Chapter 17
Land Use and Land Cover Change in the Galapagos: Economic and Natural Drivers

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Introduction

Oceanic islands around the world are intense microcosms of global environmental pressures, including land use and land cover (LULC). Small size and isolation make oceanic islands especially vulnerable to environmental change (Alomía Herrera et al. 2022), while complicating socioeconomic challenges brought on by limited land resources and institutional capacities (Benítez et al. 2019). These environmental and social pressures make islands compelling "natural laboratories" for ecological, economic, and sociological research, and few have garnered as much scholarly attention as Ecuador's Galapagos Islands. With acute land limitations, brisk economic growth, and severe exposure to climate change, they are an ideal place to study the ecologies and economics of land use and land cover in a rapidly changing world. Despite strict and extensive environmental protections, land use and land cover are changing more quickly than ever before (Percy et al. 2016), alongside a rapidly growing population and tourism industry. More than a 1000-km from the South American mainland, the archipelago went unseen by humans until 1535, after which inhospitable terrain and limited freshwater staved off permanent settlement until 1832. While any notion of the Galapagos as an "untouched" wilderness is misconceived, the archipelago is indeed closer to its pre-human state than almost any other place on Earth (Orellana and Smith 2016; Izurieta et al. 2018), providing valuable opportunities to study the early effects of human use on a range of ecosystems (Khatun 2018; González et al. 2008).

Land use and land cover changes in the Galapagos reflect both competition and synergy among environmental and social goals. The "Galapagos paradox" (Walsh and Mena 2016) describes this uneasy balance; the tourism-dependent economy

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rests heavily on the islands' ecological integrity, both real and perceived, while tourists' presence degrades the ecosystems that attract them. Tourism is the Galapagos' largest driver of land use and land cover change (Benítez et al. 2019; Walsh et al. 2010), as lodging, dining, entertainment, and transportation accommodations expand to meet growing demand. The industry meanwhile siphons labor and population from the agricultural highlands, accelerating the spread of invasive plants that thrive on abandoned farmland (Barrera et al. 2021). This intersects with the ongoing tension between conservation interests and local economic growth and well-being. The Galapagos' current regulatory framework, while extensive, is failing both in sustaining ecosystems and maintaining the faith of local stakeholders. This chapter outlines a web of ecological and human processes to present a comprehensive picture of ongoing land use and land cover challenges and underpin holistic planning that embraces social and economic realities.

Land Cover History and Trajectory

Each Galapagos Island has unique ecological characteristics (Watson et al. 2010), but the islands are unified by "altitudinally compressed" land cover systems wherein disparate vegetation and climate zones exist in close proximity to each other (Laso et al. 2019). The largest islands have six altitudinal zones: the bare zone (lava rock and beaches near the coastline), littoral zone (shrubs, mangroves, and other salt-tolerant species), arid zone (low scrubs, cacti), transition zone, humid zone (scalesia shrubs and trees), and very humid zone (miconia, sedges, and ferns) (Orellana and Smith 2016). These varied land covers support the archipelago's flagship fauna, such as sea lions in the bare zone, land iguanas in the arid zone, and giant tortoises in the humid highlands. Since the first successful human settlement in 1832, land use has entailed the clearing of native vegetation and the spread of plants introduced for food and ornamentation, altering these habitats and shifting balances among plants, humans, and other animals. National and international designations now make the Galapagos one of the most regulated regions in the world in terms of land cover and land use; Galapagos National Park, established in 1959, occupies 79% of land surface (Orellana and Smith 2016). The Galapagos Special Law, passed at the national level in 1998, restricts virtually all immigration, at least in theory, and increased the authority of the national park administration (Hoyman and McCall 2013). However, immigration continues (Villacis and Carrillo 2013), and current policies fail to stem the loss of biodiversity and natural land covers.

Agricultural Highlands

The humid highlands are the archipelago's most biologically productive regions and the most conducive to agriculture (Laso et al. 2019), putting them at the forefront of early land cover changes. First came small-scale farmers, targeting lands with the

deepest soils (Alomía Herrera et al. 2022), clearing forest and vegetation and introducing familiar Ecuadorian crops (Astudillo 2018), some of which would become naturalized or invasive (Laso et al. 2019). The 1860s saw the rise of the El Progreso plantation on San Cristobal, along with the first large-scale deforestation powered by hired workers from the mainland, vastly expanding existing cleared spaces (Astudillo 2018). The largest wave of migration came in the 1970s, and although by this point farmers comprised less than one-half of arrivals (Walsh et al. 2010), agricultural land area continued to expand with illegal migration from mainland Ecuador (Pizzitutti et al. 2020). Today, the amount of agricultural land is around 19,000 hectares (Barrera et al. 2021), having contracted from its peak in some regions during the late twentieth century as farmers abandon plots and take other jobs (Alomía Herrera et al. 2022).

While agriculture's tenure as the primary livelihood in the Galapagos was short-lived, its impacts on land cover are extensive and permanent. Invasive plants, the strongest driver of land cover change in the Galapagos (Percy et al. 2016), proliferate on active and abandoned cropland. Areas of human settlement contain more introduced than native plant species, and 42% of humid highland area on the four inhabited islands is altered by agriculture and invasives (Trueman et al. 2010). More than 800 non-native plant species have been documented on the archipelago (Gardener et al. 2013; Trueman et al. 2010; Walsh et al. 2010), most of them deliberately for food or ornamental purposes (Barrera et al. 2021), and most in the latter half of the twentieth century (Gardener et al. 2013). About one-third of these species have naturalized, one-sixth have become invasive, and 3% have transformed within their new environment (Trueman et al. 2010). With less than two hundred years of settlement, the archipelago is at an "early stage" of invasion where most introduced species are confined to farms and gardens (Gardener et al. 2010), but "early stage" should not be interpreted as "mild." Invasive plants are already replacing natural ecosystems far more quickly than current management regimes can contain, and "extinction deficit" may be building up for the coming decades and centuries (Trueman et al. 2010). Key invasive species in the agricultural highlands include guava, blackberry, quinine, supirosa, and pomarrosa (Laso et al. 2019), among which guava is especially prevalent and aggressive. This highly tolerant shrub forms dense thickets that crowd out native vegetation, and it thrives on both abandoned and active agricultural land (Walsh et al. 2010). Invasive plants, especially guava, make cultivation more difficult on remaining cropland, closing a feedback loop in which invasive plants and cropland abandonment exacerbate each other. This may push highland ecosystems to new equilibria where key ecological relationships are damaged beyond repair (Wilkinson et al. 2005).

Despite agriculture's central role in introducing invasive plants, it is also critical in controlling their spread. While cropland retirement contributes to ecologically beneficial reforestation in many regional contexts (Li and Li 2017), in the Galapagos, it accelerates biodiversity loss as invasive species proliferate across abandoned cropland and into naturally vegetated zones (McCleary 2012). Various policy mechanisms may keep farmers on their lands controlling invasive species, including subsidizing local produce to compete with cheaper imports from the mainland (Khatun

2018; Miller et al. 2010), and directly subsidizing farmers' efforts to remove invasive plants (Miller et al. 2010). Other recommendations include re-engaging abandoned agricultural land for crop and livestock production, creating a framework for farmers to rent land to each other (Puente-Rodríguez et al. 2019), improving productivity through technology (Barrera et al. 2021), and strengthening enforcements against removing or harvesting native vegetation (Quiroga et al. 2011). While eradication, when possible, is usually ecologically and economically ideal, it usually proves untenable in the Galapagos (Gardener et al. 2010). An intensive 5-year effort to eradicate raspberry on uninhabited Santiago Island did lead to declines in plant and seed bank densities in managed areas, but new populations continued to crop up on other parts of the island, while collateral damage by herbicides on native plants outweighed conservation benefits (Renteria et al. 2012). Further, eradication is an appropriate goal only when reintroduction is unlikely (Meyer 2014), and frequent foot traffic across the four inhabited Galapagos Islands, and some uninhabited, keeps cross-island reintroduction possible.

Agriculture-related land cover change and invasive species threaten the survival of wildlife in addition to native plants (Khatun 2018), perhaps most visibly the Galapagos giant tortoise. Agricultural land cuts off migration routes (Benitez-Capistros et al. 2019) and removes forage, leading to lower tortoise densities and diets dominated by invasive plants (Laso et al. 2019). The high presence of invasives in tortoise diets further accelerates their proliferation and destruction of native food sources through seed dispersal (Walsh et al. 2010). Meanwhile tortoises sharing land with livestock may harbor and disperse antibiotic resistance, putting themselves, humans, domestic animals, and other wildlife at risk (Nieto-Claudin et al. 2021). While agriculture itself threatens tortoises, the decline in agriculture may be a greater threat; tortoise densities are even lower on abandoned cropland than on active cropland. Some farmers, however, have covered former cropland with semi-natural environments to attract giant tortoises and tourists. While the practice is relatively new and may not fit a purist's definition of conservation, research suggests these "tortoise farms" are successful in attracting the animals (Pike et al. 2022). However, these are profit-driven enterprises that require concerted upkeep, and with a finite market for this tourist experience, "tortoise farms" will probably amount to a very small fraction of the highlands' land use portfolio.

As new plant species shift competitive balances in the ecosystem, climate change introduces new pressures that complicates efforts to preserve natural land cover. The narrow ecological niches that make oceanic islands susceptible to invasion make them especially sensitive to warming temperatures and rising sea levels (Escobar-Camacho et al. 2021; Pizzitutti et al. 2020). The Galapagos National Park Service and Charles Darwin Foundation identify climate change as the main cause of biodiversity loss after invasive species (Dueñas et al. 2021), and the two forces interact at many spatial and temporals scales (Escobar-Camacho et al. 2021). Rising sea surface temperature will increase rainfall in both the humid highlands and arid lowlands, altering plant growth patterns, increasing erosion, and widening the competitive advantages of some already-robust invasive species (Dueñas et al. 2021; Escobar-Camacho et al. 2021). This is especially true for guava, which may

expand into new areas as the humid zone grows and tortoises disperse seeds into newly hospitable areas (Ellis-Soto et al. 2017). As more frequent and intense droughts and floods (Izurieta et al. 2018) push more farmers out of agriculture, the archipelago may also lose its first line of defense against invasive species expansion, making the conservation of native vegetation cover even more expensive and untenable. While coastal lowlands are currently less affected by invasive species than agricultural highlands (Watson et al. 2010), increased rainfall will shrink the arid zones and leave them open to some of the same invasive plants that dominate much of the highlands (Ellis-Soto et al. 2017).

Urbanized Lowlands

While demand for agricultural land has plateaued and even contracted in many areas, demand for urban space is growing quickly. Urban space in the Galapagos is generally concentrated along the coast in arid zones (Guézou et al. 2010), driven directly and indirectly by tourism. To accommodate more than 250,000 tourists per year (Escobar-Camacho et al. 2021), built areas are becoming denser and more expansive (McCleary 2012), while jobs in the tourism industry draw farmers from the Galapagos highlands and (illegally) from mainland Ecuador, who further increase demand for permanent built infrastructure. The Galapagos have a population growth rate three times higher than that of the mainland (Escobar-Camacho et al. 2021), and impervious surface on the three main inhabited islands (Santa Cruz, San Cristobal, and Isabela) increasing from 2.2% to 5.7% between 1990 and 2015, putting pressure on the health of humans, wildlife, and endemic vegetation (Benítez et al. 2019). This expansion creates its own demand for freshwater, energy (Percy et al. 2016), material imports, and waste management systems, and few concerted efforts have been undertaken to mitigate these loads (Alava et al. 2022). Traditionally, the land use imprints of water and waste management in the Galapagos have been minimal and handled at the household level, with cisterns and rooftop tanks (Grube et al. 2020), septic tanks (Ragazzi et al. 2016), and most families burying their own trash (Ragazzi et al. 2014). However, as the archipelago's population surpasses 30,000 with more than seven times that many tourists over the course of a year (Mena et al. 2020), municipal treatment plants and landfills have slowly taken root. The first landfill was constructed near Puerto Ayora in 2009 (Ragazzi et al. 2014), and now all four inhabited islands have landfills (Jaramillo et al. 2020). No working wastewater treatment plants existed in the Galapagos as late as 2010 (Walsh et al. 2010). San Cristobal and Isabela islands received wastewater treatment plants in 2012 and 2015 respectively, although Santa Cruz, the archipelago's most populous island, still does not have one (Mateus and Quiroga 2022) due to technological difficulties (Ragazzi et al. 2016). Ongoing intensification and extensification of urban land cover will make centralized water management systems increasingly critical, as demand for safe water rises while loss of forest and wetland reduce the islands' natural stormwater filtration (Mateus and Quiroga 2022). With land prices

rising and available space depleting, the provincial and municipal governments will need to act quickly to secure appropriate water management infrastructure, both built and natural. While national park boundaries and rough topography constrain urban growth more strictly than on most oceanic islands, the impacts of urbanization spread far outside town limits. The tourism industry has motivated park management to open previously off-limits land areas to visitors, replacing habitat with built infrastructure, disturbing wildlife, and introducing new species (Orellana and Smith 2016). Meanwhile rising land prices have driven some residents to build homes in unincorporated rural areas, further decreasing natural vegetation cover (Pizzitutti et al. 2020). As on many other oceanic islands, there may also be informal and peri-urban development that puts coastal ecosystems at risk (Sierra and Feng 2018).

An especially compelling consequence of urban transformation in the archipelago famous for inspiring the theory of natural selection is its effect on wildlife's evolutionary trajectories. Evolutionary processes have been less affected by human land use in the Galapagos than on longer-settled islands (González et al. 2008), but there is a growing body of work demonstrating mixed effects on Darwin's finch. The availability of human food in urban areas helps finches survive and reproduce during dry years with limited natural food sources, and urban finches produce more offspring (Harvey et al. 2021) and have higher population densities than rural finches. However, processed human foods may degrade health and overall fitness, and the urbanized niche brings Darwin's finch into more direct competition with other species (De León et al. 2019). Meanwhile finches use human-made debris to build nests, and some die from entanglement (Harvey et al. 2021; Theodosopoulos and Gotanda 2018). Urban expansion also impacts the Galapagos sea lion, which competes closely with humans for space on beaches and streets. Sea lions living on more crowded beaches are less reactive to, and avoidant of, human presence (Pavez et al. 2015), and human presence affects behavior, nursing patterns, and mother-pup recognition (Denkinger et al. 2015). With urban infrastructure and humans increasingly encroaching on sea lion rookeries, this may lead to new selection processes with uncertain long-term impacts on the endangered species' health, reproduction, and survival.

Galapagos coastal towns are among the world's most climate-vulnerable communities, with sea level rise, flooding, and exacerbated ENSO events degrading physical safety and economic security. These risks are only growing as population and infrastructure expand to accommodate more residents and tourists and the built environment replaces natural flood-regulating landscapes (Quiroga et al. 2011). Emerging physical realities will meet with uneven economic geography and force the local, provincial, and national governments to make difficult choices to preserve the Galapagos' social and economic future. With tourism accounting for 80% of the economy (Escobar-Camacho et al. 2021), preserving businesses, infrastructure, and comfort in coastal towns will undoubtedly be a high priority. However, this may create conflicts of equity when public spending disproportionately benefits wealthier coastal populations and tourists at the expense of rural citizens. Such visible disparities in both economic status and public funds may exacerbate the exodus of

farmers, whose work is critical for food security and controlling invasive plants. These imbalances may be resolved with international funding for climate resilience throughout the Galapagos as a matter of global environmental heritage, so the burden does not fall entirely on a tiny, remote province or a small, middle-income country. International nongovernment organizations already spend millions of dollars each year on broad conservation efforts in the Galapagos, largely on education and projects that directly conserve habitats and endemic species. The author is unaware of any major international funding efforts to assist Galapagos farmers in continuing agricultural production and invasive species management amid growing economic and environmental pressures. As farmers are the primary custodians of disturbed highland ecosystems, and pillars of the archipelago's long-term economic diversity and food security, environmental groups may be justified in directing some funds toward farmers' success and security. With market forces strongly favoring coastal urban economies, it is up to the public and nonprofit sectors to protect and support the other keepers of this natural laboratory.

Closing Remarks

The Galapagos' millennia-old land cover patterns are permanently altered from a few centuries of human use. When the first boots introduced alien plant species and later the first residents-built farms and towns, the terrestrial ecosystems were sent on a path toward new equilibria that, even now, may not be reached for centuries. While the archipelago is undoubtedly "more pristine" than longer-settled oceanic islands, it is far from untouched, and it is too late to plan for a Galapagos without a bustling population of residents and visitors. Land use and land cover are changing more rapidly than ever before, and it is critical that policies and infrastructure are carefully designed to contain human impacts past and present, namely the replacement of native environments with concrete surfaces and aggressively invasive plants. The economics of the Galapagos push toward rapid coastal development and abandonment of farming, both of which threaten the integrity of their respective ecosystems. It is thus up to policymakers and funders to react to prevailing market forces to preserve the pristineness that remains on the "Enchanted Islands."

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