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Mangroves of the Galapagos

VU

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Abstract

Mangroves of the Galapagos is a regional ecosystem subgroup (level 4 unit of the IUCN Global Ecosystem Typology). It includes the marine ecoregions of Eastern Galapagos Islands, Northern Galapagos Islands, and Western Galapagos Islands. The Galapagos province mapped extent in 2014 was 36.6 km^2, representing 0.03% of the global mangrove area. The biota is characterized by four species of true mangroves.

Today the Galapagos mangroves cover between 37-45 km^2, which is about two to three times our broad estimate for 1970. Since 1970 the rate of change has been 1.1% per year. If this trend continues, an overall change of +18-26% is projected over the next 50 years, although there is a great deal of uncertainty in these figures.

Nonetheless, under a high sea level rise scenario (IPCC RCP8.5) ≈-25.2% of the Galapagos mangroves would be submerged by 2060. Moreover, 3.1% of the province's mangrove ecosystem is undergoing degradation, with the potential to increase to 9% within a 50-year period, based on a vegetation index decay analysis. The mangroves in the Galapagos are subject to a high number of potentially catastrophic threats, including tsunamis, volcanic eruptions, forest fires, and invasive species. Given these potential threats to mangroves, and their restricted geographical distribution (Extent of Occurrence, EOO, of 34,692 km^2), the Galapagos mangrove ecosystem is assessed as **Vulnerable (VU).**

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Mangroves; Red List of ecosystems; ecosystem collapse; threats.

Ecosystem classification
MFT1.2 Intertidal forests and shrublands
Assessment's distribution:
Galapagos province
Summary of the assessment:

Criterion	A	B	C	D	E	Overall
Subcriterion 1	**LC**	**VU**	**DD**	**DD**		
Subcriterion 2	**LC**	**LC**	**LC**	**LC**	**NE**	**VU**
Subcriterion 3	**DD**	**VU**	**DD**	**DD**		

VU: Vulnerable, LC: Least Concern,
DD Data Deficient, NE: Not Evaluated

Mangroves of The Galapagos

VU

1. Ecosystem Classification

IUCN Global Ecosystem Typology (version 2.1, Keith *et al.* 2022):

Transitional Marine-Freshwater-Terrestrial realm

MFT1 Brackish tidal biome

MFT1.2 Intertidal forests and shrublands

MFT1.2_4_MP_44 Mangroves of the Galapagos

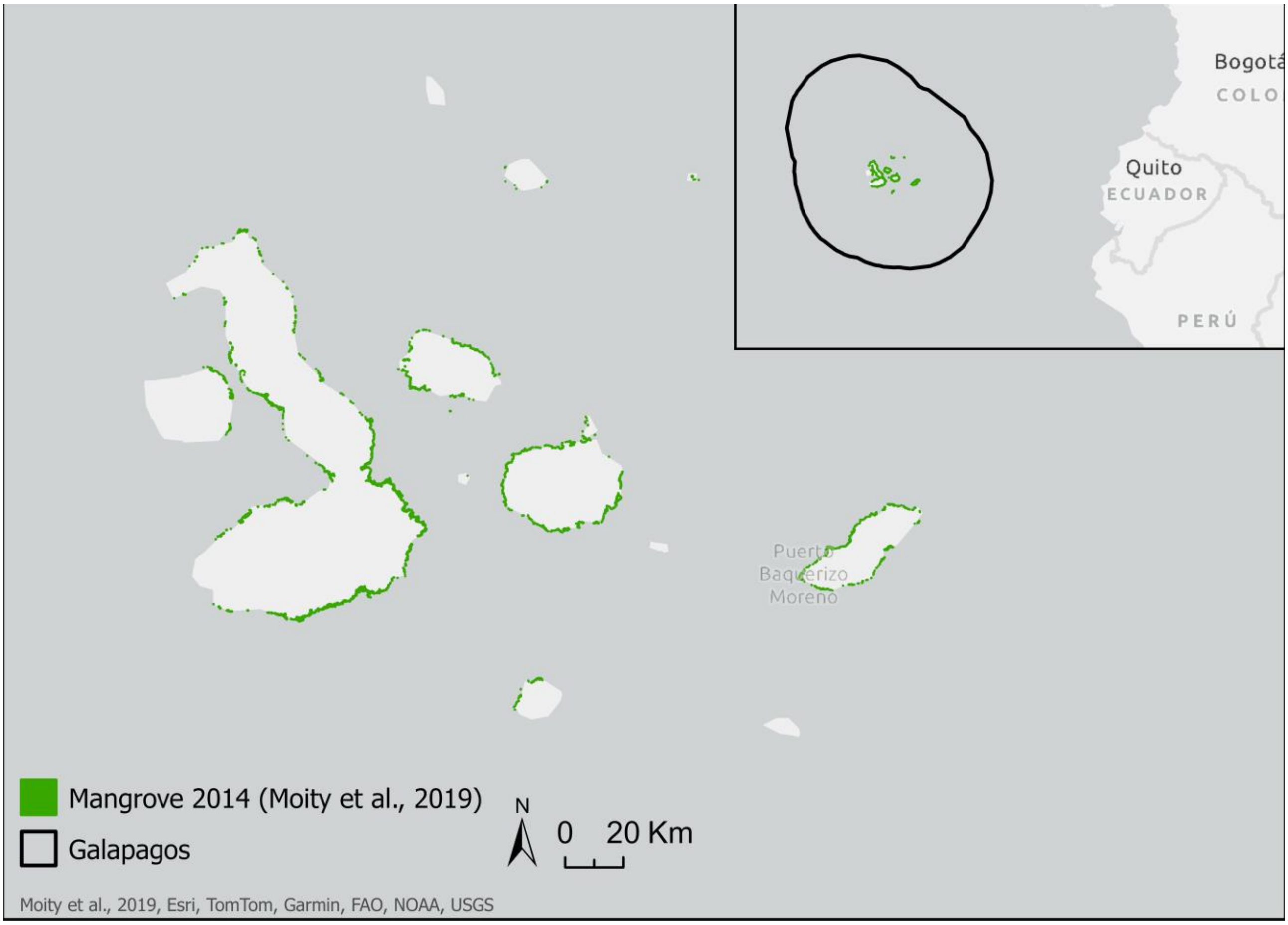
IUCN Habitats Classification Scheme (version 3.1, IUCN 2012):

1 Forest

1.7 Forest – Subtropical/tropical mangrove vegetation above high tide level *below water level*[1]

12 Marine Intertidal

12.7 Mangrove Submerged Roots



Moity et al., 2019, Esri, TomTom, Garmin, FAO, NOAA, USGS

Figure 1. The distribution of mangroves in the Galapagos.

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[1] Note on the original classification scheme. This habitat should include mangrove vegetation below water level. Mangroves have spread into warm temperate regions to a limited extent and may occasionally occur in supratidal areas. However, the vast majority of the world's mangroves are found in tropical/subtropical intertidal areas.

2. Ecosystem Description

Spatial distribution

The Galapagos province includes intertidal forests and shrublands of the marine ecoregions of Eastern Galapagos Islands, Northern Galapagos Islands, and Western Galapagos Islands, that extend across Ecuador (Figure 1).

In the Galapagos, extensive studies spanning from ~1950 to 2016 have explored the distribution of mangroves. However, variations in methodologies have led to discrepancies in the results across studies and over time (Moity *et al.*, 2019). According to Bunting *et al.* (2022) the estimated extent of mangroves in this province was 50.0 km^2 in 2020, representing about 0.03% of the global mangrove area, which suggests a 1.7 % net area change since 1996. However, when using higher resolution imagery, Moity *et al.*, 2019, found that the extent of mangroves in 2014, was 36.57 km^2 (about 0.025% of the global mangrove area), and that the mangrove forest cover had increased naturally by 24% over the period 2004 to 2014 without any human intervention. The same study determined that mangroves forests cover about 35% (720.5 km) of the archipelago's coastline.

Although most mangrove patches are small (<0.5 ha), there are areas with high continuous mangrove cover, particularly on Isabela Island, which is the island with the greatest mangrove extent (80% of Galapagos' mangrove extent). In the Galapagos there are no estuaries or permanent rivers supplying fresh water to the coast, and the coastal climate is semi-arid, with a mean annual precipitation of less than 500 mm (Moity *et al.*, 2019).

An old white mangrove (Laguncularia racemosa) on bare lava rock (Photo credit: Nicolas Moity/CDF).

Moity *et al.* (2019) found that younger islands have comparatively more mangrove coverage than geologically older islands, suggesting that mangroves act as pioneering coastal vegetation in the Galapagos.

There are also some islands without mangrove colonisation, such as Española and Pinta, as well as Darwin and Wolf islands in the far northernmost corner of the Galapagos Marine Reserve. This is despite the presence of propagules floating around the islands (Moity, pers. obs.), and is probably due to the prevailing currents around the islands, with major currents coming from the southeast and northeast. On these islands, ideal conditions for mangrove settlement are also lacking, such as the escarped coastline and rough seas found at Darwin and Wolf islands.

Most of the Galapagos coastline consists of lava rock that is exposed to wave action, with no permanent rivers or estuaries and an abrupt coastal topography that narrows the intertidal zone. Nonetheless, mangroves grow directly on these lava fields, forming bands of lush coastal vegetation adjacent to barren lava on younger islands and to arid vegetation on older islands. However, in a few enclosed bays and coastal areas protected from the wave energy, mangrove forests are tall, lush and extremely well developed, with trees over 25 m high in some bays of Isabela Island (Moity, pers. obs.).

Galapagos mangroves can be considered as fringing mangroves, as 90% of the mangrove coverage is within 500 m of the coastline (Moity *et al.,* 2019), although in certain locations, mangroves are also present up to 2.5 km inland of the coastline. One unique feature of the mangroves of the Galapagos is the presence of land-locked mangrove patches. These mangrove forests have no surface connection to the sea. Regular tidal exchange occurs, but it is via subsurface/groundwater flows only. These landlocked forests are a vitally important category of mangroves in the Galapagos as they are the only location where the critically endangered Mangrove finch can be found at present.

Biotic components of the ecosystem (characteristic native biota)

There are three recorded, true mangrove plant species in the Galapagos province, belonging to three families: *Rhizophora mangle* (red mangrove, Rhizophoraceae), *Avicennia germinans* (black mangrove, Acanthaceae) and *Laguncularia racemosa* (white mangrove, Combretaceae). Appendix 1 lists four plant species considered true mangroves according to the Red List of Threatened Species (RLTS) spatial data (IUCN, 2022). However, in the Galapagos, *Conocarpus erectus* (button or buttonwood mangrove, Combretaceae), is considered a mangrove associate, found in the transition zone between true mangrove forests and the arid zone of non-mangrove species along with other species like *Hippomane mancinella* (manchineel or poison apple) and *Cryptocarpus pyriformis* (salt bush) (Wium-Andersen and Hamann, 1986). *C. erectus* is sometimes found as the dominant mangrove species at some sites and is favoured by park rangers for management of tourist sites because it grows quickly and provides shade (Moity, pers. obs.). Appendix 2 includes the list of taxa that are associated with mangrove habitats in the Red List of Threatened Species database (Table A1 and A2).

Left: Red mangrove (Rhizophora mangle) dominates the fringe (Photo credit: Nicolas Moity/CDF). Right: R. mangle are extremely well developed at some sites (Photo credit: Rashid Cruz/CDF).

There are at least 70 animal and plant species in the IUCN Red List of Threatened Species (IUCN, 2022) that have natural history collection records, or observations, within the distribution of this province (GBIF, 2021 and in the Charles Darwin Foundation biodiversity database). Mangrove associated fauna in the mangroves of the Galapagos province comprise at least 100 species of fish, 110 species of marine macroinvertebrates, 64 species of birds, four species of reptiles, four species of mammals, and an undetermined number of algae, lichens, fungi, terrestrial and marine invertebrates. In addition, the mangroves of the Galapagos province are key ecosystems for hammerhead and black tip sharks, rays, green turtles, groupers, snappers, lobsters and sea cucumbers, which together form the basis of the Galapagos tourism and fishing economies. The Mangrove finch, *Camarhychus heliobates*, which is Critically Endangered, is the most vulnerable species living in the mangrove ecosystem in the Galapagos. The Charles Darwin Foundation, in conjunction with the Galapagos National Park, has a long-term project to manage this species to try to save it from extinction. The population of Mangrove finches has always been small, but now there are less than 100 individuals remaining (Fessl et al., 2010). Although they once thrived in the mangroves along the coast of Isabela, today they only breed in two mangrove stands on the northwest side of Isabela. This decline is primarily due to threats from three invasive species: black rats and feral house cats, which prey on the Mangrove finch, and *Philornis downsi*, a parasitic fly that weakens nestlings by sucking their blood. Without control of invasive species, the combined effects of these predators and parasites result in a mortality rate of 85% of nestlings (Fessl et al., 2010).

Endemic and threatened marine iguanas (Amblyrhynchus cristatus) using red mangrove branches to rest (Photo credit: Fernanda Loayza/CDF).

Abiotic Components of the Ecosystem

Lava rock substrata are low in nutrients, especially nitrogen and phosphorus. Regional mangrove distributions are influenced by interactions among landscape position, rainfall, hydrology, sea level, sediment dynamics, subsidence, storm-driven processes, and disturbance by pests and predators. Rainfall and sediment supply from terrestrial sources and ocean currents promote mangrove establishment and persistence, while waves and large tidal currents destabilise and erode soft substrata, mediating local-scale dynamics in ecosystem distribution. High rainfall reduces salinity stress and increases nutrient loading from adjacent catchments, while tidal flushing also regulates salinity.

The terrigenous material that makes up the sediment in Galapagos mangrove forests is young lava rock on geologically younger islands (those closest to the volcanic hot spot), while on older islands the lava rock may be more weathered (Moity *et al.*, 2019). Soil depth is on average shallow (around 60 cm), although there is a wide range of soil depths. At some places, mangroves grow directly on lava rocks with virtually no soil or only a very thin layer of 6 cm (on average), while at other places the soil is deep, down to more than 2 m (Moity, 2023). Soil composition is variable too: including mangrove peat, fine and coarse sand of organic and inorganic origin, and lava gravel. There are no permanent rivers on the islands, thus, the sediment supply is not from rivers but rather from native materials of organic origin or from weathering of local lava rocks.

In addition to the lack of permanent rivers, the semi-arid climate means that salinity is neither reduced by river flow or high rainfall. However, in many mangrove patches pore water salinity is lower than seawater salinity (as low as 7.2 PSU), indicating freshwater inputs; although at other sites salinity tends to be higher than the adjacent sea water (as high as 37 PSU) (Moity, 2023). Although rainfall is scarce along the coastline, with an average annual rainfall of only 400 mm, the coastal fringing mangroves thrive. The islands are characterised by prominent volcanoes, with an average maximum height of 1000 metres. These volcanoes act as natural barriers, causing clouds to accumulate and leading to annual precipitation levels of 1800 mm/y. A small portion of rainwater reaches the coast as superficial runoff. But most precipitation seeps through the highly permeable volcanic rocks, feeding perched subterranean aquifers that eventually provide freshwater underground to the mangroves, percolating through the volcanic rock (Figure 2). Since surface freshwater inputs to mangroves are negligible in Galapagos, and as Galapagos is surrounded by a very productive ocean (Palacios, 2004) the ocean is the most likely source of key nutrients (such as nitrogen, phosphorus, and potassium), especially on Western Isabela and Fernandina, the areas most influenced by the Cromwell current and the upwelling areas (Figure 2).

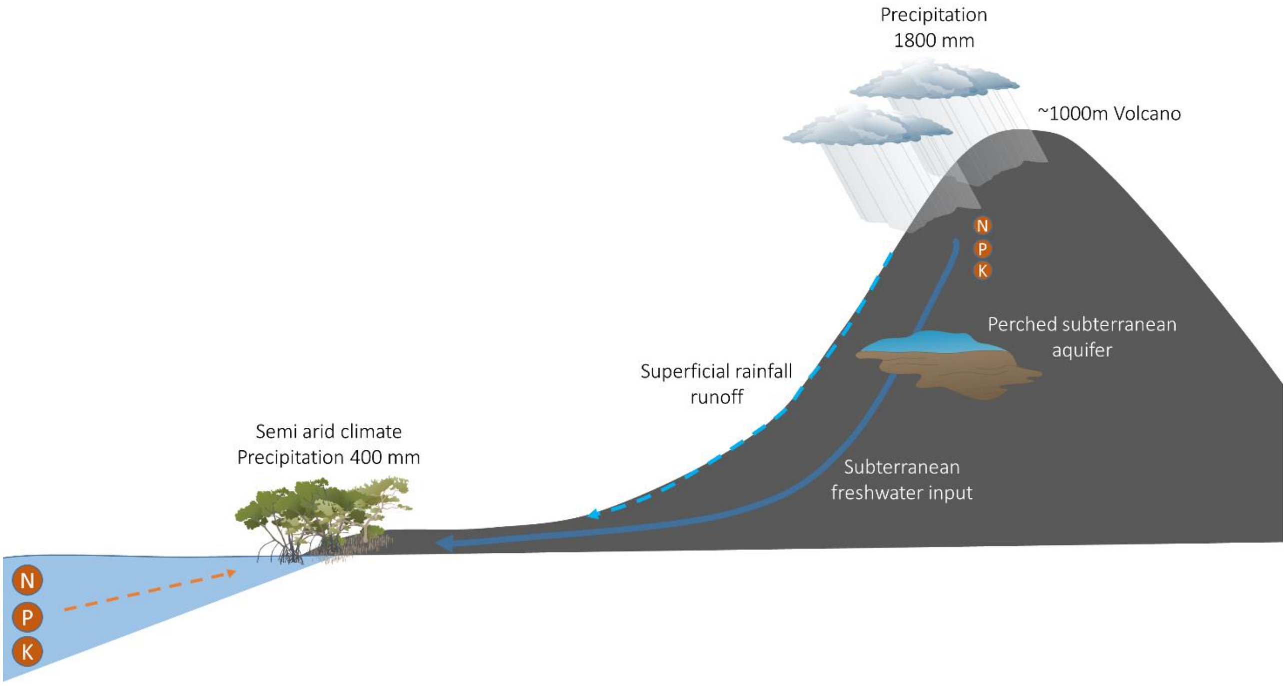

Figure 2. Conceptual model of abiotic factors influencing the Galapagos mangrove ecosystem. Source: N. Moity. Symbols courtesy of the Integration and Application Network.

Like Hawaii, some mangrove patches in the Galapagos most probably overlay flooded anchialine habitats such as lava tubes and are found in other anchialine habitats such as tectonic faults (locally known as “grietas”) and other volcano-created spaces filled with water like lava rock pools. There are some open water pools with access points to these underwater cave systems, which are connected to seawater but with no surface connection to the sea (Holthuis, 1973). The fauna of these habitats in the Galapagos has been shown to be endemic, diverse and specialised (Iliffe, 1991), although the species tend to be found in the deeper parts of anchialine habitats rather than on the surface, where mangroves are found.

Key processes and interactions

Mangroves act as structural engineers possessing traits such as pneumatophores, salt excretion glands, vivipary, and propagule buoyancy that promote survival and recruitment in poorly aerated, saline, mobile, and tidally inundated substrata. They exhibit high efficiency in nitrogen use and nutrient resorption. Indeed, mangroves in the Galapagos can be considered a pioneering vegetation since they are able to colonize newly formed substrata (such as bara lava flows, Fig. 3) (Moity *et al.*, 2019); usually by *R. mangle* and *L. racemosa* propagules (Moity, pers. obs.). By doing so they are able to transform a harsh, seemingly simple and unhospitable environment, into a very complex one, thereby creating microhabitats for a myriad of terrestrial and marine species.

Mangroves in the Galapagos are a very important habitat for marine species, helping to support the local, small-scale, artisanal fishing community (Tanner *et al.*, 2019). Mangroves are also pivotal to shark species, rays and sea turtles, but are also used by the Galapagos sea lions and marine iguanas to rest; and by the Galapagos penguins and flightless cormorants to feed and occasionally to nest. These species attract diving and snorkelling tourists to the Galapagos (Moity et al., 2019), significantly contributing to the tourism industry, which accounts for 70% of the regions GDP (Rosero, 2015). Mangroves are mainly used by larvae and juvenile stages of groupers, snappers, mullets, lobsters, sea cucumbers, black tip sharks, and hammerhead sharks. White-tip sharks, rays, green sea turtles and small pelagic fish (sardines, herrings) use them as resting, reproduction and feeding areas (Figure 3). Rocky reefs located from 0.1 to 10 km from mangroves are used by mature fish, sea cucumbers, sharks and rays, while inlets, seamounts and oceanic islands located much further from mangroves are used by sharks, groupers, snappers, lobsters and sea-cucumbers (Figure 3). Other pelagic species such as the sunfish and yellow fin tuna are only found in pelagic areas.

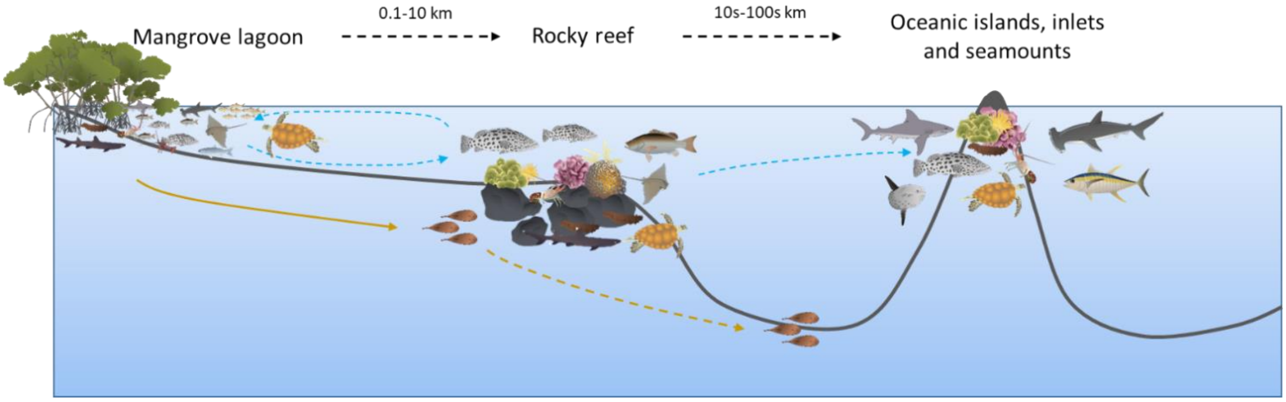

Figure 3. Conceptual model on marine species use and interaction between the mangrove ecosystem and the other marine habitats of the Galapagos. Mangrove detritus (represented by brown leaves in the diagram) are exported to the rocky reef ecosystem and possibly to the deep ocean. Source: N. Moity. Symbols courtesy of the Integration and Application Network.

Mangroves produce large amounts of detritus (e.g., leaves, twigs, and bark), which is either buried in waterlogged sediments, consumed by crabs and gastropods, and then decomposed further by meiofauna, fungi and bacteria, thus mobilising carbon and nutrients to other trophic levels in the mangrove and coastal waters food web. Some of the detritus can be found in marine ecosystems, such as subtidal rocky reefs down to 20-30 m, and might constitute an important addition of organic matter to the ocean (Moity, pers. obs.; Figure 3). Mangrove ecosystems are important blue carbon sinks, sequestering organic matter in sediments and living biomass. Preliminary results indicate that mangroves in the Galapagos have, on average, 200 Mg C_{org} ha^{-1} above ground carbon stock, and 280 Mg C_{org} ha^{-1} below ground; although this is highly variable and seems to be related to pore water salinity and island geological age. Lower salinity sites have an average total ecosystem carbon stock of 550 Mg C_{org} ha^{-1} and higher salinity sites an average total of 335 Mg C_{org} ha^{-1} (Moity *et al.* 2023). There is high variability between nearby sites within the same island, both in terms of pore water salinity and total ecosystem carbon.

3. Ecosystem Threats and vulnerabilities

Main threatening process and pathways to degradation

Mangrove deforestation arises from various factors, including aquaculture, urbanization, associated coastal development, over-harvesting, and pollution stemming from domestic, commercial, and agricultural land use. The location of mangrove forests within intertidal areas renders them vulnerable to predicted sea-level rise as a result of climate change. The increase in the frequency and intensity of storms can damage mangrove forests through direct defoliation and destruction of trees, as well as through the mass mortality of animal communities within the ecosystems.

Due to the history of human colonisation of the Galapagos Islands and the early recognition of its universal value, we find a very special situation where most of the archipelago (97% by area) is protected by the National Park, and only 3% of the emerged area is used for humans settlements, agriculture, livestock farming, roads and transportation (DPNG, 2014). Thus, most of the threats associated with human activities and development, are confined to urban areas or regions under the influence of agriculture and livestock farming. Importantly, despite human settlements occupying only 3% of the land, approximately 330,000 tourists visit the islands annually (DPNG, 2023). These visitors explore 222 designated sites across the archipelago, utilising more than 100 boats for transportation (DPNG, 2023; Observatorio de Turismo de Galápagos). Additionally, 500 active artisanal fishers operate 150 boats throughout the islands (Ramirez-González et al., 2022). Therefore, the main threats to mangroves can be divided into three broad categories: major threats, low-level threats (which may have an impact over long periods of time), and threats specific to inhabited areas. Table 1 summarizes the threats to the mangroves of the Galapagos province. Major threats are those that can cause mangrove ecosystem collapse over large areas, affecting many mangrove patches at the same time and completely eliminating their ecosystem functions. Low-level threats are those that occur over long periods of time and can bring the ecosystem to a state of collapse by reducing its resilience. Finally, threats associated to human settlements have the potential to locally eliminate mangrove patches or reduce the resilience of mangroves in areas under the influence of agriculture and farming.

Table 1. Threats affecting mangroves of the Galapagos province.

Threat type	Threat	Potential outcome
Major threats	Tsunami	Total destruction of all or almost all mangroves in coastal areas. The Galapagos Islands are affected by tsunamis that originate from the Pacific Ocean. In addition, due to their volcanic origin, tsunamis can be generated within the Galapagos after eruptions, earthquakes, and landslides.
	Volcanic eruption	Complete destruction of entire mangrove forests. Release of sequestered organic carbon into the atmosphere. Exposure of nearby mangrove areas to extreme heat from gas and heated water.
	Sea level fluctuations	El Niño and La Niña phenomena are expected to increase in magnitude and frequency with associated sea level fluctuations that can drown or dry out mangroves for long periods of time, causing mass die-offs (Duke et al., 2022). On a longer time scale, sea level

		rise can also cause mangrove collapse, especially where mangroves cannot retreat with rising sea levels. The high volcanic activity is also associated with earthquakes and other drastic terrain movements. In 1954 an upward movement of magma suddenly raised Urvina Bay by more than 6 m, exposing several square kilometers of seabed and completely changing the geomorphology of the area (Colgan & Hollander, 1987).
	Droughts	In the Galapagos, La Niña events are associated with a sharp decrease in precipitation. If La Niña events become more frequent and more intense, the decrease in precipitation over long periods of time could have severe consequences for the Galapagos mangroves since there are no rivers nor other sources of freshwater.
	Introduced and invasive species	Galapagos is particularly vulnerable to the impacts of introduced and invasive species (Toral-Granda et al., 2017). To date, two introduced species have been identified that could potentially affect mangrove forests: a fungus, the sooty mold, an ascomycete of the genus *Capnodium* sp. that threatens the plant's ability to photosynthesize, and the bore beetles (Coleoptera Curculionidae: Scolytinae), that are found on propagules.
	Fire	Fires may originate from nearby inhabited areas and recreational-touristic areas. Fishing camps along the coast could eventually spark a forest fire in the mangrove forests, destroying entire areas. The potential risk is high because the Galapagos authorities have no means of fighting forest fires in remote areas.
Low-level threats	Storms, changes in wind patterns	In some areas of the Galapagos, mangroves thrive and grow up to 25 m. In these same areas, winds are frequent (Forryan et al., 2021) and break the tallest trees. If winds become stronger with future climate change, this could lead to tree toppling, especially during periods of heavy rainfall (such as during El Niño events).
	Oil spills	Contamination from hydrocarbons has occurred in the Galapagos, as all fuel arrives by sea (Gelin et al., 2003), and although its potential impact on mangrove trees is unclear, it does affect the associated fauna. On a smaller scale, hydrocarbons from the presence of boats (such as tourist and fishing boats in or close to mangrove bays) and sunscreen from snorkeling tourists can accumulate on mangrove sites over years, with unknown consequences.
	Human disturbance	Human visitation to mangrove sites, through tourism and fishing, may affect mangrove-using species more than previously thought. During the COVID-19 pandemic closure, the number and size of fish and sea turtles in a mangrove lagoon were significantly higher than before the pandemic (Moity et al., 2022). These results suggest that human use of mangrove sites may have a greater impact than we previously thought, particularly at sites with high visitation rates. On the other hand, hunting for introduced species in or around mangrove forests could affect terrestrial and marine wildlife. Scientific and management activities within mangrove forests (e.g., to manage the Mangrove Finch) may also have localized impacts,

		particularly related to soil disturbance, trampling of mangrove seedlings, and cutting of branches or trees to create access trails.
	Light and noise pollution	Visits to the mangroves by the tourism industry and fishers impact the mangrove bays through engine noise, which is known to have an impact on species (Parra Díaz et al., 2024). Light and noise pollution from piers and urban areas can have localized effects on species that use the mangroves in these areas, such as the brown pelican, the black tip shark, and rays.
	Fishing	Mangrove sites are used by fishers to rest but also to catch fish bait and some fish species usually found in mangroves such as mullets, snappers, or the white snook (*Centropomus viridis*) (Pontón-Cevallos et al., 2022). These activities are typically conducted using bottom-setting gill nets, which have the potential to catch non-target species, including sharks and sea turtles. In experimental settings, the capture of up to 5.6 juvenile blacktip sharks per hour and net has been documented (Llerena et al., 2015).
	Soil erosion	Continuous visitation, especially by the tourism industry, could have some low-level, but continuous impacts on the soil. The waves created by boats visiting mangrove lagoons could cause soil erosion over long periods of time.
	Plastic and microplastic contamination	Mangroves are very good at trapping sediments and other materials such as plastics (Martin et al., 2020). The Galapagos mangroves are at the crossroads of major currents that bring in plastic pollution (mainly from overseas) that get trapped in the mangrove's intricate aerial root system, especially on the E-SE coastlines of the archipelago. The potential impact of plastic pollution and decomposition in mangroves is unknown.
	Tree logging	In some places, traditionally used by fishers to rest and build camps, there is evidence of mangrove cutting. Sometimes trees are cut to facilitate access by fishing boats to enclaved bays with small entry areas (Moity, pers. obs.). Although rare, there have been instances at tourist sites where mangrove trees were damaged, such as the case of a black mangrove that was broken when a tourist hung on it. During the "gold rush" of the sea cucumber fishery (1990-2000), fishers would build semi-stationary base camps to live and process sea cucumber Bêche-de-Mer on site. Tree felling is thought to have been more widespread during this period. In 2024, an operation led by the Galapagos National Park Directorate, the Environmental Protection Unit of the National Police, and the Environmental Management Directorate of the Isabela GAD resulted in the seizure of 122 *Conocarpus erectus* logs in Puerto Villamil, Isabela (Primicias, 2024a).
Threats associated to human settlements	Pollution, waste water, sewage	On inhabited islands, some sites are contaminated with sewage and wastewater, introducing high loads of organic matter and coliform bacteria into the mangrove ecosystem. Pollution from human activities (mangrove lagoons used as natural harbors, pollution from rainfall runoff, etc.) is another threat for mangroves.

	Agrochemicals and livestock farming pollution	The agricultural and livestock farming lands of the Galapagos occupy 25,235 ha. The agrochemicals, fertilizers and the associated pollution to livestock farming leaks into the volcanic soil and perched aquifers that eventually discharge their contents in the coastal zone, where mangroves grow.
	Modifications on ground water reservoirs	The extraction of water for human use (domestic, commercial or agricultural) in the agricultural and urban areas of the Galapagos Islands can potentially alter the natural sources of fresh water that reach the mangrove forests.
	Urban and commercial development	Nearly all inhabited harbors in the Galapagos Islands have been cleared of mangroves due to urban and commercial development (including roads) along the coast. Currently, 34 hectares of mangroves in urban areas are at risk of deforestation.

Definition of the collapsed state of the ecosystem

Mangroves, acting as structural engineers, possess specialized traits that facilitate high nitrogen use efficiency and nutrient resorption, influencing critical processes and functions within their ecosystem. Ecosystem collapse is recognized when the tree cover of diagnostic true mangrove species dwindles to zero, indicating complete loss (100%).

Mangrove ecosystems exhibit remarkable dynamism, with species distributions adapting to local shifts in sediment distribution, tidal patterns, and variations in local inundation and salinity gradients. Disruptive processes, such as increasingly extreme, climate change driven mechanisms, can trigger shifts in this dynamism, potentially leading to ecosystem collapse. Ecosystem collapse may manifest through the following mechanisms: a) restricted recruitment and survival of diagnostic true mangroves due to adverse climatic conditions (e.g., low temperatures); b) alterations in rainfall, river inputs, waves, and tidal currents that destabilize and erode soft substrata, hindering recruitment and growth; c) shifts in rainfall patterns and tidal flushing altering salinity stress and nutrient loadings, impacting overall survival; d) alterations in currents patterns and oceanographic features (such as changes in salinity), hindering propagule floatability; e) sea-level fluctuations due to El Niño, exposing mangrove trees for relatively long periods of time, resulting in massive die-offs. In the Galapagos province, volcanic eruptions, tsunamis, fires and invasive species may cause mangrove ecosystem collapse on a local to extensive scale (see details in section B3).

Threat Classification

IUCN Threat Classification (version 3.3, IUCN-CMP, 2022) relevant to mangroves of the Galapagos province:

1. **Residential & commercial development**
    - 1.1 Housing & urban areas
    - 1.2 Commercial & industrial areas
    - 1.3 Tourism & recreation areas
4. **Transportation & service corridors**
    - 4.1 Roads & railroads

- 4.2 Utility & service lines

5. Biological resource use

- 5.1 Hunting & collecting terrestrial animals
    - 5.1.1 Intentional use (species being assessed is the target)
    - 5.1.3 Persecution/control
- 5.3 Logging & wood harvesting
    - 5.3.1 Intentional use: subsistence/small scale (species being assessed is the target [harvest]
- 5.4 Fishing & harvesting aquatic resources
    - 5.4.1 Intentional use: subsistence/small scale (species being assessed is the target)[harvest]
    - 5.4.3 Unintentional effects: subsistence/small scale (species being assessed is not the target)[harvest]
    - 5.4.4 Unintentional effects: large scale (species being assessed is not the target)[harvest]

6. Human intrusions & disturbance

- 6.1 Recreational activities
- 6.2 War, civil unrest & military exercises
- 6.3 Work & other activities

7. Natural system modifications

- 7.1 Fire & fire suppression
    - 7.1.3 Trend Unknown/Unrecorded
- 7.2 Dams & water management/use
    - 7.2.5 Abstraction of ground water (domestic use)
    - 7.2.6 Abstraction of ground water (commercial use)
    - 7.2.7 Abstraction of ground water (agricultural use)

8. Invasive & other problematic species, genes & diseases

- 8.1 Invasive non-native/alien species/diseases
    - 8.1.2 Named species
- 8.4 Problematic species/diseases of unknown origin
    - 8.4.2 Named species

9. Pollution

- 9.1 Domestic & urban wastewater
    - 9.1.1 Sewage
    - 9.1.2 Run-off
- 9.2 Industrial & military effluents
    - 9.2.1 Oil spills
- 9.3 Agricultural & forestry effluents
    - 9.3.1 Nutrient loads
    - 9.3.2 Soil erosion, sedimentation
    - 9.3.3 Herbicides & pesticides
- 9.4 Garbage & solid waste
- 9.6 Excess energy
    - 9.6.1 Light pollution
    - 9.6.3 Noise pollution

10. Geological events

- 10.1 Volcanoes

- 10.2 Earthquakes/tsunamis

11. Climate change & severe weather

- 11.1 Habitat shifting & alteration
- 11.2 Droughts
- 11.3 Temperature extremes
- 11.4 Storms & flooding

4. Ecosystem Assessment

Criterion A: Reduction in Geographic Distribution

Subcriterion A1 measures the trend in ecosystem extent during the last 50-year time window. To estimate the Galapagos mangrove area from 1996 to 2020, we first used the Global Mangrove Watch (GMW v3.0) spatial dataset. The mangrove area in the province was corrected for both omission and commission errors, utilizing the equations in Bunting *et al.* (2022). Results from the analysis show that the area in 2020, was 50 km^2, with a net area change of 1.7% (1996-2020). However, a more specific study on the Galapagos Islands, conducted at a finer resolution (~3m pixels compared to ~25m in GMW) and using high-resolution imagery (Moity *et al.*, 2019), shows that the mangrove area for 2014 was 36.571 km^2. This study found a significantly smaller extent than GMW, likely due to the finer resolution of the imagery used, but is higher than other Galapagos mangrove estimates (Table 2) except for the GMW v.3 results. The authors attribute the variations in mangrove area to the different methodologies used. It is therefore reasonable to suggest that the GMW area estimate of 50 km^2 may be an overestimate of the actual area.

Table 2. List of selected studies considered to have reliable information on Galapagos mangrove area.

Study	**Year**	**Mangrove area (km^2)**
Moity *et al.*, 2019	2014	36.571
Briones *et al.*, 1997	<2002	33.791
Rivas-Torres *et al.*, 2018	2016	14.704
Giri *et al.*, 2013	2000	23.663
INGALA, 1989	1946-1985	24.367
Wium-Andersen and Hamann, 1986	1959-1960	10.000

The estimates by Moity *et al.*, (2019) show an overall 24% increase in mangrove area between 2004 and 2014. It was observed that mangroves were expanding in the Galapagos, with a differentiated growth pattern dependent on the location of the mangroves. Mangroves on the western islands exhibited the most rapid growth, with a positive change of over 40%. In contrast, the central island of Santa Cruz demonstrated a lower positive change of 9.8%. Furthermore, other regional studies (Table 3, with the exception of Rivas-Torres *et al.*, 2018, which aimed to map invasive species, not mangroves or coastal vegetation) also show an increase in area over the years, with a similar slope.

Table 3. Change in mangrove area in the Galapagos.

	Area 2020* (km^2)	Area 1970* (km^2)	Net area Change 1970-2020 (km^2)	% Net Area Change 1970-2020	Rate of change (%/year)
Mangroves of the Galapagos	36.6	16.1 (10.0-22.2)	20.5 (14.4-26.6)	56.0 (39.3-72.7)	1.1 (0.8-1.5)

** Mangrove area in 1970 estimated on the basis of mangrove area change between 2004-2014 (Moity et al., 2019) and Wium-Andersen and Hamann, 1986. Total mangrove area in 2020 is based on the Moity et al. (2019) dataset for 2014.*

Based on the above, and assuming a linear increase in mangrove area, it can be estimated that in 1970 the mangrove cover was between 10.0-22.2 km^2. This means that mangroves in the Galapagos province increased in area by approximately ~56% (39-72%) over the last 50 years (1970-2020) (Table 3). Assuming that these trends are maintained in the future, the mangrove cover for 2070 would be around 50.9-71.7 km^2 (Figure 4). Because these projected changes in mangrove extent are below the 30% risk threshold, the Galapagos mangrove ecosystem is assessed as **Least Concern (LC)** under subcriteria A1 and A2.

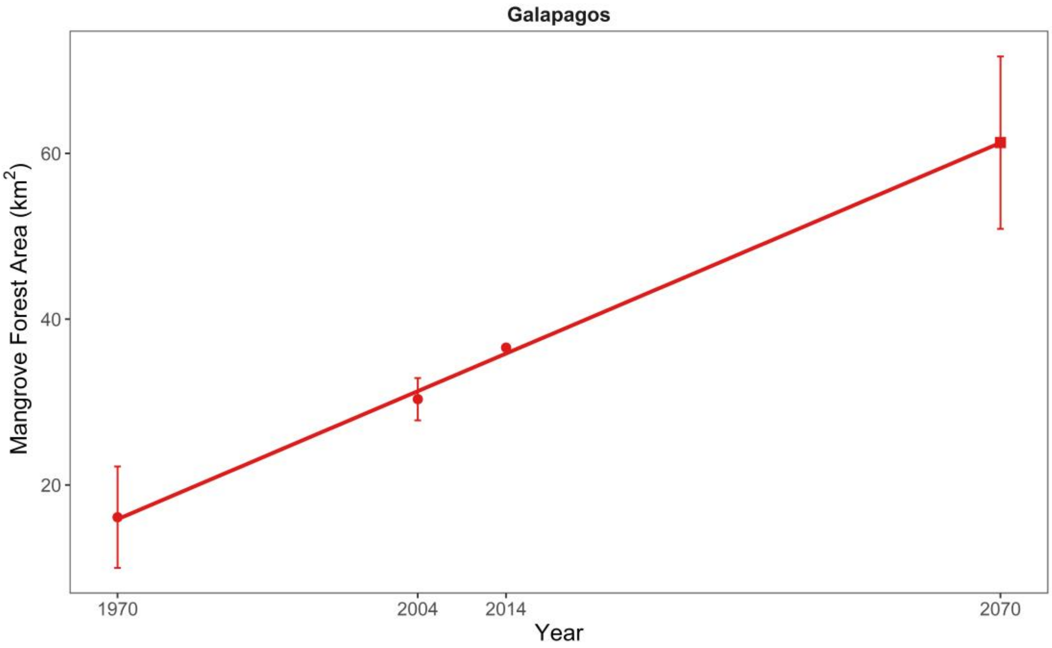

Figure 4. Historical and future potential changes for the Galapagos based on Moity *et al.*, (2019). Year 1970 and 2070 are based on linear projections based on ten-year (2004-2014) positive area increment. Red line represents linear trend.

Subcriterion A3 measures changes in mangrove area since 1750. Unfortunately, there are no reliable data on the mangrove extent for the entire province during this period, and therefore the Galapagos mangrove ecosystem is classified as **Data Deficient (DD)** for this subcriterion.

Overall, the ecosystem is assessed as **Least Concern (LC)** under criterion A.

Criterion B: Restricted Geographic Distribution

Criterion B measures the risk of ecosystem collapse associated with restricted geographical distribution, based on standard metrics (Extent of Occurrence EOO, Area of Occupancy AOO, and Threat-defined locations). These parameters were calculated based on Moity *et al.* (2019) mangrove extent, and 2020 GMW v.3 spatial layer, for comparison.

Table 4. Standard metrics (Extent of Occurrence EOO, Area of Occupancy AOO, and Threat-defined locations) based on Moity *et al.* (2019) mangrove extent, and GMW 2020.

Source	**Province**	**Extent of Occurrence EOO (km^2)**	**AOO**	**AOO (<1%)**	**AOO (≥1%)**	**Criterion B**
GMW v3.	Galapagos 2020	31,250.1	99	25	74	**Vulnerable (VU)**
Moity *et al.*, 2019	Galapagos 2014	34,691.6	103	36	67	**Vulnerable (VU)**

For 2014 (the closest to 2020 high resolution mangrove area available for the Galapagos, Moity *et al.*, 2019), AOO and EOO were measured as 67 grid cells 10 x 10 km and 34,691.6 km^2, respectively (Table 4). The AOO was initially recorded as 103 grid cells (10 x 10 km). However, after excluding those grid cells that collectively contain patches covering less than 1% of the total mapped area of the ecosystem, the AOO is estimated as 67, 10 x 10 km grid cells (Figure 5, red grids).

In contrast, subcriterion B1 is assessed as **Vulnerable (VU)** given that the EOO is ≤ 50,000 km^2, plus it was observed inferred threatening processes that are likely to cause a sustained decline in geographic distribution, environmental quality or biotic interactions within the next 20 years (condition b) and the ecosystem is present in ≤ 5 threatened locations (see following ‘threat-defined locations’ section for rationale). In contrast, given that the AOO is above 50 grids, criterion B2 does not apply, and the ecosystem is assessed as **Least Concern (LC)** for this subcriterion.

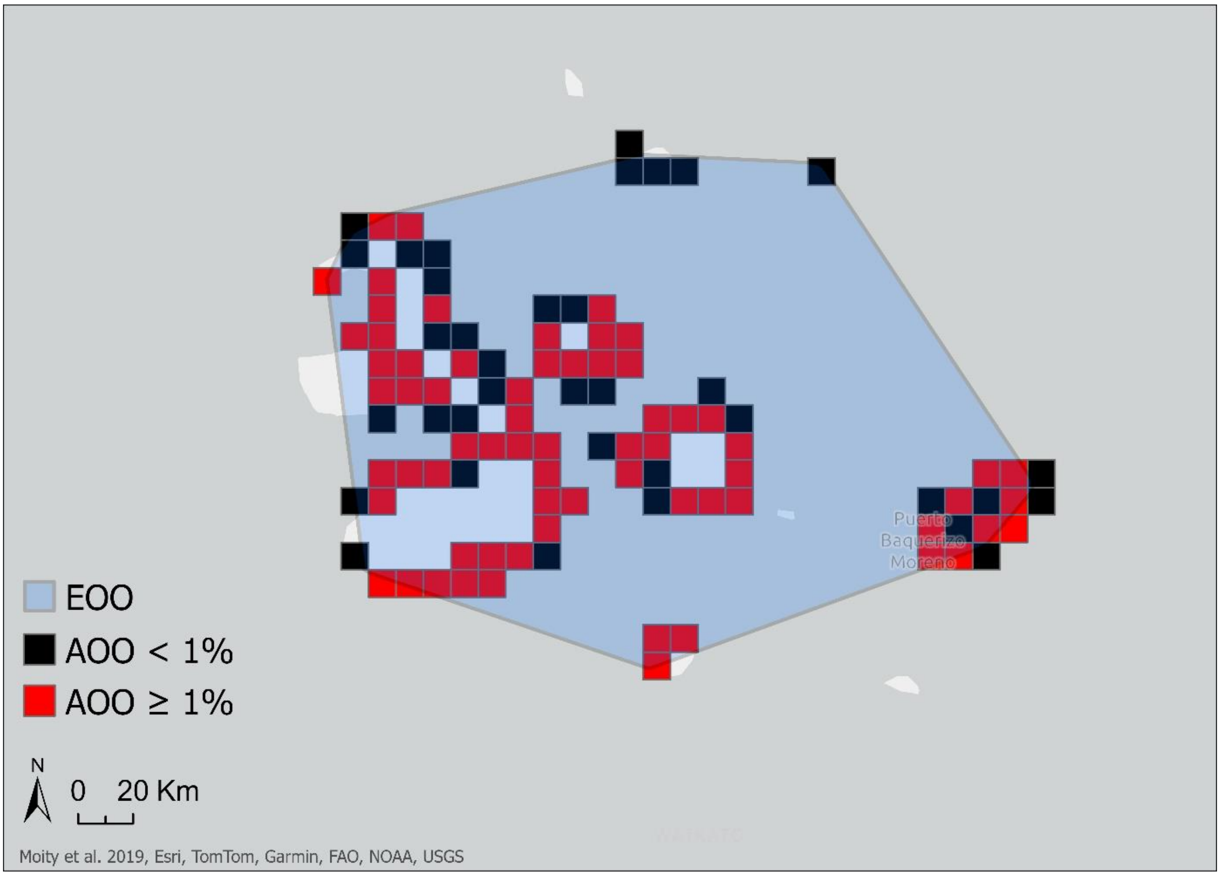

Figure 5. The Galapagos mangrove Extent Of Occurrence (EOO) and Area Of Occupancy (AOO) in 2020. Estimates based on the Galapagos mangrove spatial layer (Moity *et al.*, 2019). The red 10 x 10 km grids (n=67) are more than 1% covered by the ecosystem, and the black grids <1% (n= 36).

Threat-defined locations

The Galapagos Islands are vulnerable to several threats that could lead to ecosystem collapse regarding the threat-defined locations criteria: volcanic eruptions, invasive species, and fire.

Volcanic eruptions

Volcanic eruptions are the primary threat to the Galapagos mangrove ecosystem and can destroy large areas of mangrove forest in a matter of days if lava flows reach the coastline. Lava flows can completely cover mangrove patches, while mangrove areas in the vicinity that are not directly covered by the flows can die due to the sharp rise in sea temperature, causing damage to roots, soil, and leaves. Areas further away may experience temperature shocks that do not kill the plants but does make them more susceptible to disease. In addition, lava flows can cause forest fires that decimate continuous mangrove patches, even if they are not directly affected by the lava flows.

The Galapagos archipelago is one of the most active volcanic areas in the world (Kurz and Geist, 1999) and there are records of eruptions since 1150 (SI Global Vulcanism Program). Since 1990, eruptions of several volcanoes have had lava getting to the coastline in at least seven occasions. In 2018, the Sierra Negra volcano in Isabela erupted and the lava reached the coastline, adding 1.5 km^2 of land to the island and completely wiping out 13.3 ha of mangroves that ended up covered in lava. The sudden rise in water temperature also killed mangrove trees in the surrounding area (see photograph below).

The die-off of mangroves, primarily Rhizophora mangle*, occurred as a consequence of overheating of the water caused by a lava flow reaching the nearby seawater in 2018. Two years later (photo taken in September 2020), no signs of recruitment can be observed. (Photo credit: N. Moity)*

In 2022, Wolf volcano erupted and the south-eastern flow stopped just 200 m from the sea and less than 50 m from a mangrove patch (Figure 6). On March 2, 2024, La Cumbre volcano on Fernandina Island erupted and 36 days later (April 7, 2024), the lava flows reached the sea (Figure 6). This event expanded the island's surface by 10 hectares in an area devoid of mangroves, coming within just seven kilometres of the nearest mangrove zone. Over the past seven years, this same volcano has erupted four times, with lava flows reaching the coast in two instances (2018 and 2024). Fernandina Island holds the record for the most frequent eruptions in the Galapagos archipelago; since the 1800s, it has erupted approximately 30 times. Fernandina has 118 ha of mangrove forests as of 2014 (Moity *et al*., 2019).

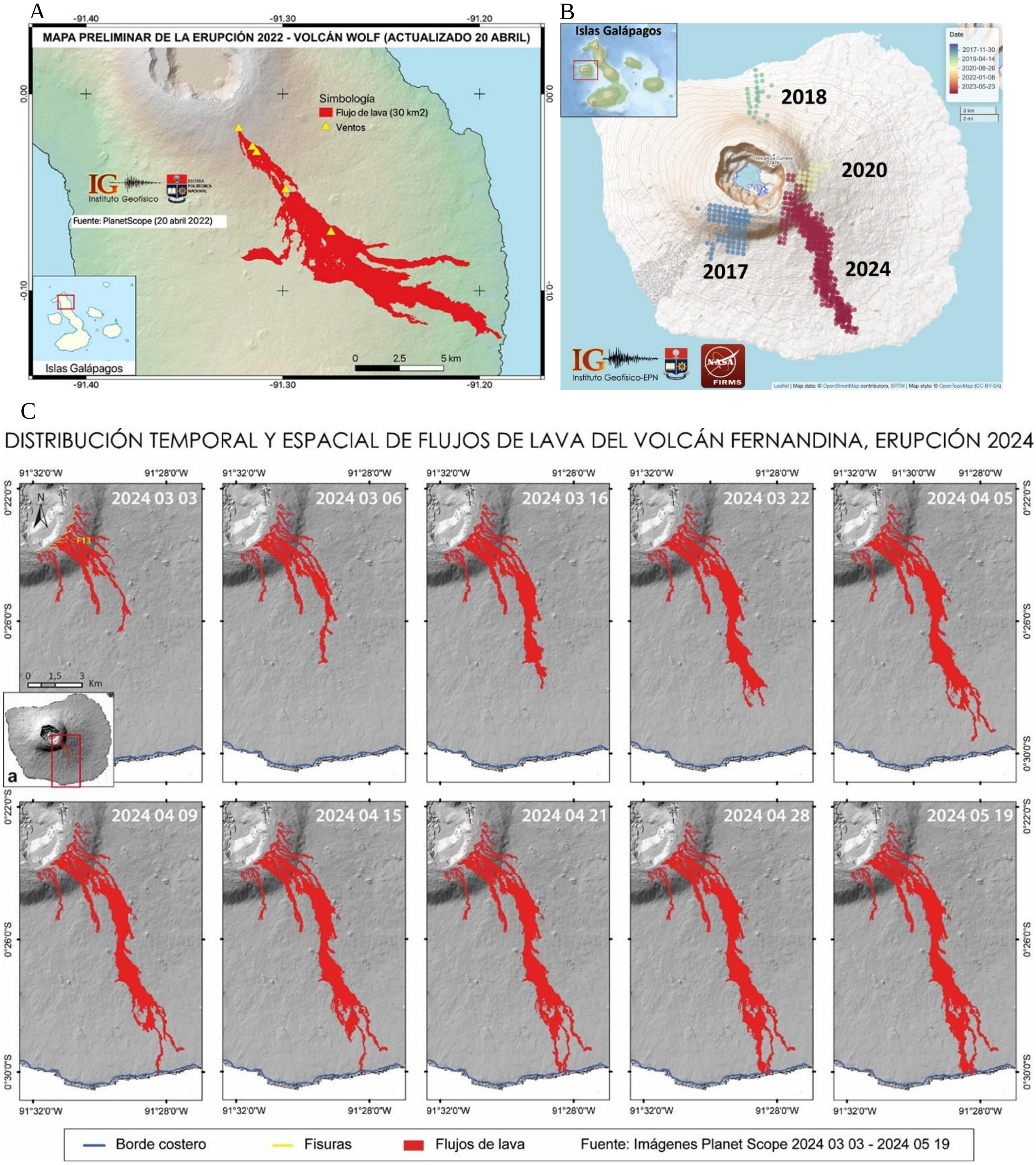

Figure 6. A) Map showing the lava flow from Wolf volcano in 2022. B) Map showing the different eruptions from La Cumbre volcano in Fernandina island, and the different lava flows by date, according the VIIRS satellite sensor. C) In 2024 eruption of La Cumbre volcano, the lava flow eventually arrived to the sea adding 0.1 km^2 of new land. (Source: IGEPN, 2022, 2024b, 2024a)

Lava flow from the La Cumbre volcano in Fernandina, arriving to the sea on May the 1st, 2024 (Photo credit: GNPD).

The probability of a volcano erupting is derived from the frequency of historical volcanic eruptions (during the Holocene) of the different volcanoes in the archipelago. We divide the risk of eruption into three categories: high, medium, and low risk (Figure 7). High-risk volcanoes are those with a history of recurrent and recent eruptions (since 2000). Medium-risk volcanoes are those with last eruptions before the year 2000 until the beginning of the 20th century. Low-risk are volcanoes with known eruptions before the 20th century and less than 1000 years old. Medium and high-risk volcanoes have erupted seven times since 2015 and 12 since 2005, which is equivalent to 1-1.5 eruptions every two years. Using this classification, we can identify four threat-defined locations for volcanic eruptions (Figure 9). Under the threat of volcanic eruptions, given that the number of threat-defined locations is very small (four) and prone to stochastic events, within a short period of time (1-1.5 eruptions every other year) in an uncertain future, and capable of collapsing the ecosystem in entire regions, subcriterion B3 is assessed as **Vulnerable (VU)**.

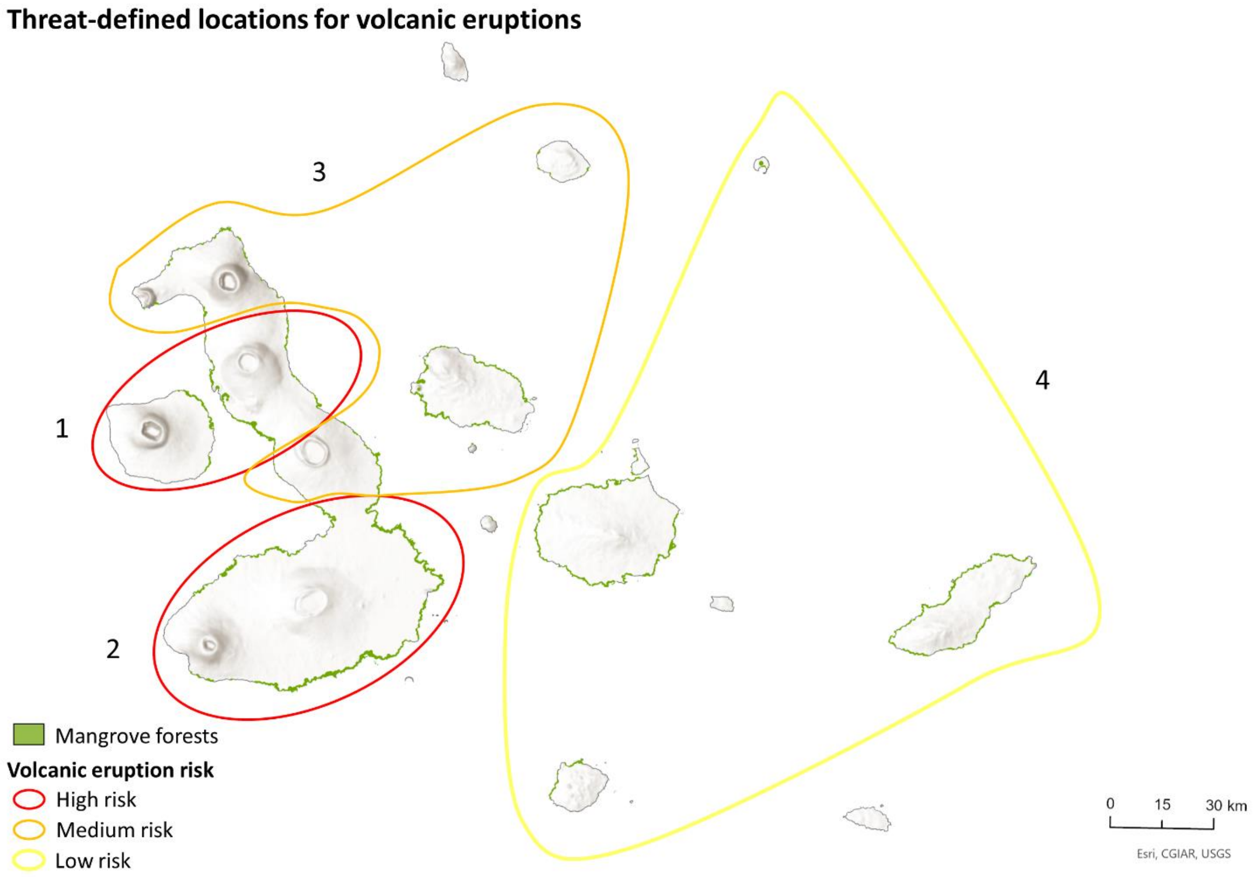

Figure 7. Threat-defined locations for volcanic eruptions. Locations are categorized according to the risk of volcanic eruption, based on the probability of eruption. Source: N. Moity

Tsunamis

The western coast of South America is prone to frequent earthquakes caused by the subduction of the Nazca Plate beneath the South American Plate. Ecuador is particularly affected by heightened seismic activity due to the subduction of the Carnegie Ridge, which also elevates the risk of tsunamis in the region (Chunga and Toulkeridis, 2014). Indeed, there is documentation of at least 59 tsunamis in Ecuador since year 1500 (Contreras López, 2013). The Galapagos archipelago is highly vulnerable to tsunamis generated across the Pacific Ocean, which is regarded as the most tsunami-prone region in the world and accounts for 80% of global tsunamis (Moreano *et al.*, 2012; Levin and Nosov, 2016). During the period 1933-2022, the Galapagos registered 24 tsunamis, four of them were destructive (Contreras López, 2013). The last tsunami for which damage was recorded in Galapagos, was the 2011 Tohoku tsunami (originating from Japan). This tsunami generated flow/run-up elevation of up to 6 m with water surging inland up to 300 m (Arcos *et al*., 2013; Lynett *et al.*, 2013; Figure 8).

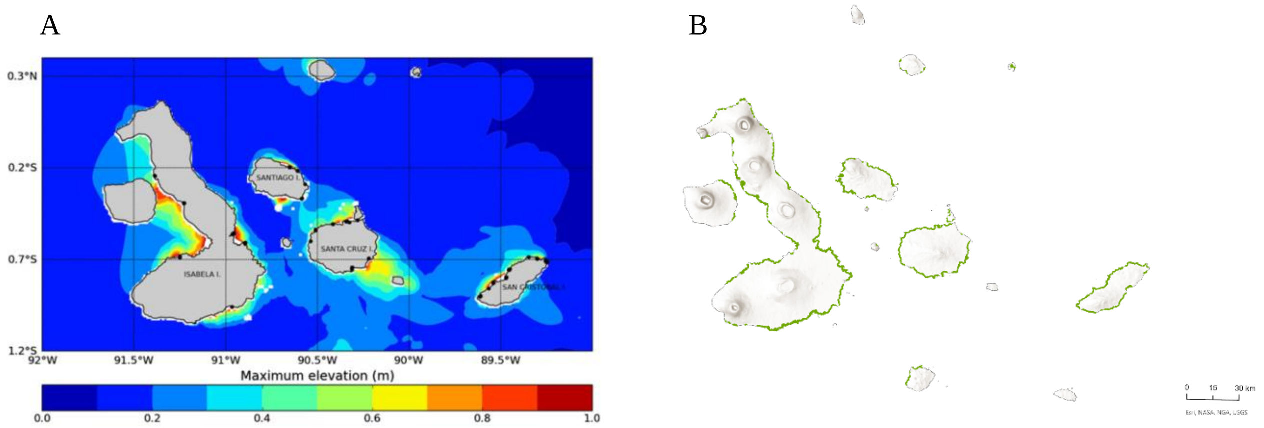

Figure 8. A) Map showing the maximum elevation of the water during the Tohoku tsunami originating in Japan, in 2011. (Source: Lynett *et al.*, 2013) B) Map showing the areas with mangroves forests in the Galapagos for comparison with map A (N.B. a large contour thickness has been used to aid visualization). Note that the areas with the maximum tsunami elevation correspond to the densest and tallest mangrove forests in the Galapagos. (Source: Moity et al., 2019).

This event caused a mangrove dieback in the affected coastline of the Galapagos, particularly on the west coast of Isabela and Fernandina, although mangrove dieback was also documented in most of the areas represented in Figure 8A (Moity, unpublished data). A rough estimate of the mangrove area affected yields more than 250 ha of mangrove forest affected along the Galapagos coastline. A recent tsunami affected the Galapagos on the 15th of January of 2022, due to eruption of the Tonga volcano. The coastline suffered from erosion, but no mangrove dieback was detected.

Left: Mangrove forest where the 2011 tsunami wave was measured at 6.12 m, with dead white mangroves in the foreground (Photo credit: Rashid Cruz/CDF). Right: Stones embedded in the trunk of a white mangrove due to the force of the tsunami (Photo credit: Nicolas Moity/CDF).

Emerging from the surface of the ocean, ~25 km from the northern end of Isabela Island is the volcano, Roca Redonda. This emergent peak of a submarine shield volcano rises more than 3,000 m from the seafloor (Toulkeridis, 2011) and is constantly surrounded by fumaroles in the nearby shallow water, suggesting the volcano is still active (Toulkeridis, 2011). The eruption of this volcano is likely to cause a mega-tsunami capable of destroying all the ports of Galapagos (Toulkeridis, 2011; Figure 9) and probably all the mangroves along the Galapagos mangrove province. In August 2007 an earthquake between Fernandina and Isabela caused a section of Ecuador volcano to collapse into the sea (Toulkeridis, 2011), and it is predicted that larger earthquakes and/or landslides may also create tsunamis (Toulekeridis, 2011; Contreras López, 2013).

Figure 9. Impact times of catastrophic tsunami waves of a potential tsunami generated at Roca Redonda in the Galapagos. In less than one hour all coastlines of the Galapagos would be destroyed, and most probably all mangrove forests decimated. (Source: Toulkeridis, 2011)

Given that the number of threat-defined locations is virtually one and is prone to stochastic events, within a short period of time in an uncertain future (since 2000 there has been one tsunami every two years, and one destructive tsunami every 12 years). Thus, under the threat of tsunamis, subcriterion B3 is assessed as **Vulnerable (VU)**.

Invasive species

Invasive species have the potential to spread rapidly and affect mangrove forests in the Galapagos province. The cottony cushion scale (*Icerya purchasi*) was first reported in 1982 and has spread to most of the larger islands, affecting 80 plant species (Causton *et al.*, 2006), including mangroves such as *Avicennia germinans*, *Rhizophora mangle*, *Conocarpus erectus*, and especially, *Laguncularia racemosa* (Alvarez *et al.*, 2012). Infection with *I. purchasi* significantly reduces plant fitness by impacting branch and root production and growth (Alvarez *et al.* 2012). Several invasive species of soft scales of the genus *Ceroplastes* have also been identified in mangrove species in the Galapagos since 2001 and are present on the islands of Santa Cruz, Santiago, San Cristobal and Isabela (Loor Mosquera, 2017). There is one fungus, the sooty mould, an Ascomycete, genus *Capnodium*, usually associated with the presence of scale insects (since they consume the sugary excretions of the scales). This fungus forms persistent sooty mould deposits on mangrove species, especially *L. racemosa*, although it also affects *Rhizophora mangle, Avicennia germinans* and *Conocarpus erectus*, and other coastal dry vegetation species (Miranda *et al.*, 2022). By covering the leaves with mould deposits, the fungi interfere with photosynthesis, ultimately causing the defoliation and death of the tree.

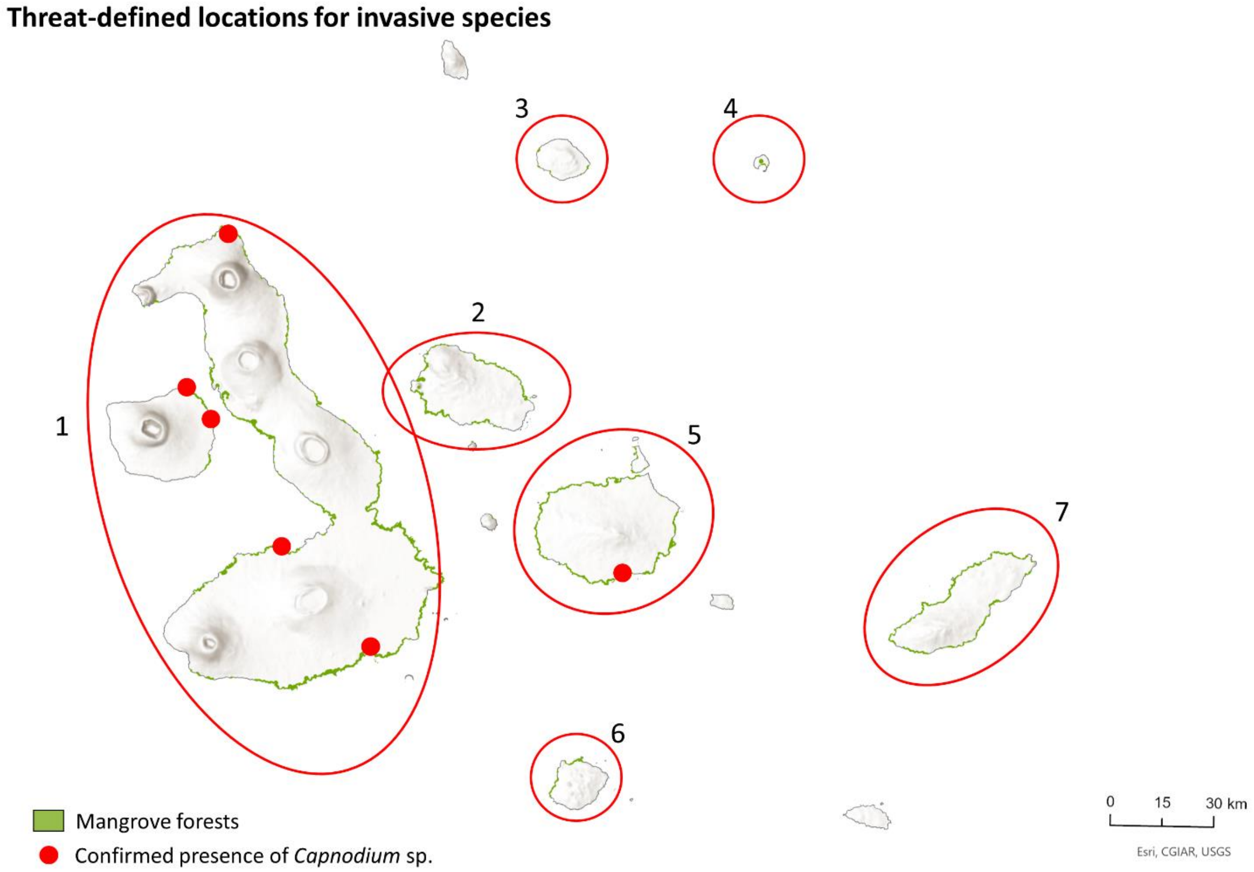

Figure 10. Threat-defined locations for invasive species. Red dots represent the recent presence of the fungus *Capnodium* sp.

I. purchasi has been controlled biologically with *Rodolia cardinalis* and is no longer a major threat (Alvarez *et al.*, 2012). However, *Ceroplastes* sp. has only been controlled on inhabited islands and sites (Miranda *et al.*, 2022), and the sooty mould is present not only on inhabited islands, but also in remote areas where human presence is negligible (Figure 10; Moity, 2023). We identify seven threat-defined locations for these invasive species (Figure 10), assuming that an outbreak on one island (or island group, as in the case of Isabela and Fernandina due to their proximity) is unlikely to affect other islands. However, this may not be the case, as it has been demonstrated that *Icerya purchasi*, *Ceroplastes* sp. and *Capnodium* sp. can spread to several islands in a relatively short period of time. In this scenario, there would be approximately 1-2 threat-defined locations. Considering all these particularities, subcriterion B3 for invasive species threat-defined locations would be assessed as **Vulnerable (VU)**.

The sooty mould (Capnodium sp.) growing on a white mangrove (L. racemosa) (Photo credit: Nicolas Moity/CDF).

Fires

Human-caused fires have the potential to wipe out entire areas of mangrove forest. This has happened previously, including the Isabela Island fire in 1985, which burned 20,000 ha of highland forest, and in 1994, which burned 4,500 ha and was active for five months (Márquez *et al.*, 1995). The most recent anthropogenic fire occurred in July 2023 near populated areas on the island of Isabela, where 0.5 ha of mangrove forest burned (see photo below).

Park rangers from the Galapagos National Park extinguishing a fire of human origin that burned 0.5 ha of the mangrove forest next to Puerto Villamil on Isabela island in July 2023 (Photo credit: GNPD).

The potential of fires to burn mangrove forests remains relatively high near populated areas due to the continuous presence of people, and the increasing population and urbanisation density (Figure 11). However, fires do occur in remote areas, such as the 1985 fire caused by hunters lighting a fire to cook their food. Fishers also camp in coastal areas to rest and cook, which, depending on climatic conditions, can pose a high fire risk. Although most mangrove patches in the Galapagos can be considered remote, there are many visitor sites within mangrove forests (110 sites within 1.5 km of mangrove patches, Figure 11). This increases the likelihood of fires within mangrove forests, even in remote areas, particularly in instances where naturalist guides fail to enforce compliance with the regulations of the Galapagos National Park. Nonetheless, we assess this risk to be relatively low.

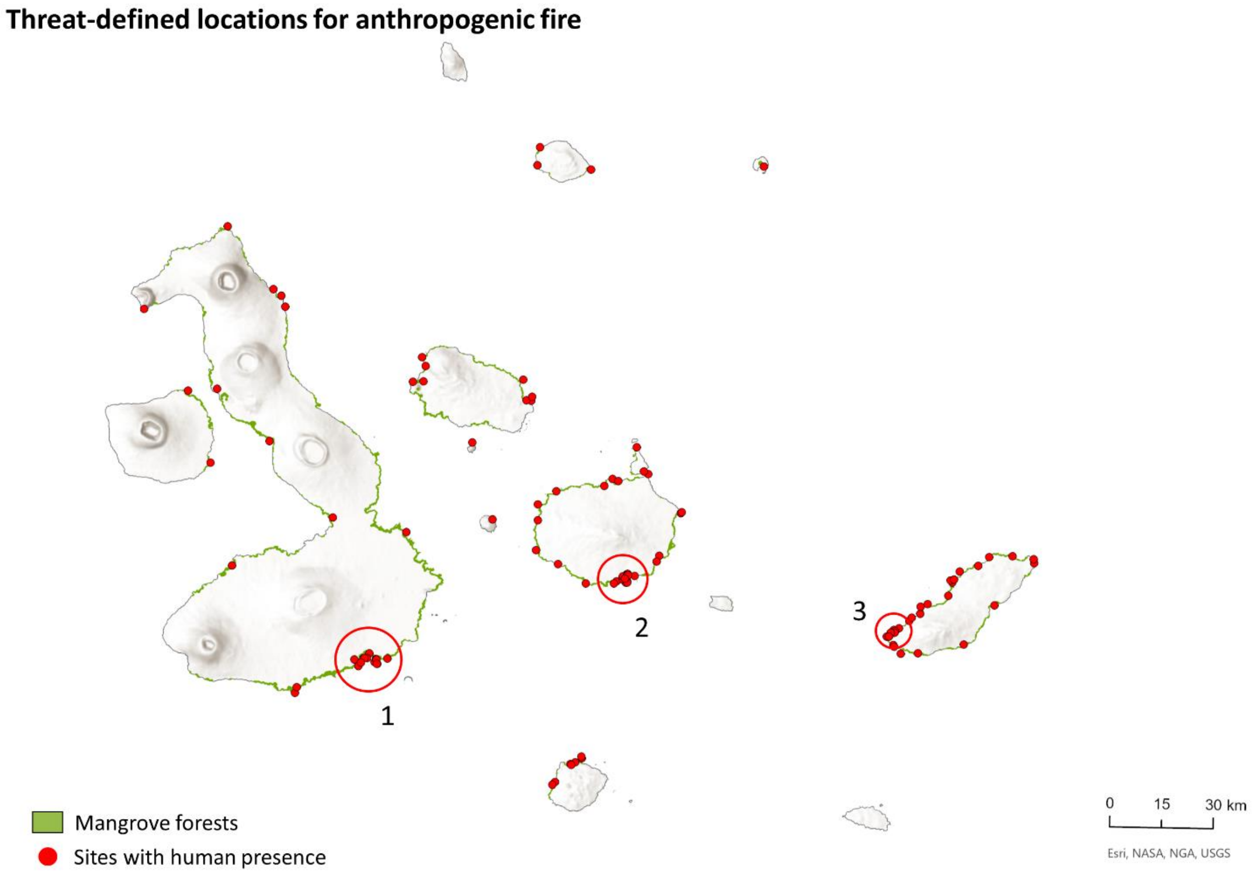

Figure 11. Threat-defined locations for anthropogenic fires. Red circles indicate the three main areas where fires are most likely to occur due to continuous human presence and activities. Red dots indicate areas where there is temporary human presence (tourist sites) that could potentially lead to a fire.

Fishers' campsites are difficult to locate and are therefore largely un-georeferenced, making it difficult to assess the associated fire risk. However, they were much more ubiquitous in the past, when sea cucumber fishing was at its peak (Ramírez-González *et al.*, 2020). At this time permanent camps were set up inside the mangroves to rest, cook, and salt sea cucumbers, with the associated risks of fire, as well as deforestation and other related ecosystem impacts (e.g. fuel pollution, fishing). Illegal sea cucumber fishing camps have recently been dismantled on Isabela and Santa Cruz islands, both of which were in mangrove forests, as they are easy to hide from patrolling Galapagos National Park and Navy boats (Primicias, 2024b).

In the case of anthropogenic fires, the threat-defined locations are numerous (more than 100, Figure 11) as while fires may affect many locations, they are unlikely to spread between these locations. This is because most mangrove patches occupy relatively small areas and are physically separated from each other (Moity *et al.*, 2019). Currently, older islands have more dry coastal forest cover (deciduous forest and shrubland) in the coastal areas that include mangrove forests than younger islands (Moity *et al.*, 2019), which increases the risk because fires that start in dry coastal forests can easily spread to mangroves. An analysis based on the vegetation cover of each island and its connectivity with mangrove forests has not yet been conducted, although we recommend that it should be done to assess fire risk more accurately. Overall, subcriterion B3 is assessed as **Least Concern (LC)** for the sites defined as threatened by anthropogenic fires.

As a result of the assessment under criterion B, the Galapagos mangrove ecosystem is classified as **Vulnerable (VU).**

Criterion C: Environmental Degradation

Criterion C measures the environmental degradation of abiotic variables necessary to support the ecosystem.

Subcriterion C1 measures environmental degradation over the past 50 years: There are no reliable data to evaluate this subcriterion for the entire province, and therefore the Galapagos mangrove ecosystem is classified as **Data Deficient (DD)** for subcriterion C1.

Subcriterion C2 measures environmental degradation in the future, or over any 50-year period, including the present. In this context, the impact of future sea level rise (SLR) on mangrove ecosystems was assessed by adopting the methodology presented by Schuerch *et al.* (2018). The published model was designed to calculate both absolute and relative change in the extent of wetland ecosystems under various regional SLR scenarios (i.e medium: RCP 4.5 and high: RCP 8.5), with consideration for sediment accretion. The Schuerch *et al.* (2018) model was applied to the Galapagos mangrove ecosystem boundary, using the spatial extent in 2010 (Giri *et al.*, 2018) and assuming mangrove landward migration was not possible.

According to the results, under an extreme sea-level rise scenario of a 1.1 m rise by 2100, the projected submerged area is ~ -25.2% by 2060, which remains below the 30% risk threshold. Therefore, considering that no mangrove recruitment can occur in a submerged system (100% relative severity), but that -25.2% of the current ecosystem extent will be affected by SLR, the Galapagos mangrove ecosystem is assessed as **Least Concern (LC)** for subcriterion C2.

Subcriterion C3 measures change in abiotic variables since 1750. There is a lack of reliable historic data on environmental degradation covering the entire province, and therefore the Galapagos province is classified as **Data Deficient (DD)** for this subcriterion.

Overall, the ecosystem is assessed as **Least Concern (LC)** under criterion C.

Criterion D: Disruption of biotic processes or interactions

The global mangrove degradation map developed by Worthington and Spalding (2018) was used to assess the level of biotic degradation in the Galapagos province. This map is based on degradation metrics calculated from vegetation indices (NDVI, EVI, SAVI, NDMI) using Landsat time series (≈2000 and 2017). These indices represent vegetation greenness and moisture condition.

Mangrove degradation was calculated at a pixel scale (30m resolution), on areas intersecting with the 2017 mangrove extent map (GMW v2). Mangrove pixels were classified as degraded if two conditions were met: 1) at least 10 out of 12 degradation indices showed a decrease of more than 40% compared to the previous period; and 2) all twelve indices did not recover to within 20% of their pre-2000 value (detailed methods and data are available at: maps.oceanwealth.org/mangrove-restoration/). The decay in vegetation indices has been used to identify mangrove degradation and abrupt changes, including mangrove die-back events, clear-cutting, fire damage, and logging; as well as to track mangrove regeneration (Lovelock *et al.*, 2017; Santana, 2018; Murray *et al.*, 2020; Aljahdali *et al.*, 2021; Lee *et al.*, 2021). However, it is important to consider that changes observed in the vegetation indices can also be influenced by data artifacts (Akbar *et al.*, 2020). Therefore, a relative severity level of more than 50%, but less than 80%, was assumed.

The results from this analysis show that over a period of 17 years (~2000 to 2017), 3.1% of the Galapagos mangrove area is degraded, resulting in an average annual rate of degradation of 0.18%. Assuming this trend remains constant, an additional 9% of the Galapagos mangrove area will be classified as degraded over a 50-year period. Since less than 30% of the ecosystem will meet the category thresholds for criterion D, the Galapagos mangrove province is assessed as **Least Concern** (**LC)** under subcriterion D2b.

No data were found to assess the disruption of biotic processes and degradation over the past 50 years (subcriterion D1) or since 1750 (subcriterion D3). Thus, both subcriteria are classified as **Data Deficient (DD).**

Overall, the Galapagos ecosystem remains **Least Concern (LC)** under criterion D.

Criterion E: Quantitative Risk

No model was used to quantitatively assess the risk of ecosystem collapse for this ecosystem; hence criterion E was **Not Evaluated (NE)**.

5. Summary of the Assessment

CRITERION			
A. Reduction in Geographic Distribution	**A1** Past 50 years	**A2** Future or any 50y period	**A3** Historical (1750)
	LC	**LC**	**DD**
B. Restricted Geo. Distribution	**B1** Extent of Occurrence	**B2** Area of Occupancy	**B3** # Threat-defined Locations 1
	VU	**LC**	**VU**
C. Environmental Degradation	**C1** Past 50 years (1970)	**C2** Future or any 50y period	**C3** Historical (1750)
	DD	**LC**	**DD**
D. Disruption of biotic processes	**D1** Past 50 years (1970)	**D2** Future or Any 50y period	**D3** Historical (1750)
	DD	**LC**	**DD**
E. Quantitative Risk analysis	**NE**		
OVERALL RISK CATEGORY	**VU**		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

Overall, the status of the Galapagos mangrove ecosystem is assessed as **Vulnerable (VU).**

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7. Appendices

1. List of Key Mangrove Species

List of plant species considered true mangroves according to Red List of Threatened Species (RLTS) spatial data (IUCN, 2022). We included species whose range maps intersected with the boundary of the marine provinces/ecoregions described in the distribution section.

Class	Order	Family	Scientific name	RLTS category
Magnoliopsida	Lamiales	Acanthaceae	*Avicennia germinans*	LC
Magnoliopsida	Myrtales	Combretaceae	*Conocarpus erectus*	LC
Magnoliopsida	Magnoliopsida	Rhizophoraceae	*Rhizophora mangle*	LC
Magnoliopsida	Myrtales	Combretaceae	*Laguncularia racemosa*	LC

2. List of Associated Species

List of taxa that are associated with mangrove habitats in the RLTS database (IUCN, 2022). We included only species with entries for Habitat 1.7: “Forest - Subtropical/Tropical Mangrove Vegetation Above High Tide Level” or Habitat 12.7 for “Marine Intertidal - Mangrove Submerged Roots”, and with suitability recorded as “Suitable”, with “Major Importance” recorded as “Yes”, and any value of seasonality except “Passage”. We further filtered species with spatial point records in the GBIF (some species are excluded due to mismatch in taxonomic names, or lack of georeferenced records). The list includes the recorded species from the RLTS database that intersect with Galapagos mangroves (Table A1). We also include a list of the species (Table A2) that are within 0.5 km from mangrove forests (Moity *et al.*, 2019), from an analysis of threatened biodiversity from the Galapagos (Moity, unpublished data). NE species are included in this list because they are listed in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

Table A1. Species from the Red List of Threatened Species (RLTS) database that intersect with Galapagos mangroves (Moity *et al.*, 2019) The common names are those shown in the RLTS, except common names in brackets, which are from other sources.

Class	Order	Family	Scientific name	RLTS category	Common name
Actinopterygii	Gobiiformes	Eleotridae	*Dormitator latifrons*	LC	Pacific fat sleeper
Actinopterygii	Gobiiformes	Eleotridae	*Eleotris picta*	LC	
Actinopterygii	Mugiliformes	Mugilidae	*Xenomugil thoburni*	LC	
Actinopterygii	Perciformes	Epinephelidae	*Mycteroperca olfax*	VU	Sailfin grouper
Actinopterygii	Perciformes	Sciaenidae	*Odontoscion eurymesops*	VU	Galapagos croaker
Actinopterygii	Perciformes	Sciaenidae	*Umbrina galapagorum*	VU	Galapagos drum
Actinopterygii	Perciformes	Sparidae	*Archosargus pourtalesii*	NT	Galapagos seabream
Actinopterygii	Perciformes	Uranoscopidae	*Kathetostoma averruncus*	LC	Smooth stargazer
Actinopterygii	Pleuronectiformes	Achiridae	*Achirus klunzingeri*	LC	Brown sole
Actinopterygii	Pleuronectiformes	Achiridae	*Trinectes fonsecensis*	LC	Spotted fin sole

Class	Order	Family	Scientific name	RLTS category	Common name
Actinopterygii	Pleuronectiformes	Cynoglossidae	*Symphurus melanurus*	LC	Drab tonguefish
Actinopterygii	Tetraodontiformes	Tetraodontidae	*Sphoeroides annulatus*	LC	Bullseye puffer
Aves	Coraciiformes	Alcedinidae	*Megaceryle alcyon*	LC	Belted kingfisher
Aves	Cuculiformes	Cuculidae	*Coccyzus melacoryphus*	LC	Dark-billed cuckoo
Aves	Gruiformes	Rallidae	*Laterallus spilonota*	VU	Galapagos rail
Aves	Passeriformes	Mimidae	*Mimus melanotis*	NT	San Cristobal mockingbird
Aves	Passeriformes	Mimidae	*Mimus parvulus*	LC	Galapagos mockingbird
Aves	Passeriformes	Thraupidae	*Geospiza heliobates*	CR	Mangrove finch
Aves	Pelecaniformes	Ardeidae	*Ardea herodias*	LC	Great blue heron
Aves	Pelecaniformes	Ardeidae	*Butorides striata*	LC	Green-backed heron
Aves	Suliformes	Fregatidae	*Fregata magnificens*	LC	Magnificent frigatebird
Aves	Suliformes	Fregatidae	*Fregata minor*	LC	Great frigatebird
Chondrichthyes	Myliobatiformes	Potamotrygonidae	*Styracura pacifica*	VU	Pacific chupare
Magnoliopsida	Myrtales	Combretaceae	*Conocarpus erectus*	LC	Silver-leaved buttonwood

Table A2. Species from the Red List of Threatened Species (RLTS) database within 0.5 km from mangrove forests (Moity et al., 2019) according to databases from the Charles Darwin Foundation life-history collections and other databases (Moity, unpublished data).

Class	Order	Family	Scientific name	RLTS category	Common name
Teleostei	Perciformes	Serranidae	Mycteroperca olfax	VU	Galapagos Sailfin grouper
Holothuroidea	Synallactida	Stichopodidae	Isostichopus fuscus	EN	Brown sea cucumber
Teleostei	Perciformes	Serranidae	Paralabrax albomaculatus	EN	Whitespotted sandbass
Teleostei	Perciformes	Sphyraenidae	Sphyraena idiastes	LC	Galapagos barracuda
Squamata		Iguanidae	Amblyrhynchus cristatus	VU	Marine iguana
Anthozoa	Antipatharia	Antipathidae	Antipathes galapagensis	DD	Black coral
Mammalia	Carnivora	Otariidae	Arctocephalus galapagoensis	EN	Galapagos fur seal
Aves	Charadriiformes	Scolopacidae	Arenaria interpres	LC	
Aves	Strigiformes	Strigidae	Asio flammeus galapagoensis	LC	Galapagos short-eared owl
Aves	Passeriformes	Parulidae	Setophaga petechia aureola	LC	Yellow warbler, mangrove warbler

Teleostei	Perciformes	Gobiidae	Bathygobius lineatus	VU	Lined triplefin blenny
Aves	Accipitriformes	Accipitridae	Buteo galapagoensis	VU	Galapagos Hawk
Magnoliopsida	Caryophyllales	Talinaceae	Calandrinia galapagosa	CR	
Aves	Charadriiformes	Scolopacidae	Calidris alba	LC	
Aves	Charadriiformes	Scolopacidae	Calidris mauri	LC	
Aves	Charadriiformes	Scolopacidae	Calidris minutilla	LC	
Aves	Charadriiformes	Scolopacidae	Calidris pusilla	NT	
Aves	Passeriformes	Thraupidae	Camarhynchus heliobates	CR	Mangrove finch
Aves	Passeriformes	Thraupidae	Camarhynchus pallidus	VU	
Aves	Passeriformes	Thraupidae	Camarhynchus pauper	CR	
Aves	Passeriformes	Thraupidae	Camarhynchus psittacula	VU	
Aves	Charadriiformes	Charadriidae	Charadrius semipalmatus	LC	
Testudines		Cheloniidae	Chelonia mydas	EN	Green sea turtle
Testudines		Testudinidae	Chelonoidis porteri	CR	
Anthozoa	Scleractinia	Dendrophylliidae	Cladopsammia gracilis	NE	
Teleostei	Perciformes	Dactyloscopidae	Dactyloscopus lacteus	LC	
Magnoliopsida	Asterales	Asteraceae	Darwiniothamnus lancifolius	VU	
Teleostei	Perciformes	Labrisomidae	Dialommus fuscus	LC	
Elasmobranchii	Carcharhiniformes	Carcharhinidae	Galeocerdo cuvier	NT	Tiger shark
Anthozoa	Scleractinia	Agariciidae	Gardineroseris planulata	LC	
Mammalia	Cetacea	Delphinidae	Grampus griseus	LC	
Aves	Charadriiformes	Recurvirostridae	Himantopus mexicanus	NT	
Testudines		Cheloniidae	Lepidochelys olivacea	VU	
Teleostei	Perciformes	Tripterygiidae	Lepidonectes corallicola	VU	
Aves	Charadriiformes	Scolopacidae	Limnodromus griseus	LC	
Teleostei	Perciformes	Labrisomidae	Malacoctenus zonogaster	VU	Galapagos Blenny
Aves	Passeriformes	Mimidae	Mimus trifasciatus	EN	Galapagos Mockingbird
Anthozoa	Antipatharia	Myriopathidae	Myriopathes panamensis	NE	Black coral
Aves	Charadriiformes	Scolopacidae	Numenius phaeopus	LC	
Teleostei	Perciformes	Sciaenidae	Odontoscion eurymesops	VU	
Anthozoa	Scleractinia	Rhizangiidae	Oulangia bradleyi	NE	
Aves	Accipitriformes	Pandionidae	Pandion haliaetus	LC	
Anthozoa	Scleractinia	Agariciidae	Pavona clavus	LC	
Anthozoa	Scleractinia	Agariciidae	Pavona varians	LC	
Aves	Suliformes	Phalacrocoracidae	Phalacrocorax harrisi	VU	
Aves	Charadriiformes	Scolopacidae	Phalaropus fulicarius	LC	
Aves	Charadriiformes	Scolopacidae	Phalaropus lobatus	LC	
Aves	Procellariiformes	Diomedeidae	Phoebastria irrorata	CR	
Anthozoa	Scleractinia	Caryophylliidae	Phyllangia consagensis	NE	
Aves	Charadriiformes	Charadriidae	Pluvialis squatarola	LC	
Anthozoa	Scleractinia	Pocilloporidae	Pocillopora damicornis	LC	
Anthozoa	Scleractinia	Pocilloporidae	Pocillopora elegans	VU	

Anthozoa	Scleractinia	Pocilloporidae	Pocillopora inflata	VU	
Aves	Passeriformes	Hirundinidae	Progne modesta	EN	Galapagos Martin
Anthozoa	Scleractinia	Psammocoridae	Psammocora stellata	VU	
Aves	Procellariiformes	Procellariidae	Pterodroma phaeopygia	CR	
Magnoliopsida	Asterales	Asteraceae	Scalesia aspera	VU	
Magnoliopsida	Asterales	Asteraceae	Scalesia atractyloides	CR	
Magnoliopsida	Asterales	Asteraceae	Scalesia crockeri	VU	
Magnoliopsida	Asterales	Asteraceae	Scalesia incisa	VU	
Magnoliopsida	Asterales	Asteraceae	Scalesia stewartii	VU	
Aves	Sphenisciformes	Spheniscidae	Spheniscus mendiculus	EN	
Elasmobranchii	Carcharhiniformes	Sphyrnidae	Sphyrna zygaena	VU	
Teleostei	Perciformes	Pomacentridae	Stegastes beebei	LC	Galapagos Damselfish
Teleostei	Perciformes	Scombridae	Thunnus albacares	LC	Yellowfin tuna
Teleostei	Perciformes	Scombridae	Thunnus obesus	VU	Bigeye tuna
Aves	Charadriiformes	Scolopacidae	Tringa flavipes	LC	
Aves	Charadriiformes	Scolopacidae	Tringa incana	LC	
Aves	Charadriiformes	Scolopacidae	Tringa melanoleuca	LC	
Anthozoa	Scleractinia	Dendrophylliidae	Tubastraea coccinea	NE	
Teleostei	Perciformes	Sciaenidae	Umbrina galapagorum	LC	
Mammalia	Carnivora	Otariidae	Zalophus wollebaeki	EN	Galapagos Sea lion

3. National Estimates for subcriterion A1

To estimate the Galapagos mangrove ecosystem extent in 1970, we gathered reliable information on the mangrove area around this period (Table a, b) and then estimated the mangrove area in 1970, assuming a linear relationship between mangrove extent and time. However, using mangrove area estimates from different sources can lead to uncertainty (Friess and Webb, 2014)[2] thus, the estimates for 1970 should be considered only indicative.

Table a. Estimated mangrove area by country in 1970 and 2020. Estimates for 2020* mangrove area are based on the Moity et al (2019) dataset. The references used to calculate mangrove area for each country in 1970 are listed below in Table b.**

Year	Within province 2020*	Within province 1970**
The Galapagos	36.6	11.8 (1.4-22.2)

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[2] Friess, D. A. and Webb, E. L. (2014). Variability in mangrove change estimates and implications for the assessment of ecosystem service provision. *Global Ecology and Biogeography*, 23 (7). 715-725 doi:10.1111/geb.12140

Table b. List of selected studies considered to have reliable information on mangrove area for the period around 1970 in each country of the Galapagos province.

Region, Country	**Year**	**Mangrove Area (km^2)**	**Reference**
Galapagos, Ecuador	2014	36.571	Moity, N., Delgado, B., and Salinas-de-León, P. (2019). Mangroves in the Galapagos islands: Distribution and dynamics. *PLOS ONE* 14, e0209313. doi: 10.1371/journal.pone.0209313
Galapagos, Ecuador	2016	14.704	Rivas-Torres, G. F., Benítez, F. L., Rueda, D., Sevilla, C., and Mena, C. F. (2018). A methodology for mapping native and invasive vegetation coverage in archipelagos: An example from the Galápagos Islands. Progress in Physical Geography: Earth and Environment 42, 83–111. doi: 10.1177/0309133317752278
Galapagos, Ecuador	2002	33.791	Briones, E., E., Flanchier, A., Gómez, D., Tirira, H., Medina, H., Jaramillo, I., et al. (1997). Inventario de Humedales del Ecuador. Primera parte: Humedales lénticos de las provincias de Esmeraldas y Manabí. Quito, Ecuador: EcoCiencia/INEFAN/Convención Ramsar.
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