Galápagos Islands (Viteri et al., 2022; Castrejón et al., 2024), as with other oceanic islands (Thurstan et al., 2021). Artisanal fishermen shifted from catering to overseas markets and tourists to providing local food (Viteri et al., 2022) while Galápagos residents also modified their seafood consumption patterns (Castrejón et al., 2024). During this time, the Galápagos Genetic Barcode Project also encouraged economic resilience while promoting citizen science by employing fishermen and guides to participate in microbiome research and invasive species identification (Chaves et al., 2023). The risks of over-reliance on tourism were highlighted by the pandemic and served as further impetus to promote economic diversification (Galaípagos Government Council, 2021). In 2021, the Galápagos Government Council released a Reactivation Plan that outlined a framework for socioeconomic recovery in the wake of the pandemic, with wellbeing, productivity, connectivity, and institutionality as key defined areas for action. Today, the Galápagos Islands are considered free of COVID-19 and its population is highly vaccinated. However, with such high tourism rates and the potential for new strains of SARS-CoV-2 to emerge, continued vigilance is necessary. In addition, while no screening of marine mammals for SARS-CoV-2 has yet been performed in the Galápagos Islands, other groups have highlighted this potential threat (Mathavarajah et al., 2020; Audino et al., 2022; Johnstone and Báez, 2021).

Given the complicated interrelationship between tourism, conservation and socioeconomic sustainability in the Galápagos Islands, further research is also warranted into the downstream effects of the COVID-19 pandemic on ecosystem health in this region. Lockdowns during the COVID-19 pandemic resulted in widespread reduction in human movement, including travel and presence outdoors. Rutz et al. (2020) proposed the term "anthropause" to describe this period, and suggested that the pandemic provided a unique setting in which to study the effects of human activities on wildlife. No published studies to date have evaluated the impacts of the pandemic on Galápagos biodiversity. Reduced human activities have the potential to diminish anthropogenic threats to wildlife, such as plastics, fuel, and air pollution; light and noise pollution; and vehicular and boat collisions. However, a decline in tourist traffic to protected areas suggests a corresponding decrease in the presence of local law enforcement and naturalist guides; it is unknown whether this decrease in monitoring could have facilitated illegal wildlife trade activities in the Galápagos Islands.

In other regions, researchers have evaluated wildlife population distribution and behavior during the anthropause in comparison to pre-pandemic trends, suggesting that lockdowns reduced foot traffic, vehicular accidents, and environmental pollution (Corlett et al., 2020). Reduced human presence also coincided with reduced wildlife disturbance, increased proximity of wildlife to roads and movement of wildlife back into formerly abandoned habitats (Thurstan et al., 2021; Tucker et al., 2024; Cukor et al., 2021). While Bates et al. (2021) suggested that reduced human presence benefited wildlife conservation overall, others have proposed that the anthropause was also associated with negative impacts on wildlife. Conservation efforts were impacted by cancellation of research trips and project delays, funding declines, and infrastructure deficits (Thurstan et al., 2021). Decreased monitoring and enforcement personnel resulted in impairment of invasive species management, and also coincided with increased poaching in some areas (Behera et al., 2022; Waithaka et al., 2021; Manenti et al., 2020). Online forums also persisted as reservoirs of the illegal wildlife trade despite pandemic-associated lockdowns (Morcatty et al., 2021). Poaching also increased as a result of economic instability in areas heavily reliant on tourism; the Seychelles, for example, lost 3.8 million USD in tourism income (Thurstan et al., 2021), associated with a subsequent increase in unsustainable harvesting of natural resources and wildlife trafficking.

4 Steps towards a sustainable future

In this two-part review, we outline the complex interrelationships between tourism, biodiversity, and sustainability in the Galápagos Islands and demonstrate the need to incorporate a One Health perspective when developing management and conservation strategies for the region. Despite the many protections in place to safeguard wildlife health, maintain biosecurity, and limit human impacts, the archipelago remains under mounting pressures. These threats include ecological degradation secondary to agricultural land use, pollution, and invasive plant species; predation, competition, and habitat destruction due to invasive vertebrates; parasitism and disease spread by invasive arthropods; and population declines secondary to overfishing and the illegal wildlife trade. Many of these pressures also increase susceptibility to infectious disease outbreaks, which in turn have the potential to decimate endemic wildlife populations, as well as threaten food security or cause human disease. In this era of globalization, infectious diseases can rapidly spread to new locations through passenger travel or along shipping routes in contaminated cargo, making it imperative to maintain vigilance for pathogens that have emerged in other regions and have the potential to spread to the Galápagos Islands.

To address these issues, multimodal surveillance efforts are key to prevent the entry of introduced and invasive species. Centralization of regional biosecurity management under ABG has resulted in significant improvement in the efficiency and scope of surveillance for current and emerging threats. However, there are multiple potential avenues for improvement, including targeted inspection of cargo crates, reduction in storage time for cargo between inspection and loading, enhancing vaccination efforts for domestic animals, and controlling canine overpopulation, Furthermore, prompt reporting of non-native species is necessary to rapidly detect any threats that may have evaded initial surveillance efforts, and to implement timely control and eradication measures. Several routes of human-domestic animal-wildlife contact also fail to be fully regulated by current guidelines. For example, backyard poultry may come into direct or environmental contact with endemic or migratory birds; grazing livestock may interact with migrating giant tortoises; and feral dogs or cats may engage with wildlife. Because of the natural fearlessness of Galápagos wildlife, it is also common for wildlife to approach tourist areas. For example, birds frequently land on restaurant railings or approach outdoor markets, and thereby may retrieve processed foods, even without tourists actively attempting to feed them. The use or improper disposal of banned products by tourists is also difficult to regulate, given the volume of visitor traffic to the region.

We propose that more rigorous education for tourists may help mitigate certain gaps in biosecurity. Namely, we suggest the development of a certification program of environmental stewardship for cruise ships, dive boats, and other tour operators, which often have contact with tourists prior to arrival. Encouraging buy-in from tour companies provides an unexplored avenue for promoting ecosystem-conscious behavior among the tens of thousands of visitors to the archipelago each year. To earn the certification, participating tour companies could be required to meet benchmarks demonstrating commitment to sustainable tourism. For instance, the list of prohibited items could be delivered electronically to passengers before the trip, with suggestions for compliant alternative products. With younger generations being increasingly technology-minded, informational videos could similarly be distributed, with reminders to avoid ecosystem disruption. Corresponding print materials could also be available before and during the trip, to access a wider audience. Bringing this information to the forefront of tourists' minds may promote voluntary, individual avoidance of activities that may be otherwise difficult to monitor or enforce, such as the use of reef-toxic sunscreens, or improper disposal of antibiotics, plastics, and cigarette butts, which have the potential to detrimentally impact wildlife and environmental health. In many cases, prohibited items may be brought in passenger baggage without malicious intent, and may be used without awareness of their detrimental impacts. By enhancing tourist education in advance of the trip, more sustainable choices could be made. In addition, participating cruise ships could also require passengers to step through disinfectant shoe baths and provide designated areas for the disposal of prohibited items or other waste before disembarking, thus augmenting local biosecurity and waste management efforts.

Addressing current threats to the archipelago requires not only the development of management plans and regulations, but also necessitates appropriate infrastructure and monitoring and enforcement personnel, as well as encouraging buy-in from local stakeholders. Therefore, wildlife and environmental conservation strategies must also consider challenges facing human populations in the region, such as barriers to education and scientific research, unsustainable water and energy use, and deficits in sanitation and waste management. The socioeconomic stability of the archipelago is also highly linked to the tourism sector; the detrimental impacts of this overreliance were made abundantly clear during the COVID-19 pandemic.

Investing in local infrastructure development and economic diversification are key to building resiliency and sustainability across multiple sectors. Enhancing secondary education and professional training will increase the availability of Galápagos residents to fill open positions within regulatory agencies such as ABG, thus enhancing the capacity for research and surveillance while promoting economic diversification. Similarly, capacity-building activities for local farmers would be a key effort to improve buy-in for sustainable agricultural practices, and would thus promote food security while simultaneously encouraging

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TABLE 1 Recommendations for progress in One Health in the Galápagos Islands.

Domain	Goals	Pillar			
		Education	Regulations & Infrastructure	Monitoring	Research
Invasive Species	–Reduce introduction of invasive species –Develop plans for existing invasive species	–Publish digital and print lists of prohibited organic products in English and increase distribution to tourists	–Limit mainland cargo holding time –Develop secure storage environments for cargo holding that limit moisture and vermin	–Involve local stakeholders to develop, implement, and oversee management and eradication plans for existing invasive species	–Investigate the current status previously understudied invertebrates –Continue to study potential mechanisms of entry for invasive species
Infectious Diseases	–Monitor pathogens of public and veterinary importance –Efficiently identify new threats	–Public education campaigns to encourage personal hygiene, biosecurity, and reporting infectious disease concerns	–Implement disinfectant baths for sanitization of shoes and luggage wheels at docks and tourist sites within the GNP –Develop a One Health monitoring network to centralize and share data	–Perform screening tests such as PCR and ELISA on livestock serum, fecal, and milk samples –Screen wildlife non-invasively for infectious diseases	–Develop new tests for pathogen surveillance that can be implemented on-site, such as colorimetric tests or rapid detection swabs –Perform risk assessment on biological control methods
Pollution	–Mitigate and reduce the impacts of tourism Reduce terrestrial and marine pollution	–Incentivize sustainable behavior via a certification program for tour companies –Implement educational videos and pamphlets at ports of entry –Restrict tourist import of single-use plastics, microplastic-containing products, reef-toxic sunscreens, and antibiotics, and provide secure drop-boxes for tourists to discard prohibited products	–Develop permanent regulations to limit the number of tourists per year, as requested by UNESCO, including a moratorium on new tourism projects and limits on the number of flights –Regulate products sold by stores to limit accessibility of products with detrimental environmental effects	–Expand upon GGMN and DiveStat programs and conduct load studies to monitor tourist activities and revise visitor site quotas	–Develop sustainable/reusable versions of single use items that are produced and/or recycled locally
Local Capacity Building	–Invest in community education, training, and development for conservation and biosecurity	–Establish clear parameters for curriculum development and assessment at all levels of education, incorporating active learning and subjects related to environmental conservation –Enhance specialized training to meet demands for professions focused on the environment, including microbiology and biosecurity –Provide continuing education for tourist-facing processions	–Construct and operate universities in the Galápagos Islands –Improve internet connectivity for and access to print and digital media educational facilities –Enhance accessibility to peer-reviewed literature	–Enhance training for National Park guides in identifying and reporting invasive species and sightings of illness in endemic animals	–Encourage NGOs to include Ecuadorian members amongst their boards and leadership, with specific emphasis on including representatives from the Galápagos Islands –Enhance local research through funding and mentorship partnerships with universities / NGOs
Conservation	–Conserve endemic species Encourage local buy-in for conservation projects	–Educate fishermen on the long-term benefits of marine zoning and observing fishing seasons and quotas –Promote local buy-in for reporting infractions of fishing regulations	–Increase go-slow zones in designated marine areas –Lobby the International Union for Conservation of Nature (IUCN) to make regional status reports readily available –Create wildlife corridors through farmland to maintain habitat connectivity and decrease human-wildlife or domestic animal-wildlife encounters	–Provide a method for anonymous reporting of concerning activities, such as illegal wildlife trade, wildlife injuries or other sightings –Foster international partnerships to curb the global sale of illegal wildlife products –Ensure appropriate patrolling of the GMR to enforce protected areas	–More frequently and accurately assess the status of endemic species, with the goal of more frequent IUCN status updates –Develop new technologies to remove plastics, POPs, oil, and other pollutants from contaminated natural waters –Encourage prospective research into population-level effects of travel restrictions on Galápagos wildlife populations

(Continued)

TABLE 1 Continued

Domain	Goals	Pillar			
		Education	Regulations & Infrastructure	Monitoring	Research
Food Sustainability	–Promote food sustainability Enhance sustainable agricultural practices –Develop clean water solutions	–Hold workshops for farmers to develop skills and learn sustainable agriculture practices, such as crop rotation –Encourage use of appropriate pesticides and fertilizers by highlighting the detriments of banned pesticides	–Establish entry restrictions for organic products that may be developed on island territory –Enforce restrictions on local sales of prohibited products, such as pesticides –Develop safe and sustainable water sources for drinking and irrigation	–Facilitate surrender of banned pesticides by providing secure drop-boxes or exchange sites accessible to farmers	–Develop novel strategies to control agricultural runoff –Develop strategies to protect farmland from invasive plant species, decreasing farmland abandonment –Diversify local food production and promote consumption of local products to decrease reliance on imported goods and promote economic stability
Energy Use	–Enhance clean energy use		–Set goals for sustainable energy sources to replace fossil fuel use		–Research strategies for implementing alternative energy sources such as photovoltaic, wind, hydroelectric, and battery systems
Waste Management	–Develop sustainable waste management	–Enhance education for Galápagos citizens and tourists on appropriate waste disposal	–Improve infrastructure for waste management, including trash collection, recycling, and composting –Implement drop-boxes for unwanted products with the potential to harm the environment if discarded as trash, such as batteries or antibiotics –Construct wastewater treatment plants on the inhabited islands		–Encourage further research on rapidly implementable water sanitization solutions that can be used in individual homesteads –Develop research projects on sustainable degradation and/or waste reduction using innovative techniques (e.g. bacterial or fungal biodegradation of waste)
Public Health	–Protect public health and safety	–Develop and implement antimicrobial stewardship guidelines in the public health and veterinary sectors, for both healthcare professionals and residents	–Standardize methods for shipping hazardous waste to mainland Ecuador –Promote biodegradable materials for packaging and shipping –Improve healthcare infrastructure within the province	–Manage epidemiological surveillance projects for monitoring of infectious diseases –Perform serologic surveys for pathogen exposure in humans and animals	–Partner with local medical facilities to develop early warning systems for AMR pathogens and diseases of public health importance
Domestic Animals	–Improve health and population management of domestic animals	–Educate farmers and pet owners on appropriate domestic animal waste management –Educate dog owners on vaccine safety and parasite preventatives –Promote sterilization and discourage breeding of pet dogs	–Lobby for the implementation of vaccines for preventable diseases in domestic animals, such as Newcastle Disease Virus in poultry –Promote local access to veterinary care and ectoparasite preventatives for pets –Mobilize veterinarians to provide spay and neuter efforts	–Promote containment of domestic animals to reduce contact and disease transmission with endemic species, including keeping pets in confined/ supervised areas and containment strategies for backyard poultry –Encourage collaboration between public health and veterinary sectors for comprehensive infectious disease monitoring	–Facilitate research on incidence and spectrum of antimicrobial resistance in poultry, livestock, and pets (dogs and cats)

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adherence to regulations that safeguard environmental and animal health. Educational workshops, for example, could emphasize practical strategies to fight invasive plants, and supplies and/or labor assistance could be offered to incentivize farmers not to abandon farmland. Financial incentives for local food producers would also augment both the quality and profitability of local produce, thereby reducing reliance on imported goods and the environmental footprint associated with shipping. Building the financial power of local farmers would allow acquisition of better technologies and investment in sustainable agricultural practices. Efforts should also be made to emphasize the long-term economic and environmental benefits of choosing sustainable pesticides while providing secure locations at which to dispose of or exchange prohibited pesticides. This strategy could appeal to farmers that still have pre-ban supplies of pesticides that they were aiming to use up before purchasing new products, as well as farmers seeking out banned compounds simply because they are historically familiar with their use and unaware of their drawbacks or alternatives. Finally, educational resources to help farmers recognize banned pesticides, and providing avenues for anonymous reporting to local authorities, could improve enforcement and enhance sanctions against suppliers, thus targeting the source of the compounds.

The Galápagos Government Council's Strategic Plan provides a birds-eye-view of goals that, once achieved, will ensure sustainability of both ecosystems and communities in the Galápagos Islands by 2030. This plan includes sustainable interactions with the environment, a diverse, stable economy, food security, robust political governance, and strong public infrastructure to provide for community needs, from waste management to access to healthcare and education. To progress towards these overarching goals, we have proposed a set of detailed and actionable recommendations, outlined in Table 1. We identify specific areas for improvement in the context of four pillars: education, regulations and infrastructure, surveillance, and research.

Anthropogenic activities have forever changed the face of the Galápagos Islands, as they have changed nearly every other region on Earth. Limitations and regulations on tourism – both in terms of numbers and activities – are necessary to prevent the industry from far outstripping the capacity of Galápagos resources if it continues along its current course. However, we must also recognize that local communities can and must be at the forefront of environmental stewardship for the archipelago, and the health of each are inextricably intertwined. Only by producing more harmonious interactions between humans and the natural world can we ensure that projected visions for a sustainable future have the chance to become a reality.

Author contributions

PV-M: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. IAJ: Conceptualization, Data curation, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. TV: Investigation, Writing – original draft, Writing – review & editing. ELH: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Writing – original draft, Writing – review & editing.

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Author PV-M was employed by the company ABG.

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