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CLIMATE CHANGE: THE NEW EVOLUTIONARY CHALLENGE FOR THE GALAPAGOS

FEASIBILITY DOCUMENT

Restoration of High Ecological Value Marine Ecosystems

An ecosystem-based approach to climate change adaptation in the Galapagos Marine Reserve

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1. SUMMARY

The Galapagos archipelago is highly vulnerable to the effects of global climate change, and the Galapagos Marine Reserve (GMR) is particularly susceptible due to its connectivity with the rest of the Eastern Tropical Pacific region and the complex system of ocean circulation supporting its unique and fragile ecosystems.

Climate change will further exacerbate the risk posed by already high climatic variability in the Eastern Tropical Pacific region, mainly influenced by the El Niño Southern Oscillation. Also, the maintenance of increasing tourism numbers in Galapagos without clearly understanding its actual effect upon the natural capital, if left unmanaged, could pose a serious threat. In addition, the lack of sufficient interventions to address marine tourism impacts, waste and energy management, marine invasive species, marine debris, illegal, unreported and unregulated fishing and the social and economic inequalities encountered at various instances within the seafood value chain, are all issues faced by the governing bodies that can hinder their ability to manage the conservation and use of the ecosystem services provided by the GMR.

To inform policies and support decision-making processes, predictions on ecosystem-wide ecological responses in the GMR to climate change and other anthropogenic stressors will be made through the development of ecosystem-based models. These models will be fed with over fifteen years of baseline data (2004 – 2020) information and expertise on marine biodiversity of the GMR, coupled with physico-chemical parameters. These models will depict diverse future scenarios for the GMR with and without Ecosystem-based Adaptation measures. The models presented as a showcase in this document suggest that future climatic scenarios will impact the distribution and settlement and recruitment of important reef building coral species, a clear sign that measures need to be taken to increase resilience against climate change.

Here, we propose to design effective Ecosystem-based Adaptation Measures to adequately manage, govern, and conserve marine ecosystems in the GMR. These are based on strengthening marine biosecurity programs for invasive species, restoring selected coral reef areas through experimental coral breeding and exclusion areas, improving surveillance and control measures to promote adequate sea turtle nesting and foraging sites and

reducing the impact of diving, anchoring and pollution related to tourism operations in selected marine high ecological value areas.

2. INTRODUCTION

Climate change is causing alterations in the abundance of species populations by affecting global crop production, facilitating alien species invasions, altering the phenology of species, creating favourable conditions for new pests and diseases, changing rates of evolution and species distributions and reducing ecosystem services; the Galapagos Islands are no exception (Ward and Masters, 2007; WWF and Conservation International, 2010; Gross, 2011; Richardson et al., 2013; Seneviratne et al., 2014; Ray et al., 2019). Although most of the territory in Galapagos is protected (97% terrestrial and 100% marine) (DPNG, 2014), the islands are highly vulnerable to the effects of this global phenomenon. In particular, the Galapagos Marine Reserve (GMR) is more vulnerable to these changes due to its connectivity with the Eastern Tropical Pacific (ETP) region (WWF and Conservation International, 2010; Liu et al., 2013). For example, it has been shown that climate change has triggered changes in the oceanographic properties of the GMR (Karnauskas et al., 2015), affecting emblematic species such as the Galapagos penguin (Vargas et al., 2006) or entire ecosystem-forming species, such as corals (Glynn et al., 1988; Manzello et al., 2014). Even though the entire marine reserve is under protection, only 32% of the GMR's total area is a no-take zone according to the 2016 zoning – which is still not implemented- and less than 1% according to the 2000 zoning. Intangible marine zones (where no tourism or fishing is allowed) cover a very small proportion of the reserve (Ministerio del Ambiente, 2016; Moity, 2018). While industrial fishing is banned from the Galapagos, the artisanal fishing fleet has overexploited some resources, notably sea-cucumbers (Ramírez-González et al., 2020) and demersal fish species, like the Galapagos sailfin grouper, which is showing signs of overexploitation (Usseglio et al., 2016). Overexploitation on top of climate change, will alter the correct functioning of marine ecosystems in Galapagos, not only affecting the rich and unique marine biodiversity of the islands and the wider ETP region, but also affecting the ecosystem services they provide, which boost economic development through income generation at local and national scales.

The above is further complicated by the increasing tourism numbers, whose actual effect on the natural capital is still not fully understood and, left unmanaged, could pose a serious threat to the conservation of the archipelago (Epler, 2007; Gonzalez et al. 2008; Grenier, 2010; Quiroga, 2009; Watkins and Cruz, 2007). Galapagos is the main tourist destination of Ecuador and the most visited national park, bringing an important cash flow to the country. The Gross Domestic Product for Galapagos was of 256.1 USD million in 2019, where tourism contributed to 65.5 % of this figure in the archipelago (BCE, 2019). Therefore, nature-based tourism in the Galapagos contributes substantially to livelihoods both locally and in the country (Reck & Martínez, 2010). Such tourism is highly dependent on maintaining the natural features of the sites, which are the attraction to visit the archipelago (Epler, 2007). The impacts of increasing tourism numbers on terrestrial ecosystems in the Galapagos are well recognized, especially regarding terrestrial invasive species (Epler, 2007; Toral-Granda et al., 2017). However, there is no such evaluation regarding the impact of tourism in marine ecosystems. Concerns have been highlighted regarding the risk of invasive species associated to the increase in marine traffic (Keith et al., 2016), impacts to marine turtles from navigation (Denkinger et al., 2013), impacts on marine ecosystems due to boat anchoring (Acuña-Marrero & Keith, 2011; Moity, 2016) and diving tourism (Moity & Espinosa-Mellado, 2013, Moity et al., 2019). Thus, it is important to promote low impact tourism activities coupled with tourism-monitoring programs, while at the same time analyse their impacts on nature and the changes in the social-ecological system that nature-based tourism represents (Moity et al., 2019).

A critical and growing threat to the sustainability and functional resilience of marine ecosystems (Doney et al. 2011), that can be exacerbated by the impacts of climate change, are invasive species. Non-indigenous species (NIS) can provide reduction of the functional diversity of the resident species assemblages by removing key organisms, which may have overall implications for ecosystem function, production and response to other environmental stressors (Katsanevakis et al., 2014). Invasions of NIS impact biodiversity and society, including ecosystem services such as fisheries and nature-based tourism. Marine NIS can impact food resources through predation and competition. For example, the European green crab (*Carcinus maenus*) and the warty comb jelly (*Mnemiopsis leidyi*) have devastated fisheries in the Black Sea (Shiganova et al., 2001). NIS can also cause substantial losses to nature-based tourism by expanding uncontrollably, forming dense beds that cover recreational sites becoming a problem for boating, swimming, and diving (Charles and Dukes, 2008). In the GMR there are reports of the invasive seaweed, *Caulerpa racemosa,* expanding in a popular tourism site known as Tortuga Bay, located in the most populous island of the Archipelago (Santa Cruz). This species of green algae competes with native species for space and forms extensive mats changing species assemblages and functional diversity as well as causing problems for tourists (Keith et al. 2016).

Invasions result from the unintended transfer of organisms by vessels, aquaculture, fishing, recreation and other human activities. NIS can hitch a ride to overcome previous barriers and/or expand to new regions due to novel favourable conditions (e.g., increasing sea-surface temperature). Furthermore, when a habitat has been changed, e.g., through climate change, invasive species can take advantage of the disturbed environment to adapt, establish and spread more effectively in the new environment, making the ecosystem less resilient to climate change (Emerton and Howard 2008). In contrast, non-disturbed environments can better resist invasions (Keith et al., 2016). The key to prevent marine invasions is to reduce the unintentional transfer of organisms combined with a detection and response capability of new NIS incursions. These are fundamental tenets of biosecurity protocols that are well understood but are only partly implemented in marine systems. As a result, the door is still open for new marine invasions in most regions. The challenge is to implement a coordinated regional marine biosecurity approach across impacted countries. This broader scope is critical: what happens in one country affects adjacent regions, as species cross borders via human activities. The biogeographic location of the GMR is key to coordinate efforts with the governments and research centres of Panama, Costa Rica and Colombia, to make the ETP region biosecure. Simply put, biosecurity (prevention, detection, and response) capability is more effective and efficient at a regional scale because it promotes sharing investments, information, tools and successful implementations.

A key marine ecosystem affected by these threats (tourism, marine NIS and climate change) are coral reefs. In Galapagos, these ecosystem-builders are highly important for marine ecosystems and tourism (Banks et al., 2016), however, their high sensitivity to changes in temperature makes them very vulnerable to climate change (Banks et al. 2016). Bioerosion and bleaching events have dramatically reduced coral cover in the GMR, with extensive loss and fragmentation of coral reefs. Because of sea warming coral reefs were reduced by 97% after the 1982-83 and the 1997-98 El Niño (Glynn et al., 2018). As temperature rises, due to climate change, many coral species could be replaced by other species that are more heat-tolerant (WWF and Conservation International, 2010).

Further, identifying the impacts of climate change and other pressures on keystone species is critical to understand how ecosystems will respond to these stressors. In the ETP, green sea turtles maintain healthy seabeds and coral reefs, providing key habitat for other marine life. However green sea-turtles are highly vulnerable to climate change (Poloczanska et al

2009): sex determination of hatchlings depends on the incubation temperature, where an increase in temperature will result in the feminization of sea turtle populations (Jensen et al. 2018). With the second most important nesting colony in the ETP found in Galapagos, the archipelago is a seeding ground for green sea-turtles in the region and provides important foraging grounds for a partly resident stock, that is widespread over the whole GMR (National Marine Fisheries Service & US Fish and Wildlife Service 1998, Seminoff 2004). Other effects of climate change include loss of nesting and feeding habitats due to sea-level rise, erosion (Gill et al 2005), eutrophication, and acidification (Hawkes et al 2009; Poloczanska et al 2009). A study conducted at the main nesting beach for the green turtle in the ETP, predicted that a sea-level rise of 5 m would lead to the loss of 54% of the suitable habitat in nesting beaches, decreasing nesting success (Calvillo et al 2015). Indeed, monitoring of the nesting sites in Galapagos showed that the number of nests affected by flood and erosion increased from 1.6% (17 nests, representing 1183 embryos) in 2007-2009 to almost 9% (128 nests, representing 8960 embryos) in 2009-13 (Parra, unpublished data). This could be an early signal of nesting habitat loss, resulting in a decrease in nesting success. The impact on nesting habitats must be monitored urgently to detect sensitive zones to flooding and erosion, and to detect less affected safe zones. Identification of safe zones will allow the implementation of adaptation measures, such as nests translocation to protect them from flooding and erosion. Furthermore, anthropogenic activities such as marine traffic are affecting sea turtles within the GMR through boat collisions, (Denkinger et al 2013; Parra et al 2013). It is crucial to improve management measurements in and around sea areas used as marine routes near nesting beaches, where large densities of turtles aggregate during the breeding season. The protection of both adult sea turtles and nests, will increase the green turtles' resilience to climate change.

In light of the potential impacts of climate change combined with other anthropogenic stressors on key marine ecosystems and the livelihoods that depend on them, it is crucial to develop research and management tools that will increase the resilience of Galapagos' marine ecosystems. The following proposed measures aim to increase the resilience of coral reefs and green sea turtle populations by restoring corals and strengthening the controls of bioerosion and bleaching in the GMR and by closely monitoring changes in nesting success and controlling boat traffic, respectively. For corals, the proposed measures will ensure that endangered corals in the region will be protected under CITES, due to their importance for marine ecosystems. Measures will also promote working on indicators in the region to ensure resilience against climate change and other related human drivers.

In a multi-use reserve such as the GMR, the maintenance of long-term marine monitoring programs is considered a valuable tool when evaluating how communities naturally develop and respond to human and environmental stressors as well as to identify changes in socio-economic factors that have direct and indirect effects on the environment. Long-term monitoring also enables to evaluate the effectiveness of management measures at identifying and mitigating any undesired negative impacts over the systems (Banks et al., 2016). The monitoring of the species, ecosystems and livelihoods proposed in these adaptation measures will produce the scientific data required to understand how climate change will interact with other existing pressures and how they will affect the GMR, that will ultimately inform policy and management decisions.

The marine ecosystems of Galapagos support the livelihoods for the tourism industry and the small-scale fisheries sector in Galapagos. The restoration initiatives proposed here focus on an integrative approach to conserve the unique marine ecosystems of the Galapagos while improving the livelihoods for the local community. By benefiting the community, this approach will ensure the long-term sustainability of the proposed measures beyond the duration of the project.

3. PROJECT IMPLEMENTATION AREA

The GMR is a multiple-use marine protected area (Figure S1) created in 1998 by the approval of the Special Law for Galapagos (LOREG). It corresponds to the marine dimension of the Galapagos National Park and is located 1,000 km off the coast of continental Ecuador (Tye et al., 2002; Piu, 2003). The GMR (138,000 km2). The GMR is the largest reserve in the ETP region and one of the largest marine reserves worldwide (Carlton et al., 2019). The GMR is known globally for its high levels of diversity, endemism and productivity (Danulat and Edgar, 2002; Tye et al. 2002). These attributes are determined by the Intertropical convergence zone, where the islands are located, and where cool and warm currents meet, resulting in unique oceanographic conditions that affect the distribution of marine species and habitats across the archipelago (Banks and Witman, 2018, Edgar et al. 2004). A major current influencing marine life in the Galapagos is the Equatorial Undercurrent (EUC), which is believed to be the main driver of primary productivity within the GMR (Palacios 2004). The bathymetry around the islands forces the cooler EUC waters to upwell in the western side of the archipelago bringing nutrients to the surface, which results in large phytoplankton blooms.

However, the location of the islands in this convergence zone also makes the marine and coastal ecosystems particularly vulnerable to climate change impacts. Warming surface waters, particularly during intense El Niño events, causes a suppression of the EUC, which results in lower primary production and a general decline in biological activity (Liu et al. 2013). During the past decades, the frequency and severity of El Niño events have increased, and climatic models have shown that this tendency will continue to worsen within the GMR under current rates of global warming (Cai et al. 2018; Liu et al. 2013), although in some cases this remains unclear (Carréric et al. 2019; Seager et al. 2019). Extreme events like El Niño can have devastating impacts on marine systems as they have been linked to significant changes in the structure and function of entire ecosystems (Harley et al. 2006). Furthermore, the steady increase of anthropogenic pressures has caused degradation on marine ecosystems around the world, resulting in significant changes and reorganizations of structure and function within ecosystems, which can lead to phase shifts (Rocha et al., 2015). For example, phase shifts from coral to macroalgal dominance on shallow tropical reefs have become more common in recent times (Fung et al. 2011) and climate change is predicted to intensify that process (Hoegh-Guldberg et al. 2007). Important highly productive habitats in the GMR, coral reefs and coral and macroalgae communities, have already been heavily impacted from previous climatic events (Glynn et al. 2015), and changes in oceanographic features have been detected (Karnauskas et al., 2015).

4. PROBLEM CONTEXT AND ANALYSES

The marine ecosystem services within Marine Protected Areas (MPAs) have been extensively assessed, described and characterized from the economic, social and environmental standpoints, as critical in the maintenance of ecological processes, functions, structures and human livelihoods. Ecosystem services are provided by a number of ecosystem functions and contribute to a wide range of benefits that human populations can use in a variety of ways (Costanza et al. 2014, de Groot et al. 2010, Lau et al. 2019). Two of the most important sectors that depend upon these ecosystems, and whose sustainability is linked to them, at global scale, are tourism and small-scale fisheries (FAO 2020). And in Galapagos Marine Reserve, this situation is not the exception.

According to this reasoning, the way we look at these key ecosystems in the Galapagos Marine Reserve (e.g., rocky reefs with coral patches) includes a comprehensive format of socio-ecological systems that are interdependent and deeply linked. Additionally, from the social perspective we highlight here: first, the importance of these ecosystems, as livelihood supporter for the tourism industry in the Galapagos Islands, and second, the relevance these spaces provides to the small-scale fisheries sector in Galapagos. The varied restoration initiatives proposed in this research thus focus on the integrative approach to ensure marine ecosystems conservation and livelihood viability in Galapagos.

The accelerated rate of anthropogenic climate change poses a great challenge for species, who must adapt in order to keep pace with such changes. The persistence of species will depend on how rapid they can adapt to novel conditions, which does not seem very optimistic, especially for the most vulnerable species, including long-lived species (Zhang et al., 2019; Bisbing et al., 2021). On the other hand, these changing conditions, also create ideal circumstances for some species to move out of their home ranges, even between regions, and eventually become invasive. Consequently, climate change facilitates the dispersion of non-indigenous species (NIS) and creates opportunities for them to become invasive (Canning-Clode et al., 2011).

Preventing NIS is the single most cost-effective action to ensure long-term sustainability of island biodiversity and avoid costly eradications (Faulkner et al, 2020). In the context of bioinvasions, EDRR protocols are a series of sustained and coordinated actions to predict, monitor, report and verify the presence of NIS before the species becomes established and spreads, continued by a rapid response process to eradicate the species before it establishes and spreads to the point where eradication is no longer feasible (Reaser et al., 2020). These protocols would not only safeguard the environment and human well-being form NIS impacts, but also potentially save billions of dollars that would otherwise have to be spent on repairing the damage caused by the NIS along with control measures that could go on indefinitely (Meyers et al., 2020; Reaser et al., 2020). EDRR protocols present a critical framework for preventing, limiting, and mitigating the spread of NIS to islands not only to Galapagos but to other islands in the ETP.

In order to design effective ecosystem-based adaptations (EBAs) to adequately manage, govern, and conserve marine ecosystems in the GMR, it is important to be able to predict ecosystem-wide ecological responses to climate change and other anthropogenic stressors (Ellison et al. 2005; Trifonova et al. 2019). To achieve this, ecosystem-based models can be developed to understand the often-complex relationships between biotic and abiotic factors in marine systems (Helmuth et al. 2006). Ecosystem-based models have already been successfully applied to a variety of ecosystems to address a wide range of questions. For example, models have allowed us to better understand how climate change affects different trophic levels of marine pelagic communities in temperate regions (Edwards & Richardson 2004), to predict species distributions (Moya et al. 2017), to prioritize areas that should receive protection due to their ecological importance (Yates et al 2016), and to estimate changes in primary production due to climate change (Brown et al. 2010; Schlenger et al. 2019). These studies demonstrate that it is possible to develop an 'ecosystem-based modelling framework' that evaluates the vulnerability of marine systems in the GMR to ecosystem-wide changes, brought on by anthropogenic threats and exacerbated by climate change. Based on these exercises, strategies can be designed to implement measures that increase response capacity and reduce the risk of impact on marine systems.

The Charles Darwin Foundation (CDF) has over fifteen years of baseline data (2004 – 2020) on marine biodiversity of the GMR, which is product of the long-term subtidal ecological monitoring program on rocky reefs (Banks et al. 2016). The sample unit consists of a 50m transect parallel to the coast at two different depths 15m and 6m at any given site. This methodology focuses primarily on recording data on three major groups of macro fauna: fish, macro invertebrates and sessile organisms (Banks et al. 2016; Edgar et al. 2004). There are 380 sites from which a minimum of 64 diagnostic sites, within the GMR that are monitored on a yearly basis (Figure S1). This effort assesses species richness, diversity, abundance and size of marine communities, as well as their distribution, composition and structure. The subtidal ecological monitoring also assesses the environmental impacts and anthropogenic disturbances that affect these ecosystems, due to natural and anthropogenic events (Table S3). Analyses this long-term assessment show that rocky reefs dominate more than 80% of the subtidal habitat at less than 40m, and that these are the areas with the highest exposure to interactions with users of the GMR (Banks et al. 2016; Edgar et al. 2004; Edgar et al. 2008; Edgar et al. 2009) (Figure S1).

The 2004 – 2020 subtidal dataset was used to identify the drivers affecting key marine ecosystem services. Ecosystem-based models were developed to predict the ongoing and potential future negative impacts of climate change and anthropogenic pressures for rocky reef ecosystems within the GMR. The Remote Ocean Modelling System (ROMS) (https://www.myroms.org/) was used to predict the oceanographic conditions under different Representative Concentration Pathways (RCPs) up to the year 2040. The ROMS model uses the Hadley Centre Global Environment Model version 2 (HadGEM2-ES), which uses the ORCA tripolar grid (Madec & Imbard, 1996; https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/climate-models/hadgem2) to generate the future climate and atmospheric forcing, and the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2) to estimate current and past climate and atmospheric data.

Currently, the Synthesis Report of the IPCC Fifth Assessment Report (AR5) describes four RCPs that represent a range of emissions (IPPC, 2014). For the purpose of this study, RCPs 4.5 and 8.5 will be used because RCP 4.5 is the scenario that Ecuador and the GNPD would aim for if the average temperature trend continues until the end of the century (DPNG, 2019). On the other hand, RCP 8.5 is considered a pessimistic scenario, which will illustrate what would happen in the GMR if no mitigation measures would be taken against climate change. The outputs from ROMS of the GMR and the surrounding ocean created in 2014 were used to create graphs and maps comparing RCPS's 4.5 and 8.5 regarding temperature and currents at two depths (5 and 15m) during the hot season (December to May). This season was chosen because it experiences the most variability during these months, most likely affecting coral populations. The resolution of the ROMS model was 5/88° by 5/88°. Each month modelled had a period of 30 days and 12 months were modelled for each year. The model was run under RCPs 4.5 and 8.5 from 2020 to 2040. MATLAB® was used to extract the outputs from their netCDF format files. These were then averaged over the 30 days of each month to get the monthly mean values for temperature and oceanic currents. Temperature variability was plotted for each month across the years, followed by a best fit polynomial using polyval and polyfit functions, to attain the coefficients and to fit the curve respectively. Currents were plotted using the quiver function which plots arrows, which represent the horizontal and vertical vectors of velocity. This was overlayed on a high-resolution bathymetry map of the GMR to clearly show the trajectories of currents around the islands.

The data for the bathymetry used, was obtained from the Pacific Marine Environmental Laboratory provided by NOAA, it was created by merging various bathymetric grids of the archipelago (Chadwick, 2007). The various bathymetric grids are as follows:

- DBDB5 global dataset, spaced at 5-minute intervals.
- NOAA/Marine Geophysical Data Center ship-track bathymetric data
- Digitized hydrographic maps (topographic contours above sea level and individual near-shore soundings below sea level), courtesy of Dave Christie and Bob Duncan, Oregon State University
- SeaMARC II data from the 87 30'W overlapping spreading center (courtesy of Laura (Perram) Penvenne and Ken Macdonald, UCSB) and the Ecuador Rift (courtesy of Suzanne Carbotte and Ken Macdonald, LDEO and UCSB)
- SeaBeam multibeam sonar bathymetry
- data from the Scripps Institute of Oceanography database
- data collected by Dave Christie and Bob Duncan, Oregon State University, in 1990
- data collected by Bob Embley, NOAA/NURP/VENTS, in 1985
- U.S. Navy SAS data collected during the 1970's

Furthermore, a particle tracking model was developed for two reef-building coral species in the GMR (*Pavona gigantea and Porites lobata*) to predict larvae dispersal under RCP 4.5 and 8.5 climatic scenarios. This model would provide a link between the data collected from the Subtidal Ecological Monitoring program and the ROMS model projections for oceanographic and climate change within the GMR over the following 40 years. The particle tracking model was run at 5-year intervals during the warm season in the Galapagos (January to May), at depths of 5 m and 15 m, which are based off the Subtidal Ecological Monitoring depths (Banks et al. 2016) and well within the common depth limits for both species. (Glynn et al., 2016). The larvae within the particle tracking model had 7 starting islands based on the locations at which these species have been found during the most recent years of the Ecological Monitoring project. These islands are Española (-89.6 -1.365) (blue), Floreana (-90.37 -1.237) (green), Santiago (-90.52 -0.3243) (red), Darwin (-91.99 1.646) (cyan), Wolf (-91.81 1.389) (black), Genovesa (-89.98 0.3243) (white), and Marchena (-90.51 0.3003) (magenta). Each starting location is marked by an X of the colour listed previously (Figure S9). Twenty particles were released per site for each month and their movement was recorded every minute, although the current data is only daily, an interpolation of this across the days at 6-hour intervals with a velocity recording every minute allows for more accurate movement of the larvae. Each movement step for each particle included a random displacement in the x and y plane of 15 m to replicate the movement by the larvae themselves swimming or small currents and eddies, which the model cannot simulate. The pelagic larval duration (PLD) of both species has never been empirically determined however it is thought to be between 20 and 50 days. For simplicity, at this stage of the model the larvae were suspended in the water for 30 days. The final location of each larvae was marked by a circle with the same colour as its starting location marker.

Further analysis can be done to evaluate the impacts of changing temperatures on the abundance of these species, as well as others, however, further work on the model is required to reach that point. The species spread can be recorded over the course of several months with each new site populated able to produce further larvae and any larvae unable to reach a location of suitable depth and temperature within their PLD killed off. However, this process is very computer intensive and time consuming so it would need longer time frames to be completed. In addition, the rapid depth-drop along the coast of each island makes it difficult to record the correct depth along the coastline without a higher resolution bathymetry across the GMR. For the islands of Darwin and Wolf it would be more useful to have a model covering a larger area north of the islands because the current maps show strong evidence of circular currents occurring, which would drag the larvae north. then back east, before looping back into the north-eastern islands of the archipelago. These results act as an example of the work that can be done through particle tracking for native species expansion and self-recruitment within the GMR, as well as the spread of and high-risk areas associated with invasive NIS.

The use of an offline particle tracking model, combined with a three-dimensional hydrodynamic model, in this case a ROMS model's outputs, has repeatedly shown to be able to successfully recreate or predict the spread of NIS throughout a marine ecosystem due to larval transport (Robins et al., 2013; Simons et al., 2013; Brickman, 2014; Wood et al., 2021). Predicting the arrival of NIS to Galapagos due to climate change is the first step in creating the EDDR framework for the archipelago. In regards to the dispersal of larvae and potential movement of species population sites across a marine ecosystem, be they native or introduced, the main external drivers are currents and thermal gradients (Garciá Molinos et al., 2017). These have been shown to either positively or negatively affect the movement of species, depending on their directional agreement, with greater directional agreement accelerating the movement of species driven by climate change and vice versa (Garciá Molinos et al., 2017). As can be seen from the ROMS outputs, the temperature and currents within the GMR increase and vary respectively, with the more extreme RCP 8.5 scenario showing more drastic effects. This change in surface current directions, caused by climate change, has the ability to create new vectors for NIS spread, as previously unconnected islands become so, particularly the increased current movement into the Elizabeth bioregion between Fernandina and Isabela which up until now has been a mostly isolated area (Edgar et al., 2004). Changing surface currents across the ETP could also become new vectors for introduction from outside the GMR, carrying marine debris with species attached from new regions to the GMR. The changes in temperature across the different bioregions also increases the risk of invasive species spread, since they are often better adapted to changing conditions unlike native species which may die back and struggle to recover with more competition for light and nutrients. Furthermore, previously uninhabitable (for introduced species) regions, particularly in the West could become more vulnerable to invasion as their yearly average temperature increases. The offline particle tracking model, in combination with the information about larval dispersal as well as barriers or accelerators such as climate change and directional agreement, has the potential to be an incredibly useful tool in predicting the future spread of introduced species around the GMR and, if expanded to the entire ETP, any external invasions from the continent. In addition, it can aid in showing the sites from which native species, such as corals, can recover and receive larvae from due to the connectivity of specific islands through sea-surface currents.

The tourism sector could also be affected by climate change as the species and ecosystems on which it depends and are of high value to this sector, are vulnerable to the impacts of climate change. The tourism sector in Galapagos should amplify its commitment to the conservation of the islands by promoting activities that contribute to increase the resilience of the Galapagos' ecosystems and reduce its vulnerability to climate change.

4.1 Expected change on temperature and oceanic currents.

In order to best analyse the impact of temperature across the Galapagos archipelago, impacts were analysed into 5 main biogeographical marine bioregions, as defined by Edgar *et al.* (2004), due to each region unique marine biota. These are defined as the 'Far Northern' (marine area surrounding Darwin and Wolf), the 'Western' (Fernandina, western and southern Isabela), the 'Central-Southeastern' (the central archipelago and eastern Isabela), the 'Northern' (encompasses Marchena, Genovesa, Pinta and the waters north of them) and finally 'Elizabeth' bioregion (better known as Canal Bolívar between the coasts of Isabela and Fernandina (Fig. 1).

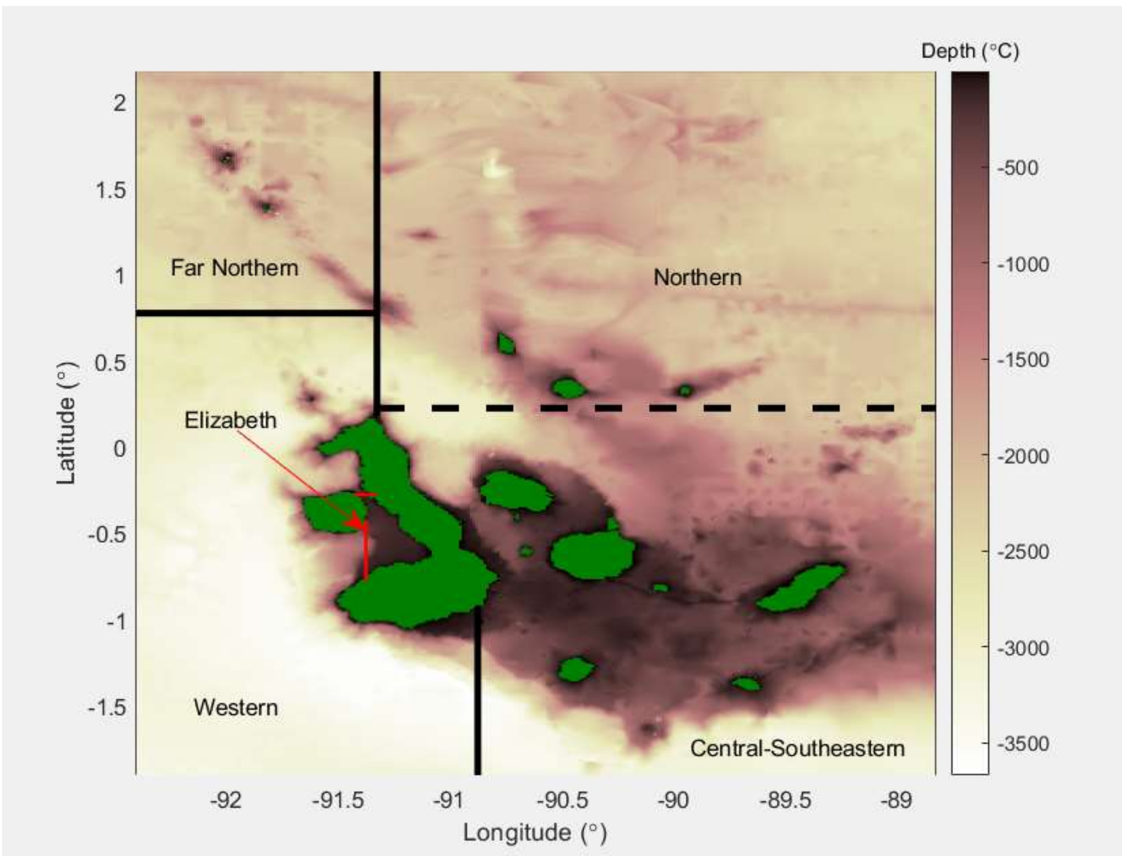

Figure 1: *Map showing the Galapagos Islands divided into the 5 main biogeographic regions.*

In our models, temperature averages during the warm season show much greater year to year variation than their cold season counterparts. However, one undeniable fact across almost every scenario is an increase in the average yearly temperature of the GMR at both 5 m and 15 m (Fig. 2-5), although the latter less so in the early months of the year. The main difference between the two years was lower average temperatures at 15 m, which would be expected since less energy from the sun penetrates. In addition, there is also a marked difference between RCP 4.5 and RCP 8.5 regarding temperature increase, with RCP 8.5 consistently returning more rapid increases and larger final temperatures in 2040 (Fig. 4-5). The largest temperature increase over the 20 years at 5 m occurred in March with an increase of 3.5°C, whilst at 15 m it was May with 4°C. These increases are a significant threat for marine life within the GMR. For example, an increase of 6°C in ocean temperatures would cause a 50% decrease in total biomass (O'Connor *et al.*, 2009). Therefore, direct action needs to be taken to prevent a total collapse of the marine food chain, particularly one with global importance due to the marine corridor running through it.

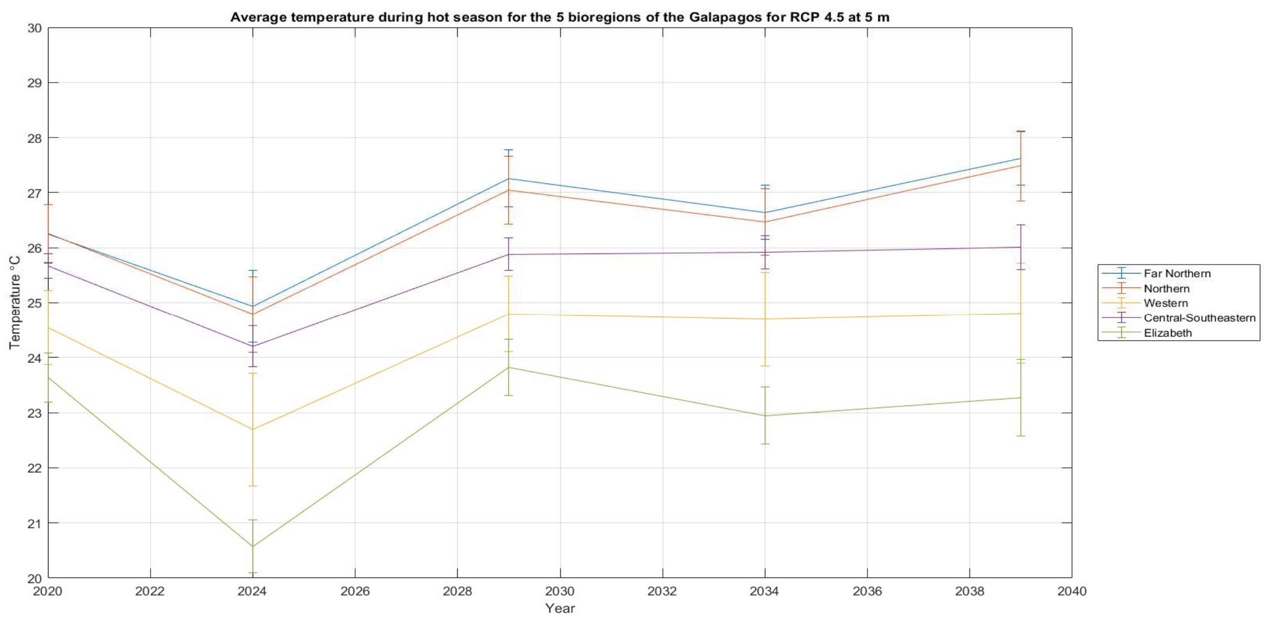

Figure 2: *Plot showing the average temperature during the hot season (December to May) for each of the 5 biogeographic regions of the Galapagos from 2020 to 2040 under RCP 4.5, at a depth of 5 m.*

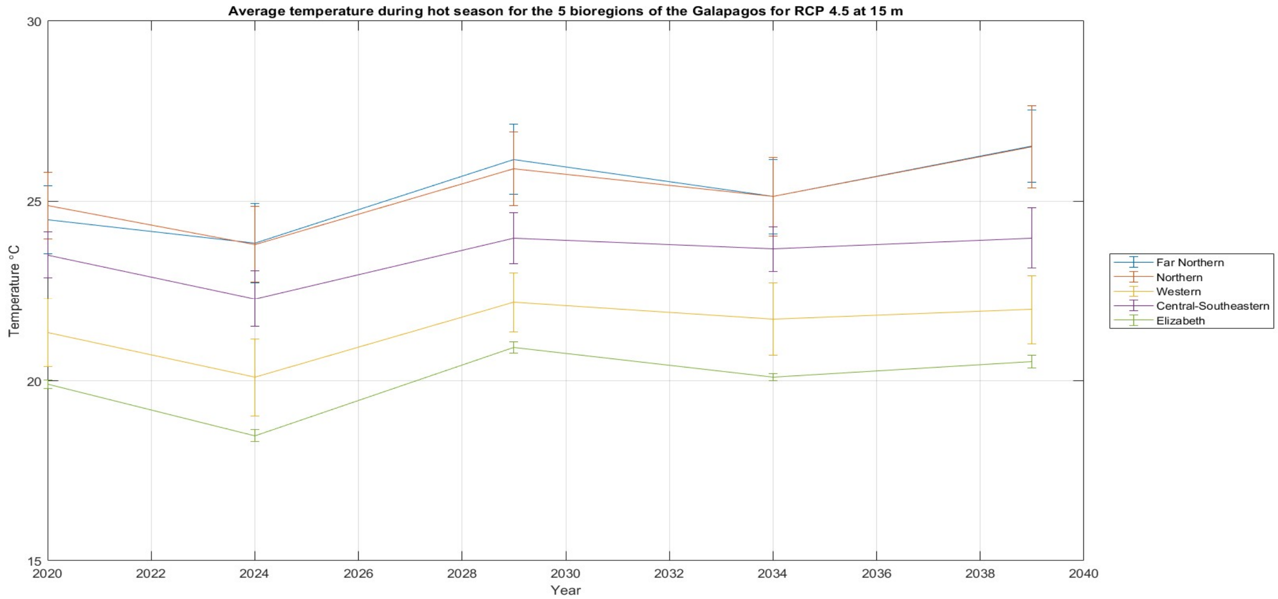

Figure 3: *Plot showing the average temperature during the hot season (December to May) for each of the 5 biogeographic regions of the Galapagos from 2020 to 2040 under RCP 4.5, at a depth of 15 m.*

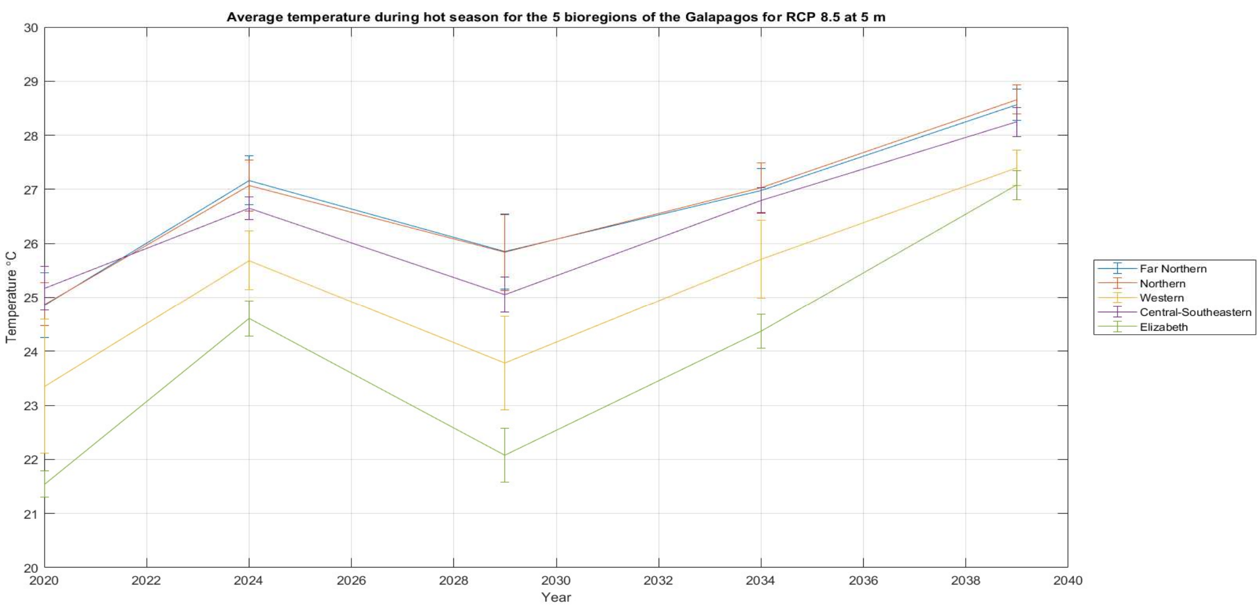

Figure 4: *Plot showing the average temperature during the hot season (December to May) for each of the 5 biogeographic regions of the Galapagos from 2020 to 2040 under RCP 8.5, at a depth of 5 m.*

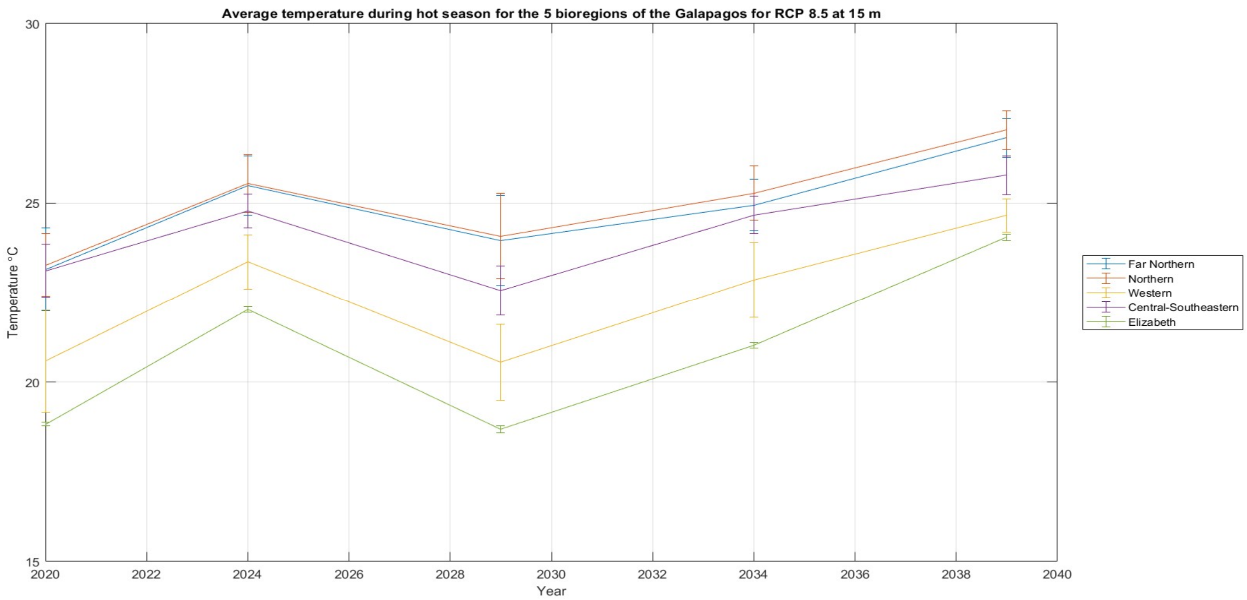

Figure 5: *Plot showing the average temperature during the hot season (December to May) for each of the 5 biogeographic regions of the Galapagos from 2020 to 2040 under RCP 8.5, at a depth of 15 m.*

Table 1: Comparison between RCP scenarios at 5m and 15m depth and the GMR bioregions.

RCP Scenario	Depth (m)	Patterns and Observations
4.5	5	-By end of 2039 the two regions showing most warming are Northern and Far Northern (1.23 & 1.38°C respectively). -All show sharp decrease in temperature in 2024, largest is Elizabeth with a 3.07°C drop. The rest lay between 1.3 and 1.9°C. -Elizabeth also shows the only decrease in temperature across 20 years with a 0.37°C drop. -All regions mostly follow a similar pattern of warming and cooling, but Western and Central-Southeastern show greatest stability overall
	15	-Northern and Far Northern both have almost identical temperature variation once again. Likely due to lack of protection from large islands and mostly uniform current flow across combined northern region. -Greatest increase in Northern and Far Northern (1.64 and 2.04°C). -Remaining 3 regions mostly stable, temperature increases all below 0.65°C.
8.5	5	-Much larger increases in temperature across the board compared to RCP 4.5. -Northern and Far Norther near identical again, followed closely by Central-Southeastern -Warm/Cold cycle delayed by 0 to 2 years in RCP 8.5 compared to RCP 4.5, as seen from overall yearly temperature cycles in impact model. Cooling seen in 2029 and not 2024 here. -Greatest cooling seen in Elizabeth again (-2.53°C, 0.63°C colder than next coldest: Western). -Greatest overall temperature increase also seen in Elizabeth with 5.53°C warming, 1.5°C greater than next best: Western. -The rest of the regions have mostly similar overall warming, between 3.05 and 4.05°C.

	15	-Northern and Far Northern very similar again. -Elizabeth shows greatest warming and cooling compared to other regions again (+5.21°C and -3.34°C). -Second largest warming and cooling in Western region again (+4.08°C and -2.81°C). -Central-Southeastern is the most stable with 2.67°C overall warming. -Warm/cold cycle same as at 5 m which is to be expected.

Furthermore, the Elizabeth region appears to be the most volatile with regards to temperature variation, both across the years and in terms of overall temperature increase. This vulnerability to temperature swings could be product of low current magnitudes in and around the region, limiting the flow of water in or out, leading to greater warming. Elizabeth is often considered one of the coldest locations to dive in the Galapagos but with a temperature increase of over 5°C, which is predicted under RCP 8.5, this would be extremely damaging to the underwater ecosystems, which are adapted to colder, nutrient rich waters. Fortunately, the effects are far smaller under the preferable RCP 4.5 scenario, with surface waters even cooling slightly by 2040. This highlights the importance of limiting the scale of climate change and working to mitigate its consequences. A closer analysis of Elizabeth region would be beneficial. Higher resolution models, which would better simulate the current movements and temperature, would be useful to help confirm changes within the channel. Further transects performed by cruise ships along Canal Bolívar, which is already a popular cruise route, would help to confirm the predicted data for this threatened region. It would also be of interest to include deep-water current flows (Humboldt, Equatorial Undercurrent, Panama), which are essential to the seasons and nutrient base of the islands, to check for possible variations or weakening in the future which could adversely affect the Galapagos.

Furthermore, both the Northern and Far Northern regions also denote substantial temperature increases, but unlike with the Elizabeth region it occurs across in both RCP scenarios, with the temperature increase close to doubling under RCP 8.5. This once again puts an extremely important and biodiverse region for both pelagic and reef dwelling species at risk. It is also noted that the Northern and Far Northern regions follow very similar temperature patterns across the years, depths, and RCP scenarios. This introduces an argument for a rearrangement of the Northern biogeographic region of the archipelago. As can be seen in Figure 6, the cause for the similarity between the two regions is the warm flow of water to the North of Pinta Island, which extends to the northern islands. A more useful arrangement would be to separate the islands of Marchena, Genovesa and Pinta into a smaller region, with its northern limit being the same as the southern limit for the Far Northern region. This would provide a more accurate depiction of the true oceanographic conditions and climate change risks posed to these islands.

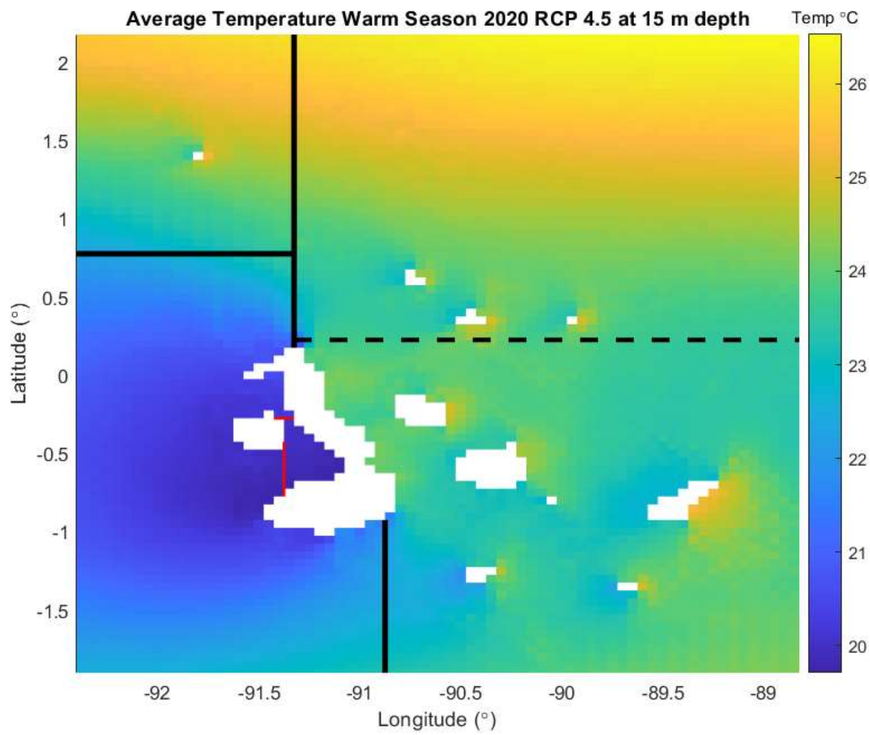

__Figure 6:__ Average temperature map of the Galapagos Islands during the warm season (December to May) for the year 2020, under RCP 4.5 and at a depth of 15 m.

Table 2: Mean temperature, standard deviation, and confidence interval for RCP 4.5 at 5m

4.5, 5 m	**Central-Southeastern Temps (°C)**		**Far Northern Temps (°C)**		**Northern Temps (°C)**		**Elizabeth Temps (°C)**		**Western Temps (°C)**	
Year	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**
2020	25.67	0.01	26.25	0.04	26.26	0.02	23.64	0.12	24.55	0.03
2024	24.21	0.02	24.93	0.05	24.79	0.03	20.57	0.13	22.69	0.05
2029	25.88	0.01	27.26	0.04	27.05	0.03	23.82	0.13	24.80	0.03
2034	25.92	0.01	26.64	0.04	26.47	0.03	22.95	0.13	24.70	0.04
2039	26.01	0.02	27.62	0.04	27.48	0.03	23.27	0.18	24.81	0.05

Table 3: Mean temperature, standard deviation, and confidence interval for RCP 8.5 at 5m

8.5, 5 m	**Central-Southeastern Temps (°C)**		**Far Northern Temps (°C)**		**Northern Temps (°C)**		**Elizabeth Temps (°C)**		**Western Temps (°C)**	
Year	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**
2020	25.17	0.02	24.86	0.04	24.87	0.02	21.55	0.06	23.35	0.06
2024	26.65	0.01	27.16	0.03	27.07	0.02	24.61	0.09	25.69	0.03

2029	25.05	0.01	25.85	0.05	25.84	0.03	22.08	0.13	23.79	0.04
2034	26.80	0.01	26.98	0.03	27.03	0.02	24.37	0.08	25.71	0.04
2039	28.25	0.01	28.57	0.02	28.66	0.01	27.08	0.07	27.39	0.02

Table 4: Mean temperature, standard deviation, and confidence interval for RCP 4.5 at 15m

4.5, 15 m	**Central-Southeastern Temps (°C)**		**Far Northern Temps (°C)**		**Northern Temps (°C)**		**Elizabeth Temps (°C)**		**Western Temps (°C)**	
Year	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**
2020	23.51	0.03	24.49	0.07	24.88	0.04	19.90	0.03	21.34	0.05
2024	22.29	0.03	23.84	0.08	23.80	0.05	18.48	0.04	20.10	0.05
2029	23.97	0.03	26.16	0.07	25.91	0.04	20.93	0.04	22.19	0.04
2034	23.67	0.03	25.13	0.08	25.13	0.05	20.10	0.03	21.72	0.05
2039	23.98	0.03	26.53	0.08	26.52	0.05	20.53	0.04	21.98	0.05

Table 5: Mean temperature, standard deviation, and confidence interval for RCP 4.5 at 5m

8.5, 15 m	**Central-Southeastern Temps (°C)**		**Far Northern Temps (°C)**		**Northern Temps (°C)**		**Elizabeth Temps (°C)**		**Western Temps (°C)**	
Year	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**	**Mean**	**C.I. ±**
2020	23.11	0.03	23.15	0.09	23.27	0.04	18.83	0.01	20.58	0.07
2024	24.77	0.02	25.48	0.06	25.55	0.03	22.02	0.02	23.36	0.04
2029	22.56	0.03	23.96	0.09	24.08	0.05	18.69	0.03	20.56	0.05
2034	24.67	0.02	24.95	0.05	25.28	0.03	21.03	0.02	22.86	0.05
2039	25.78	0.02	26.82	0.04	27.03	0.02	24.04	0.02	24.66	0.02

Changing current systems can also have large impacts upon the ecology of a marine system such as changes in larvae dispersal (Cetina-Heredia *et al.*, 2015), reduced levels of nutrients received in certain areas (Nishino *et al.*, 2015) and the appearance of new vectors for NIS to arrive at previously unaffected areas (Heyligers, 2007). Therefore, it is important to analyse the future modelled currents within the GMR during the warm season to attempt to foresee any major alterations to these patterns, product of changing climate. From January to March, at 5 m depth, (Figures S5, S6 and S7) the movement of currents across the archipelago is mostly uniform, flowing from east to west and splitting once they reach the eastern coast of Isabela. This creates an area of lower current magnitude directly to the west of Isabela during these months. The current directions mean that most particles would flow from the eastern islands towards the western ones, excluding the effects of some inner currents between the main islands, as well as a lack of connectivity between Fernandina and the western coast of Isabela with the other islands. The main change by 2040 during these months is a stronger pull to the south within the southern hemisphere, particularly under RCP 8.5, which is most evident in the map for January 2039 (Figure S5), where the currents originate from the north-east and flow southwards over the eastern islands of the archipelago. This would create new vectors for transport since normally larvae from islands such as Genovesa would not be able to reach an island such as Floreana during this month. Up until 2034 the currents in April follow much the same pattern as the previous months and continue to do so under RCP 4.5 to 2040 (Figure S8). However, after that, under RCP 8.5, the currents at 5 m begin to originate from the north-west, which allows for a flow of particles from Darwin and Wolf down to the main islands of the archipelago as well as introducing a flow onto Fernandina. By 2039 these changes, with a gyre forming as these south-easterly flowing currents, hit the westward flowing currents and this would allow particles to be cycled through the islands to the east of Isabela (Figure S8). In May once again RCP 4.5 currents mostly maintain a westerly flow across the islands which would have no great impact on the usual movement of particles, but RCP 8.5 shows much larger variations (Figure S9). In 2020 and 2029 there is a strong eastward flow which splits as it hits the western coast of Isabela, this leaves a low current magnitude zone among most of the main islands, which could be good for self-recruitment, although it is a problem for the connectivity between populations. These changes, particularly under RCP 8.5, show the importance of mitigating the effects of uncontrolled climate change within the GMR because it is very likely they could disrupt the oceanographic workings of the marine ecology.

At 15 m depth most of the current flow across the islands is similar to 5 m for the months of December to March (Figures S10, S11 and S12). One of the main new interesting features at this depth is a pull-back-in towards Fernandina and Isabela of the currents, which flow over the northern tip of Isabela. This introduces a vector not seen before at 5 m which allows particles from the main islands to reach Fernandina. The southern pull in 2039 during January is even further seen with the currents pulling towards the south-east under RCP 8.5 (Figure S10). February also shows a much greater connectivity between islands such as Marchena and Darwin and Wolf under RCP 8.5 (Figure S11). At this depth by April and May the east moving currents are already present under both RCP scenarios by 2029 and the interactions as these clash, with the westward flowing ones, creates some unique current patterns within the archipelago (Figures S13 and S14). This once again reinforces the point that more extreme climate change will lead to greater changes within current systems in the GMR even at greater depths.

4.2 Expected Impacts on coral ecosystems from particle movement and temperatures by 2040

Most coral species present within the GMR, such as *Porites lobata* and *Pavona Gigantea*, show the same responses to temperature change as most corals worldwide, with an upper temperature limit of 30°C before bleaching begins. Regarding temperature variations, at 5 m the average sea temperature within the GMR reached 30°C in April 2033 under RCP 8.5, and looking at the projections for RCP 8.5 the average temperature in March and April will surpass that threshold. This is a big worry for shallow coral populations which will be at risk, in addition to the extra stresses associated with climate change such as increased CO_2 which can also lead to bleaching. Fortunately, at a depth of 15 m the temperature increases under both scenarios are not yet close to threshold for most warm months under both scenarios.

The particle tracking aspect allows for further visualisation of the connectivity between islands due to larval dispersal. The main connections between islands at both depths and under both RCPs are Genovesa to Marchena and Pinta, Santiago to western Isabela and Santa Cruz, and Española to Floreana. At a depth of 5 m for both RCPs there is a clear drop-off by 2039 in the connectivity between populations of coral species among the main islands, excluding April (Figures S16, S17, S18, S19 and S20). This is likely due to increased current magnitude which drags the larvae out of the reserve into the open ocean, preventing them from settling. At 15 m (Figures S21, S22, S23, S24 and S25) the connectivity to Fernandina and the west coast of Isabela can particularly be seen during the month of December. As the years progress for other months, the movement of larvae becomes more chaotic at this depth. Connectivity between isolated populations is essential for growth as well as recovery from natural phenomena, like El Niño, which greatly reduce numbers, so a change in these usual patterns would likely disrupt the survivability and future growth of coral populations in the GMR. The impact is a reduction in recruitment rates due to changes in the circulation systems of the currents, together with a loss of connectivity between the populations of the different islands. It is therefore once again imperative that action be taken to mitigate these effects and preserve the incredible biodiversity of this marine reserve.

5. ECOSYSTEM-BASED ADAPTATIONS (EBA) MEASURES

As the potential impacts of climate change on Galapagos threaten to irreversibly damage its marine ecosystems, mitigation and adaptation measures must be taken by the GNPD and Galapagos Governing Council to restore these ecosystems and enhance their resilience and adaptive capacity. In the following sections, the rationale for each EBA is described, together with their objectives, activities and outputs, including a description of their impact on the resilience and adaptive capacity of the Galapagos marine ecosystems and the tourist sector that depends on them. Table 6 summarizes outcomes and outputs expected for all proposed EBA measures. Similar tables, including activities are included in the description of each EBA.

Table 6. Integrated activities of all EBA measures.

<table>
<tr><td colspan="2"><u>EBA 1.</u> Strengthen marine biosecurity programs in the GMR, to prevent and control climate driven introductions and invasions by Non-Indigenous Species (NIS)</td></tr>
<tr><td rowspan="4">1. Strengthen marine biosecurity programs in the GMR, to prevent and control marine bioinvasions by Nonindigenous Species (NIS) that could proliferate due to the effects of climate change.</td><td>1.1. Conduct one regional bioinvasion assessment for each MPA in the ETP region (Galapagos, Cocos, Malpelo, Gorgona, Coiba), considering climate change scenarios.</td></tr>
<tr><td>1.2 Develop and implement an Alert System for incursions of NIS in the GMR</td></tr>
<tr><td>1.3 Adoption and implementation of improved marine biosecurity and Early Detection and Response (EDRP) protocols, by the DPNG and ABG.</td></tr>
<tr><td>1.4 Implement a regional outreach campaign to showcase and promote the replica of the GMR NIS Alert System and EDRP, in other ETP region MPAs.</td></tr>
<tr><td colspan="2"><u>EBA 2.</u> Restore high ecological value coral reef areas through coral planting and exclusion area.</td></tr>
<tr><td rowspan="2">2. Restore high ecological value coral reefs through coral planting and exclusion areas, to enhance their ecological role in the GMR.</td><td>2.1 Produce one update assessment of the abundance and distribution of coral reefs and their associated biodiversity in the GMR considering current and future climate scenarios.</td></tr>
<tr><td>2.2 Transplant corals from the nursery developed in collaboration with the GNPD, to at least 1 degraded site in each island (Darwin, Wolf and Floreana)</td></tr>
</table>

	2.3 Design and implement a removal program for sea urchins to assess vulnerability by conducting experiments
	2.4 Mainstream the participation of the tourism sector in conservation and restoration programs carried out by the DPNG, in key touristic coral reef sites.
<u>EBA 3.</u> Reduce the impact of diving, anchoring and pollution related to tourism operations in selected marine HEVAs, to enhance ecosystems resilience and adaptive capacity to the effects of climate change.	
3. Reduce the impact of diving, anchoring and pollution related to tourism operations in selected marine HEVAs, to enhance ecosystems resilience and adaptive capacity to the effects of climate change.	3.1 Design and implement a conservation categorization system and management protocols for diving visitor sites.
	3.2 Development and adoption of Diving Tourism Best Practices Toolkit co-created with dive tourism stakeholders.
	3.3 Reinforce the control and monitoring of pollution levels from boats
	3.4 Develop a Decision Support System (DSS) portal for policymakers, with information regarding marine tourism, including impacts from the tourism activities and the health of sites.
	3.5 Implement agreements with tourism stakeholders for replacing anchoring procedures and technologies with fixed-mooring buoys signalling and the Digital Positioning Systems (DPS).
<u>EBA 4.</u> Improve surveillance and control measures for adequate sea turtle nesting and foraging in the GMR, to counteract potential effects of climate change in their reproductive success.	
4. Improve surveillance and control measures for adequate sea turtle nesting and foraging in the GMR, to counteract potential effects of climate change in their reproductive success.	4.1 Translocation of nests from current flooding areas to safer zones.
	4.2 Design and implement marine traffic regulations to avoid boat strikes at nesting and foraging sites

5.1 <u>EBA measure 1.</u> Strengthen marine biosecurity programs in the GMR, to prevent and control climate driven introductions and invasions by Non-Indigenous Species (NIS).

TARGET INDICATORS	
At the end of the project, new effective systems to effectively monitor and manage marine biosecurity are developed for the 138,000 km^2 of marine ecosystems in the GMR	
At the end of the project at least 20 climate driven NIS will be under control programs	
BENEFICIARIES	
Direct	80% technical staff of the Marine and Tourism/recreation Departments of the GNPD will participate in workshops to create the Early Detection and Response (EDRP) protocols for climate driven NIS 80% technical staff of the Galapagos Biosecurity Agency will participate in workshops to create the Early Detection and Response (EDRP) protocols for climate driven NIS 80% technical staff of the Marine and Tourism/recreation Departments of the GNPD are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 80% technical staff members of the Galapagos Biosecurity Agency are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 40% technical staff of the Ecuadorian Navy are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 40% technical staff of the Oceanographic Institute of the Ecuadorian Navy - INOCAR are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 60% staff members of the Galapagos Governing Council CGREG will receive scientific information of the Early Detection and Response

	(EDRP) protocols for climate driven NIS in order to create new regulations
Indirect	100% of active tour and dive operators in the GMR are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 100% of active Galapagos Naturalist and Dive guides are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 100% of active small-scale fishermen are trained in improved marine biosecurity and Early Detection and Response (EDRP) protocols for climate driven NIS 100% of active small-scale fishermen will benefit from rocky reefs being protected from the arrival of climate driven NIS 100% tourists will benefit from rocky reefs being protected from the arrival of climate driven NIS 100% of local schools will receive environmental education regarding the importance of EDRR for climate driven NIS and impacts these could cause. 100% locals will benefit from information regarding the impacts climate driven NIS can have on the GMR and what can be done to prevent their arrival

Logic Framework for EBA 1

Activity	Sub-activity	Deliverables
1. Strengthen marine biosecurity programs in the GMR, to prevent and control marine bio invasions by Nonindigenous Species (NIS) that could proliferate due to climate change.	1.1. Conduct one regional bio invasion assessment for each MPA in the ETP region (Galapagos, Cocos, Malpelo, Gorgona, Coiba), considering climate change scenarios.	
	1.2. Develop and implement an Alert System for incursions of NIS in the GMR	
	1.3. Adoption and implementation of improved marine biosecurity and Early Detection and Response (EDRP) protocols, by the DPNG and ABG.	

	1.4. Implement a regional outreach campaign to showcase and promote the replica of the GMR NIS Alert System and EDRP, in other ETP region MPAs.	
	1.5 Evaluate the effectiveness of the EDRR protocols for climate driven introductions	-Eight assessments of climate driven NIS (hot and cold season) to evaluate how many NIS have been detected through the Alert system and the EDRR protocols

5.1.1 Description of the current situation and baseline

Marine bio invasions by NIS are well-documented as being a critical growing threat to peoples' livelihoods and to ecosystem sustainability and functioning of coastal zones worldwide (Keith et al., 2016). NIS are species that introduced to areas beyond their natural range by direct or indirect human activity, intentionally or otherwise (Cook et al., 2016; Hilliard, 20004; Kolar & Lodge, 2001; Richardson et al. 2000; Ruiz et al. 2000). When a species causes or has the potential to cause harm to the environment, economies and/or human health the species is referred to as an invasive species (Cook et al., 2016; Emerton & Howard, 2008). Biological invasions are thus of significant interest to government agencies and the public at large, as well as to managers charged with the conservation and preservation of marine protected areas. However, biosecurity and related proactive approaches are often conducted in a strikingly regional manner, with little coordination between countries within the same bioregion, or even awareness and knowledge of the management strategies that would be mutually beneficial (Campbell et al., 2015).

Several phenomena are known to potentially increase the number of new marine bio invasions that could arrive in the warmer waters of the tropical Pacific, including the Galápagos Islands. The Islands are one of the most vulnerable sites in the ETP because of the potential impacts of climate change and because they are regularly subjected to extreme climate variability through El Niño Southern Oscillation (ENSO) events. During El Niño, prolonged increases in sea temperature are induced, as the warm surface waters of the western Pacific band migrate to the coast of South America (Banks, 2002). Thus, El Niño events are characterized by increases in temperature and changes in current circulation and precipitation patterns. These warming trends influence the dynamic of upwelling systems decreasing primary productivity, negatively affecting entire marine communities. Strong El Niño events of 1982-1983 and 1997-1998 caused widespread damage to Galapagos' marine ecosystems, largely due to changes in trophic cascades and food shortages. ENSO events are predicted to increase in intensity and frequency due to the impact of climate change (Salinas de Leon et al. 2020), which in turn will cause the deterioration of marine ecosystems altering the susceptibility of the Islands to invasions from NIS (Glynn et al., 2018; Keith et al. 2015).

BOX 1. Study case: Expansion of the macroalgae *Caulerpa chemnitzia* linked to warming-related range shifts in Darwin Island, Galapagos

The Galapagos Islands are strongly influenced by El Niño Southern Oscillation (ENSO), a global-scale phenomenon that might be amplified by climate change (Riegl et al., 2019). This climate event cause increases in sea temperature and changes in current circulation, which has caused damage to marine ecosystems in the past and alters the susceptibility of the Islands to invasions from species that expand their geographic range due to increasing temperatures (Glynn et al., 2018; Keith et al. 2015). Recent coral surveys at Darwin Island within the GMR observed a population disturbance of the algae Caulerpa chemnitzia that can be associated with warming-related range shifts (Riegl et al., 2019). These observations were noted close to Wellington Reef, the only extensive coral formation in the Galapagos. Macroalgae inhabiting coral reefs are considered strong competitors for space since they use strategies that cause damage to corals. They colonize degraded corals surfaces, forming macroalgal assemblages of different species of cyanobacteria, rhodophytes, pheophytes and chlorophytes, which can remain for years and delay the recovery of coral colonies (Ortega & de la Cruz-Francisco, 2017).

Coral reefs provide a number of ecosystem services to humans including coastal protection, maintenance of fisheries, tourism, recreation, education and research (Barbier et al., 2011). The need to understand the expansion of C. *chemnitzia* is crucial because the colonization of this algae may cause ecological problems, such as habitat alterations of coral reefs at Darwin Island. Warming-related range shifts in marine systems can describe successive stages of geographic extension or contraction for a species (Bates et al., 2014). A detailed analysis of warming-related range shifts and its relation to *C. chemnitzia* population can help to understand the different stages of extension the species has experienced; it will also allow to project a potential expansion situation linked to climate change scenarios. To generate effective adaptation measures for a potential extension of an invasive species, is highly recommended to develop models that capture the future spatial distribution of these species (Bellard et al., 2013). Darwin Island, a volcanic edifice structurally independent of the main archipelago, is centred at 1°39´20´´ N, 92°0´30´´W (Fig.7). Periodic coral surveys undertaken at Darwin Island from 2007-2018 allowed to monitor algae *C. chemnitzia* concentration at fixed transects (CDF unpublished data). The species count was evaluated in systematically placed quadrants with 5 meters interval along 50 meter transects.

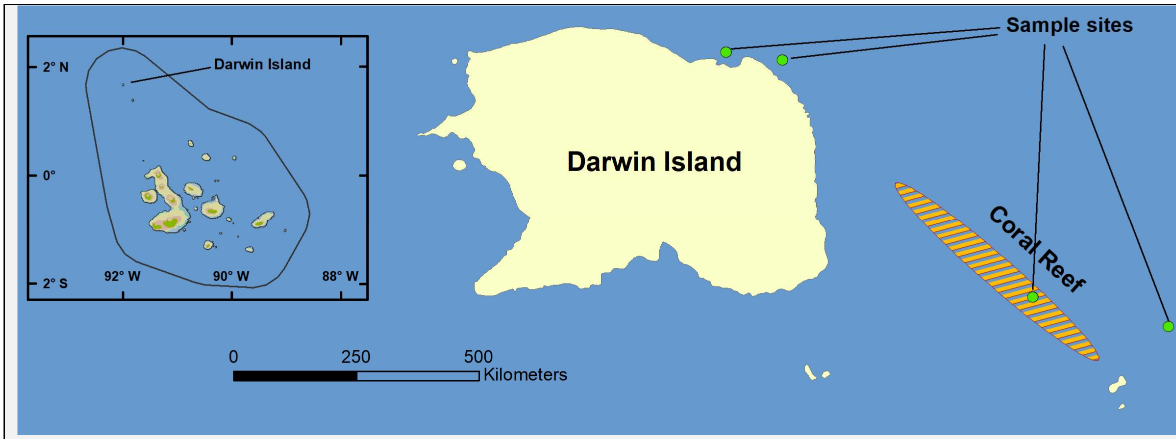

Figure 7. Location of Darwin Island in the Galapagos Archipelago, approximate position of Wellington Reef, and sampling sites (adapted from Glynn & Riegl (2009)).

To describe the relationship between *C. chemnitzia* population dynamics and warming-related range shifts, first it was necessary to establish the correlation among these variables. Annual data from transects was used. This data included an individual count of the specie, depth, and sea surface temperature. Additionally, the maximum value for sea surface temperature of each studied year was included from an ERA Interim data set (2019).

Density of species (per square meter) was calculated from the total area of each analysed quadrant within transects (0.25 square meters per quadrant) and the total species count. Density of *C. chemnitzia* showed a high correlation with the maximum sea surface temperature per year of study. A linear regression analysis ($p < 0.05$) allowed to obtain an equation that expresses the relationship between density (per square meters) and maximum sea surface temperature (Celsius degrees) per year.

$$Log10\ Density\ (per\ sqr\ meters) = Maximun\ SST\ (°C) * 0.413 - 10.046$$

Population density dynamics of C. chemnitzia can be calculated for a historic maximum sea surface temperature (SST) data set. Hence, SST values from ERA Interim (2019) (spatial resolution ~50 km) were overlaid into two sample sites at Darwin Island: Fondadero Norte and Fondadero Sur (Fig. 8) for the purposes of this study.

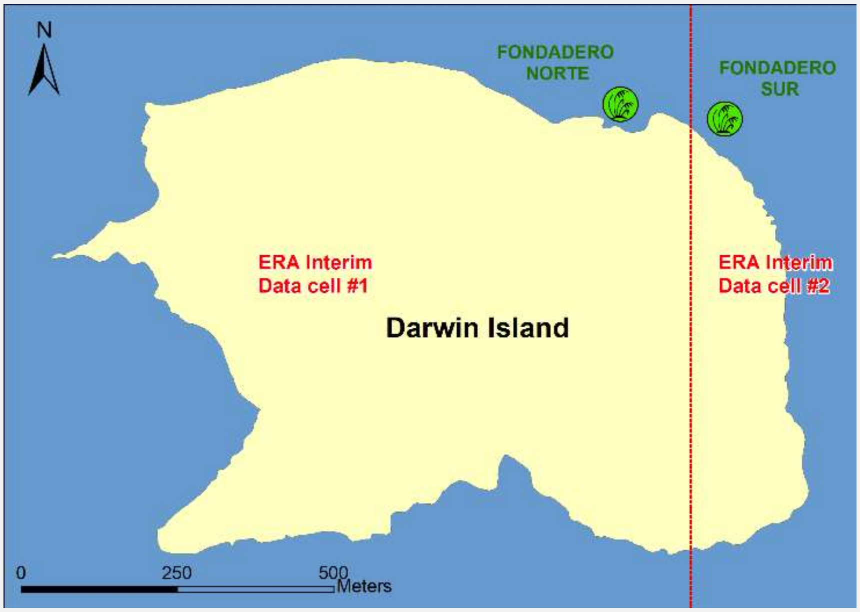

Figure 8. Location of sampling sites Fondadero Norte and Fondadero Sur, and overlaid ERA Interim data set.

Currently, the IPCC's Fifth Assessment Report (AR5) uses climate change scenarios defined as Representative Concentration Pathways (RCP) as a coherent, internally consistent and convincing description of a possible future state of the climate. A study developed by DPNG (2019) estimated RCP scenarios 4.5 and 8.5 within the GMR, in order to show the range of uncertainty in climate projections in the face of different combinations of economic, environmental, population growth, and political conditions. The DPNG (2019) study shows how SST conditions would change in a future 30-year period from 2011-2040. The present study uses maximum SST values from each projected year to estimate the population density dynamics of *C. chemnitzia* in future warming conditions at the same selected sample sites. This study also incorporates a Cellular Automata (CA) simulation model to help understand the potential distribution pattern of *C. chemnitzia* under the mentioned climate change scenarios.

CA requires specific transition rules to capture local dynamics. For the present study case, it was built and calibrated using (i) a linear regression that explains the relationship between density of species and maximum sea surface temperature (see above), (ii) a neighbourhood model using a moving window of 5 x 5 cells (0,5 x 0,5 meters), (iii) a random model that describes the inherent variation associated with the system (stochastic factor); (iv) three different scenarios (low, medium, high) for growth and decay rates. These scenarios were selected to represent the range of uncertainty of the projections in the face of different combinations of growth and decay rates. Furthermore, values for the three scenarios derived from literature review (Argyrou, Demetropoulos, & Hadjichristophorou, 1999; Guillén et al., 2010; Ruiz et al., 2011) and iterative exercises.

Table b1. Growth / decay rate scenarios for *C. chemnitziae*

	Growth rate	**Decay rate**
Scenario 1	30%	75%
Scenario 2	50%	55%
Scenario 3	10%	95%

Behaviour of Caulerpa chemnitzia density as a function of maximum sea surface temperature*.*

Resulting values for *C. chemnitzia* density for a historical period (1979-2018) at the selected sample sites (Fig. 9) evidence a clear response of the species to maximum SST. Maximum density values of the algae were related to ENSO events (i.e., 1982-83, 1997-98). Results also show, for both sample locations, how species expansion and contraction stages might have appeared across the period assessed. Further, important differences between sample sites can be observed in the maximum density values projected for each location. Maximum density values at Fondadero Sur are much higher than values obtained for Fondadero Norte*.*

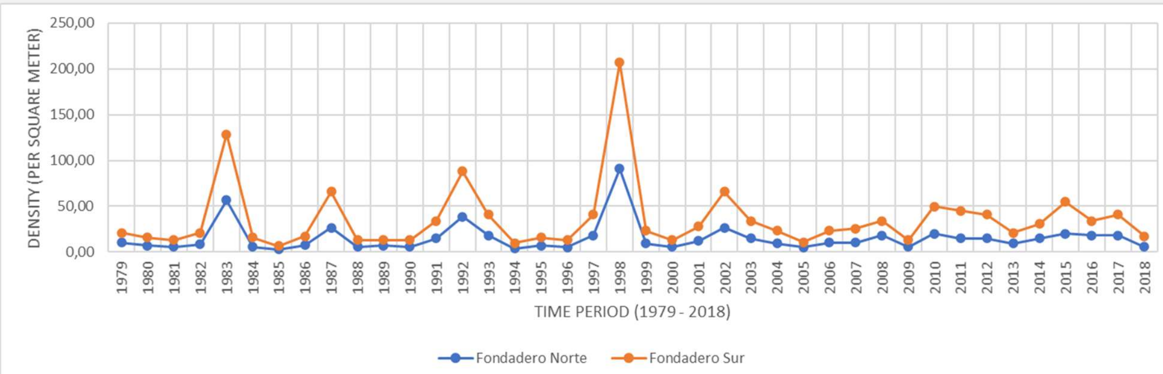

Figure 9. Observed relationship between C. chemnitziae density and maximum annual sea surface temperature in Fondadero Norte and Fondadero Sur, Darwin Island, from 1979-2018.

When analysing SST values from RCP 4.5 and RCP 8.5 scenarios, for a time period from 2011-2040, C. *chemnitzia* density for both sample sites (Fig. 10) show a trend towards expansion. Density values obtained from RCP 4.5 scenario shows an increase of the algae towards the end of the time period, with maximum extension episodes at years 2023, 2026, 2034, and 2037. A similar trend is found with values from RCP 8.5, but maximum extension episodes (2031, 2036, and 2039) show a much higher separation from the general average of the data series. Regarding the ecological problems, RCP 8.5 shows extreme episodes of extension which represent a major threat to coral reef habitats.

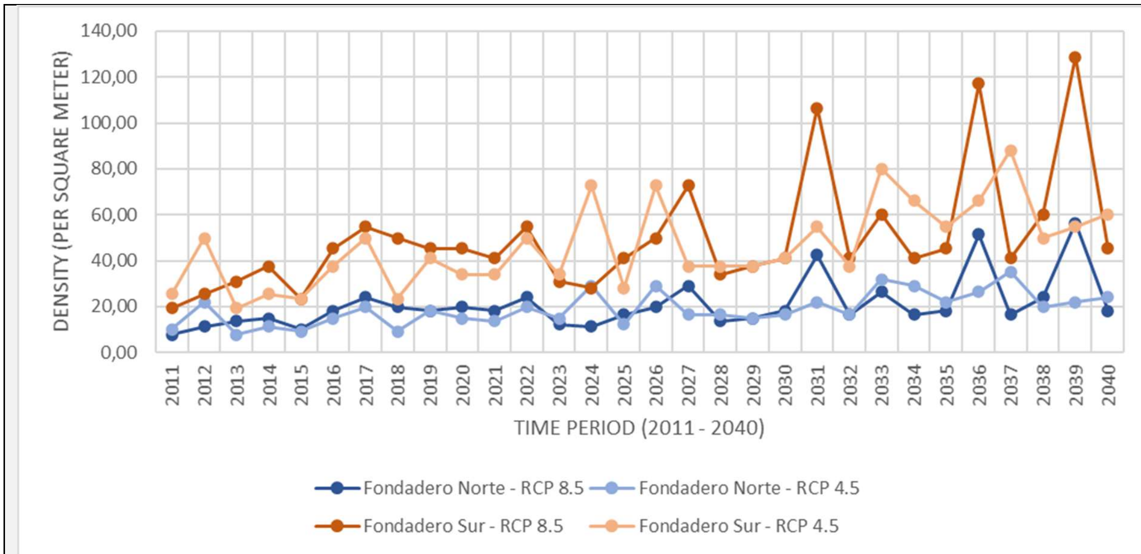

Figure 10. Relationship of *C. chemnitzia* and maximum sea surface temperature (RCP 4.5 & RCP 8.5) – Fondadero Norte and Fondadero Sur, Darwin Island, from 2011-2040.

Spatial distribution modelling

Results from running the spatial distribution model on sample sites Fondadero Norte and Fondadero Sur values (Fig. 11-12) illustrates that, while projected results for density growth in the future shows higher values at different expansion episodes with RCP 8.5, a more constant growth distribution of density values with RCP 4.5 can end in a higher concentration of spatially distributed individuals under pessimistic growth/decay scenarios such as growth/decay scenario 2.

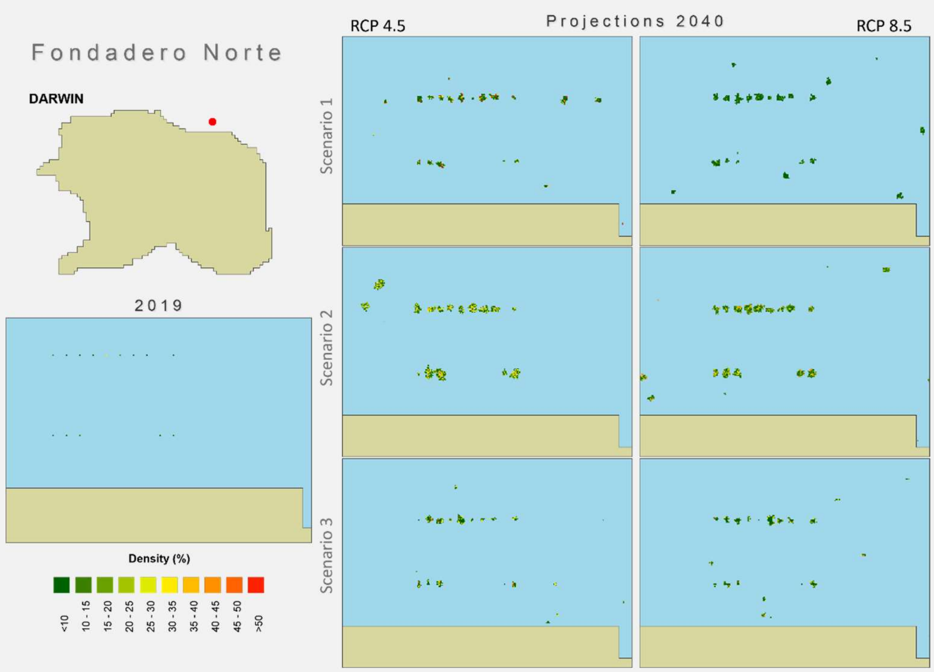

Figure 11. Potential future spatial distribution of *C. chemnitzia* from 2019 to 2040 (RCP 4.5 & RCP 8.5) – Fondadero Norte, Darwin Island

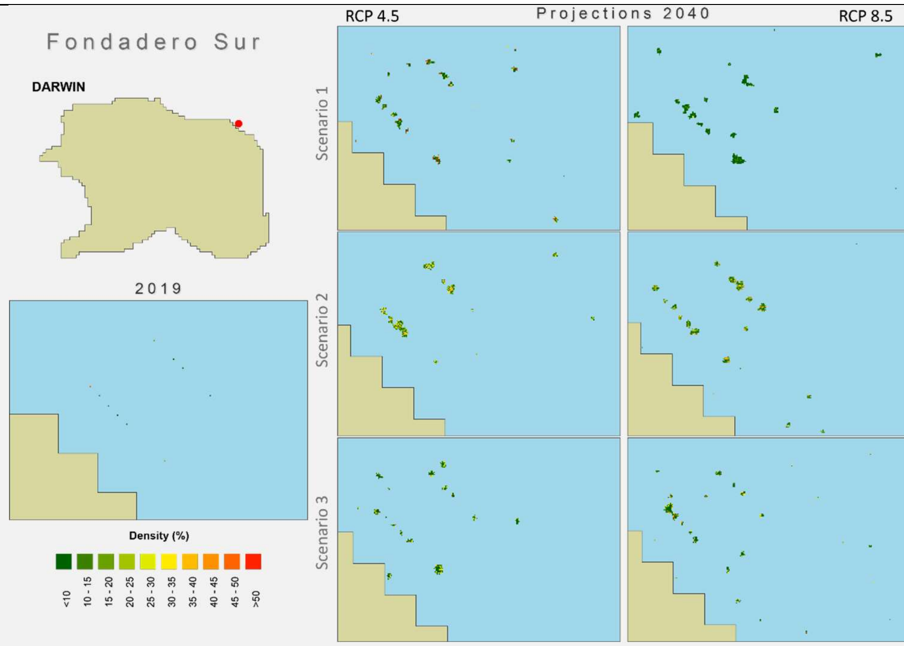

Figure 12. Potential future spatial distribution of *C. chemnitzia* from 2019 to 2040 (RCP 4.5 & RCP 8.5) – Fondadero Sur, Darwin Island

Under both climate scenarios, adaptation measurements must be taken to preserve ecosystem services provided by coral reefs such as Wellington Reef. Passive restoration (education, research, and monitor) can be implemented for both climate scenarios, to remove the impact of other environmental stressors such as pollution or uncontrolled fishing, to reduce the pressure of a potential expansion of C. chemnitzia over the coral reef habitat and allow a natural recovery of the ecosystem. Growth/decay pessimistic scenario also introduces the possibility to implement active restoration during potential episodes of maximum extension of C. chemnitzia. Hence, management techniques such as transplanting or eradication can also be considered, especially forecasting several expected maximum expansion episodes present in both climate scenarios.

Highly effective marine coastal restoration projects typically involved the community in the restoration actions, transferred knowledge among scientists, practitioners, community members, and administrative organizations (including lessons learnt from failures), and included a broad range of stakeholders in the decision- making process (Bayraktarov et al., 2016).

From a terrestrial stand point, the Ecuadorian government's biosecurity, for the most part, is well organised and seems to be effective, with a number of publications detailing observations of introduced terrestrial plants (e.g., Buddenhagen, 2006; Jager & Kowarik, 2010) and animals (e.g., Cruz et al. 2005; Carrion et al. 2011), eradications and impacts (e.g., Schofield, 1989; Itow, 2003; Renteria et al. 2012; Kueffer et al. 2010), invasion risks (e.g., Gottdenker et al. 2005), and ecosystem restoration, management and conservation strategies (e.g., Gibbs et al. 1999; Causton et al. 2006). In contrast, marine biosecurity activities lag behind and are consequently less well managed, but not for a lack of effort

(Campbell et al. 2015). In 2012 the Galapagos Biosecurity Agency (Agencia de Regulación y Control de la Bioseguridad y Cuarentena para Galápagos – ABG) was created. This agency is in charge of controlling, regulating, preventing and reducing the risk of the introduction, movement and dispersal of non-native organisms that might threaten human health, the terrestrial and marine ecosystems, the integrity of the islands and the conservation of biodiversity of the Galapagos Province (ABG, 2015). However, the ABG currently focuses more on introductions cause by marine traffic rather than on climate driven introductions. In the Galapagos Islands administrative actions and sanctions have been established regarding marine biosecurity through LOREG. The ABG is responsible for conducting hull inspections to all vessels that enter the main ports of the archipelago through the resolution No. D-ABG-032-05-2018. Article 11 and 12 of the resolution states that for vessels that set sail from national or international ports must comply with biosecurity and quarantine regulations and present, upon arrival, a hull cleaning certificate with their respective report, video and/or photographic support. This must be issued two days prior to departure by the biosecurity authority of the country of departure or a company certified in hull cleaning. Similarly, the Galapagos National Park Directorate (GNPD) through Resolution No. 0000028 and Article 31 establishes that every vessel must present the hull cleaning certificate issued by a competent authority, which shows that the vessel is free of bioincrusting organisms. In the case that vessels are found to have bioincrusting organisms during the hull inspection conducted by the ABG, the GNPD has the authority to ask the vessel to leave the GMR to have the vessels' hull cleaned and re-enter for a second inspection. Although these biosecurity actions, led by the ABG and GNPD, exist and are superior to many other countries, in the ETP region and the world they only focus on marine NIS being introduced by marine traffic and not by natural marine dispersal. Thus, it is necessary to improve biosecurity protocols and pathway management procedures considering future climatic scenarios, along with training and equipment. These are urgently required to minimize the risk of introductions of marine NIS that have the potential to significantly impact biodiversity and livelihoods in the archipelago.

In the warmer coastal waters of the Eastern Pacific Ocean, invasions by marine NIS are known from Mexico to Chile, but there remains no synthesis of the total diversity of these invasions nor their distribution or impacts across these countries. The GMR is under threat from possible marine NIS arrivals, given the connectivity that exists with the ETP, the increase in tourism and marine traffic and the increase in SST - due to climate change that can increase the habitat suitability for NIS (Keith et al., 2016). New invasions may rarely be recognized or reported in a timely manner, inhibiting an understanding of which species may be actively spreading from new sites of invasions. While invasive species know no geographic boundaries, the limitations of funding, jurisdictional authority, and manpower mean that management efforts to prevent and detect new invasions, limit their spread, or understand their economic and environmental impact may be highly constrained (Carlton, Keith and Ruiz, 2019). Despite this, the same concerns for both managing current invasions and predicting imminent invasions are faced by government agencies, managers, and scientists in many different countries.

The CDF in collaboration with the GNPD and ABG has been working since 2012 on identifying what NIS are already established in the GMR through monitoring programs in order to assess the impacts these species could have on the marine ecosystems of the GMR. The results have now revealed that the number of marine invasive species in the Galápagos Islands is 10 times the number previously believed to be present: a minimum of 53 alien marine animals and plants are now documented in the Archipelago, compared to five previously recognized invasions (Carlton, Keith and Ruiz, 2019). Measuring the consequence or impact of the arrival of a marine NIS is key for decision makers all around the world in order for them to be able to mitigate the problem, however, the impact of the majority of species worldwide is unknown, with only a small percentage having been studied (Ojaveer et al. 2015).

In 2015, a globally well-known biofouling pest, the Caribbean spaghetti bryozoan Amathia verticillata, was discovered in the Galápagos (McCann et al., 2015); in 2016, a major biofouling Asian seasquirt, Ascidia sydneiensis, was also then detected in Galápagos harbors (Carlton, Keith and Ruiz, 2019). Additionally, CDF has been working on identifying high-risk species for the GMR by conducting risk assessments on different species among these are the lionfish (Pterois volitans) and the snowflake coral (Carijoa riisei). Pterois volitans inhabits tropical marine water with temperatures ranging between 22°C - 28°C. Lower temperature ranges have been observed in the U.S. (14°C to 24°C). The depth range for this species is 10 to 175m. It is widely distributed throughout the Western Pacific and most of Oceania east of French Polynesia (Morris & Whitfield, 2009; Hare & Whitfield, 2003); P. volitans has invaded the Atlantic coasts of the U.S. and the Caribbean (Morris & Whitfield, 2009; Gonzalez et al. 2009). The areas that are currently most affected are the southeast coast of the United States, Bermuda and the Bahamas; this is due to the establishment of this species before 2005 (Hare & Whitfield, 2003; Schofield, 2009). Pelagic juveniles move over great distances explaining the geographical range of lionfish (Froese & Pauly, 2015). The natural dispersion of lionfish probably occurred during the pelagic larval stage in which larvae disperse over long distances; for example, eggs released in the Bahamas can be dispersed to New England through the Gulf Stream (Morris & Whitfield, 2009). Ballast water is another possible vector for dispersion; it can transport the eggs and larvae from one region to another (Whitfield et al. 2002). This species feeds on a variety of small fish, shrimp and crabs, which can cause serious damage to native ecosystems through predatory interactions. It is believed that the eradication of this species is almost impossible, but it could be controlled in some places (Hare & Whitfield, 2003). This species has been identified as a potential invasive species for the GMR (Keith et al. 2014) and the GMR has also been identified as highly suitable for lionfish establishment (MacIsaac et al. 2016). It is thought that this species could be introduced from the Atlantic Ocean to the Pacific Ocean through ballast water in vessels traveling through the Panama Canal. The Galapagos Islands does not allow international commercial traffic to enter the GMR, so the ship-mediated invasion of P. volitans is low as long as the species is not reported on the coasts of mainland Ecuador. However, the establishment of the lionfish on the Pacific coasts of Panama combined with an increase of SST related to climate change, can increase the habitat suitability for this species extending its range from Panama to the GMR. The introduction of this species would cause strong ecological effects to the marine ecosystems of the GMR similar to those caused by the same species in the South East Atlantic. The lionfish is a voracious predator, it is a danger to residents, tourism and for some fisheries. It reduces the recruitment of young fish, which in turn disrupts marine ecosystem processes and reduces reef biodiversity, with the possible extinction of several species (Albins & Hixon, 2008; Morris & Whitfield, 2009). In addition, its voracity can reduce populations of commercially important species such as grouper (Albins & Hixon, 2008), which can affect the local economy as Galapagos small-scale fisheries rely on these target species. P. volitans has poisonous spines and can be dangerous for divers and others practising marine tourism-related activities (Bailly, 2015b; Morris & Whitfield 2009; Schofield 2009).

Another species of concern is Cobia (*Rachycentron canadum)* that was introduced to the coast of Ecuador in 2015 for aquaculture. Cobia is present worldwide in tropical and subtropical waters but was absent in the Eastern Tropical Pacific until Ecuador introduced this species. Its distribution is as follows, Western Atlantic: Canada to Bermuda and Massachusetts, USA to Argentina, including the Gulf of Mexico and the entire Caribbean. Eastern Atlantic: Morocco to South Africa. Indo-Western Pacific: East Africa and Hokkaido, Japan to Australia. (Froese & Pauly, 2015). Due to bad maintenance of the aquaculture cages several individuals escaped and fishers started to report their presence along the coast of Ecuador. Two months later the species was reported along the coasts of Colombia and Panama. The risk that Cobia species reaches the GMR is high because this species prefers warm waters (> 20 ° C) (Kaiser & Holt, 2007; Shaffer & Nakamura, 1989) and could expand its distribution from the coasts of Ecuador, Colombia and Panama as SST increase due to climate change.

Carijoa riisei, commonly known as snowflake coral, is an octocoral native to Indo-Pacific, present in the Atlantic, Pacific and Caribbean Sea (Sánchez & Ballesteros, 2014). *C. riisei* forms dense, monospecific aggregations, capable of carpeting hard substrata. This species was reported for the first time, as an invasive species in 1972, in Hawaii (Kahng et al., 2008). This invasive octocoral has been reported in areas with rich organic matter where it inhabits rocky and artificial substrates (Sánchez, 1994). It has been commonly found in harbors, docks, reef areas, caves and in areas with low light intensity (Venkataraman et al., 2016). This species is considered a generalist passive filter feeder and is successful at adapting to new habitats. It is thought to prefer shallow waters; however, it has been reported at depths of up to 120 m (Grigg, 2003). *C. riisei* can grow 1 cm per week without the need to feed. A colony of 2.5 cm in height is ready to fertilize (male), while colonies with 5 cm in height are ready to be fertilized (females) (Kahng et al., 2008). *C. riisei* has a gonochoric reproductive pattern and an asynchronous gamete release. This species has displayed high fecundity in Brazil, Hawaii and the Caribbean (Barbosa et al., 2014). *C. riisei* has shown to negatively impact coral reefs in Hawaii (Barbosa et al., 2014), Puerto Rico (Bardales, 1981), México and Colombia (Sánchez & Ballesteros, 2014). This species is common from Florida in the USA to Catarina in Brazil where it competes successfully with black corals and invertebrates (Kahng & Grigg, 2005). Furthermore, this type of events can lead to major shifts in species interactions and changes in both nutrient cycles and energy flow, which can result in unpredictable cascading effects (Carlton, 2001). This octocoral is an aggressive competitor that monopolizes food and space, feeding mainly on phytoplankton, diatoms and zooplankton larvae (Lira et al., 2009). In some ecosystems, marine invasive species can become so dominant that finding native species becomes a difficult task to achieve (Carlton, 2001). This has been observed with *C. riisei* where negative allelopathy has been registered with other species such as Tubastraea coccinea in Colombia and Ecuador (Sánchez & Ballesteros, 2014; Keith & Martínez, 2017) as well as reports of *C. riisei* growing on bivalves, corals, and other sessile organisms (Sánchez & Ballesteros, 2014). *C. riisei* has few natural predators, amongst them are bristle worms (Souza et al., 2007) and the nudibranch Phyllodesmium poindimie, therefore, no species has been identified as potential candidate for biocontrol (Wagner et al., 2009).

Like many other introduced species, it is unknown when and where the arrival of *C. riisei* took place in Ecuador, however Colombia reported *C. riisei* being present on the coast of Colombia as well as on the islands of Malpelo and Gorgona for many years but it was only in 2009 that the aggressive behaviour was recorded (Sanchez & Ballesteros, 2014). This species could be introduced to the GMR by expanding its distribution through oceanic currents and propagule dispersal, conversely the variability in ocean temperatures and chemistry can also influence the species dynamics and spread. *C. riisei* could also be introduced by marine traffic and then expand its range within the GMR relying on SST. Due to climate change and increasing SST other native corals could be affected, as discussed earlier, and lead to mass mortalities allowing an invasive species like *C. riisei* to act opportunistically and invade the habitat.

The 2015 expansion of the Panama Canal is emblematic of a rapidly growing global maritime trade network involving more, larger, and faster ships that are transporting more and more NIS (MacIsaac et al., 2016; Muirhead et al., 2015; Ojaveer et al., 2018). Ship-mediated introductions occur through ballast water and/or biofouling on the ship's hull. It was previously thought that ballast water was primarily responsible for the introduction of NIS. One well documented example of a ship-mediated introduced is *Dreissena polymorpha*, the zebra mussel that was first reported in Canada in 1986 and then later in 1988 in the Great Lakes in the United States. This species is thought to have been initially introduced through ballast water from Europe, but further expanded through biofouling. Since its arrival it has caused problems by displacing many native muscles, it also colonises docks, locks, ship hulls, water intake pipes and has caused great damage to power plants and water treatment facilities in the area (Carlton, 2008; Ruiz et al. 1997; Lovell et al. 2006). *Dreissena polymorpha* has impacted the Great Lakes by changing the community structure and function as well as causing a huge economic impact, it is estimated it has cost the United States government 6.5 billion dollars per decade on control measures (Strayer, 2009; Sun, 1994; Ruiz et al. 1997).

Overall, the recent detection of new invasions, the high probability of impending arrivals of new invaders, and the existence of widespread phenomena that will enhance invasions highlights the vulnerability of the GMR, thus, the prevention of NIS invasions should be prioritized in the environmental agenda. Currently the ABG focuses primarily on introductions cause by marine traffic rather than climate driven ones. However, it is clear that the marine biosecurity program needs to be strengthened in order to protect the GMR from this upcoming threat. Protecting the marine ecosystems of NIS will also mitigate the impacts of climate change in the GMR, as the degradation that results from invasions can alter the ecosystems and make them more vulnerable and less resilient to changes.

5.1.2 Objective and justification of the proposed EBA

Anthropogenic climate and global change is expected to be a major driver in the introduction, establishment, distribution and impact of NIS (Ziska & Dukes, 2014). Climate change is expected to alter the geographic distribution and abundance of many species and increase invasions of NIS in many areas which could lead to species extinction (Chan et al., 2018; Sorte, 2014). It is important to emphasize the impacts of NIS on biosecurity, food security and human health will continue to increase due to global climate change unless steps are taken now to minimize their introduction, establishment and spread (Rahel & Olden, 2008). Changes in temperature and surface currents, are expected to modify both natural and human-mediated species dispersal, enhance survival and establishment of NIS in previously unsuitable localities, and amplify impacts of existing NIS in invaded habitats (Chan et al., 2018). To address these problems changes in the efficacy of mitigation strategies for invasive species need to take place not only in one country but under a global perspective (Funk, 2015). It is important to be able to predict climate change impacts on species distribution and abundance and develop Early Detection Rapid Response (EDRR) protocols to achieve these goals.

It is essential to strengthen the biosecurity program in the GMR in order to prevent and detect climate driven introductions. EDRR is a critical process in preventing, limiting and mitigating the spread and impacts of NIS. EDRR is a key element in addressing NIS issues as it ties in directly with prevention as the most cost-effective way of dealing with a multi-billion-dollar problem. In many cases the impacts of NIS may be uncertain and/or irreversible however, decision makers often react slowly and wait for more information thinking that this would be more cost-effective (Hanley &Roberts, 2019). This was the case with the invasive algae *Caulerpa taxifolia* that was first observed in 1984 in Monaco, at that time it only covered a few square meters, however there was no rapid control measures put in place for years and now this species covers several thousand hectares. This invasion was a result of the decision makers using the "wait and see" policy, now it would cost governments from several countries billions of dollars to eradicate, additionally, this species has severely impacted the marine ecosystem of this region and altering biological process (Sims & Finnoff, 2013). The "wait and see" policy or the business-as-usual scenario is one that needs to change and a functional alert system with EDRR protocols needs to be implemented in the Galapagos Biosecurity program for climate driven NIS entering the GMR. In the case of Galapagos, a climate driven NIS introduction could cause the extinction of an endemic and native species because at this time only marine traffic associated introductions are considered in the biosecurity plan. If no improvement is made to the biosecurity plan regarding climate driven NIS introduction there is the high risk that species will arrive settle and spread reaching a point of no return costing the local authorities millions in eradication efforts. In a rapidly changing climate, the very concept of invasive species becomes problematic. Increasing temperatures are associated with the increase of species, which has been illustrated in the UK, USA and China (Huang et al., 2011). Controlling NIS arising from climate change is of high importance to safeguard the marine ecosystems of the Galapagos. Investing now in the precautionary principle will allow for the adaptation mechanism to be more effective and more cost-efficient.

The objective of this module is to mobilize invasion science and management solutions to protect, empower, and strengthen the Galapagos biosecurity program, and the public and research institutions involved, to prevent and reduce the expected impacts of marine invasive species related to climate change scenarios.

Invasive species globally produce damages estimated at more than 5% of global GDP, and island and coastal communities are particularly impacted. Invasive species have devastated food production systems around the world, collapsing fisheries (e.g., lionfish) and agricultural systems and impacting food security and livelihoods (Hixon et al 2016). Invasive species also have significant impacts on biodiversity. No place is immune to invasions. Recent research reveals a surprising number of marine species that have invaded marine protected areas, including Galapagos (Carlton, Keith and Ruiz, 2019). Even these critical protected areas are at risk to invasions, which threaten to diminish their high conservation and social value. Preventing the introduction of new alien species through biosecurity is the most cost-effective strategy, rather than managing them once they become established.

Thus, effective biosecurity systems are required to minimize the risk of invasive species introductions.

Although marine invasions occur as a result of the unintended transfer of organisms by vessels, aquaculture, fishing, recreation and other human activities, climate change can play a strong role in facilitating invasive species spread and/or aid in their settlement due to favourable conditions (Burgiel and Muir, 2010). Marine organisms can overcome previous existing barriers or be dispersed to arrive at new suitable locations. To prevent marine invasions, it is necessary to reduce the unintentional transfer of organisms combined with a detection and response capability for new incursions. These are fundamental tenets of biosecurity that are well understood but are only partly implemented in marine systems. As a result, the door is still open for new marine invasions in most regions.

Biosecurity protects biodiversity and livelihoods by managing potential pathways that new invasive species may enter, while early detection and rapid response (EDRR) allows for invasive species that pass the filters to potentially be eradicated before they establish (Reaser et al. 2020). Biosecurity is an investment in reducing future costs (e.g. of the need for managing invasive species populations, and costs associated with the impact of invasive species on values such as fisheries and biodiversity). Protocols and training aim to increase the capacity of the responsible public agencies for effectively reducing the risks of invasive species establishing.

We aim to address a major driver in biodiversity loss by (a) creating risk analysis and ranking systems for biosecurity, (b) create effective EDRR protocols to diminish new NIS invasions in the marine environment and (c) create an alert system to announce new incursions of marine invasive species in the GMR. This will allow for rapid detection of threats, improve coordination between local stakeholders and authorities, and will develop both an informal and formal detection network and engaging the public through citizen science.

Risk analysis is often divided into two components: risk assessment and risk management. Risk assessment is the process by which risk is measured and can be conducted before the occurrence of any events that could cause the risk or after the possibility of risk is incurred (Carlton, 2003). Risk assessment systems have been used around the world to try to mitigate NIS arrivals (Brown, 2009). Ranking systems help identify the most problematic NIS in or near the area in question and aid stakeholders in decision-making. Impact assessments can be based on a series of questions: (1) ecological impacts, (2) economic impacts, (3) human health impacts, (4) invasive potential and (5) difficulty of control. Each section gets a score; a high score corresponds to a species that can cause a great impact on the environment. The other part of the assessment deals with the current ability to prevent and take early action, questions related to entry and transport pathways, current distribution, policy and outreach measures already in place are asked to help facilitate prevention or rapid response. (Brown, 2009).

The CDF and the Smithsonian Environmental Research Center (SERC) have been working together since 2015 to advance a regional network along the Eastern Pacific from pole-to-pole and initiated the Coastal Ocean Marine Biosecurity International Network of the Americas (COMBINA) to advance and coordinate marine biosecurity across the Americas, with an initial focus on the Eastern Pacific coast and islands, from Chile to the United States (Alaska). The first meeting and workshop was held in the Galapagos Islands in June 2019, including representatives from 12 Latin American countries and the US. This included resource managers, policy makers, and scientists. To date, this type of regional coordination has been absent, even though all participants faced similar challenges and had many of the same priorities and needs. During the meeting break out groups were formed to discuss the creation of a biosecurity network throughout the region, which resulted in COMBINA whose mission is to provide scientific and management knowledge of non-native species in the region and work together to create high biosecurity standards throughout the South-eastern Pacific region to conserve biodiversity. The networks next steps are to create shared tools, resources, and protocols for application in each of the countries, establish mechanisms to accelerate knowledge exchange on biosecurity approaches and successes, allowing rapid uptake and cross-pollination, including those for management and policy strategies, and finally to expand public engagement and outreach, especially through citizen science to increase detection capability.

5.1.3 Description of sub-activities and outputs

To achieve the proposed objective, the following sub-activities and outputs are proposed:

Sub-activity 1.1. Conduct one regional bioinvasion assessment for each MPA in the ETP region (Galapagos, Cocos, Malpelo, Gorgona, Coiba), considering climate change scenarios.

In the GMR, diving expeditions will be conducted to test for spill over of NIS from anthropogenic habitats (e.g., docks and moorings) (Carlton, Keith and Ruiz, 2019) to natural habitats across the archipelago; this will provide an updated assessment of bio invasions in the GMR. Complementarily, using the existing biosecurity network (COMBINA) and key existing initiatives such as the Eastern Tropical Pacific Marine Corridor (CMAR), for its acronym in Spanish, a bibliographic assessment of what NIS are present in the region will be gathered in order to have a better understanding of the current situation of bio invasions in the ETP region. By coordinating with and learning from colleagues from throughout the ETP region, we seek to expand the tools, technologies, and approaches available to the ABG and the GNPD for enhanced biosecurity of the GMR specifically, but also to seek to apply this knowledge broadly throughout the ETP region. These assessments will be led by the CDF in collaboration with the GNPD and the representatives of each country in both the COMBINA network and the CMAR initiative. Recognizing the performance of an MPA is linked to that of neighbouring MPAs as part of a functional and connected network, it is expected that a regional bio invasion assessment will enhance the need for stronger more integrated biosecurity protocols not only in the GMR but in each MPA in the ETP region.

CMAR was formally established in April 2004, through the signing of the "Declaration of San José", a voluntary agreement between the Ministries of the Environment of the four participating countries (Costa Rica, Panama, Colombia and Ecuador). Since then, numerous initiatives by governments and various international organizations such as the United Nations Environment Program (UNEP) in 2002, UNESCO's World Heritage program in 2002, and the actions of the governments of Colombia, Panama, Ecuador and Costa Rica, have made it possible to carry out or promote programs among the main marine ecosystems of the ETP region. At the regional level, five regional working groups have been formed based on the thematic areas identified in the CMAR (Science, Marine Protected Areas, Fisheries, Communications and Tourism). These Regional Working Groups are composed of delegates from government institutions, research, NGOs, and academia. Each group has a coordinator who, in coordination with the group members and the secretariat work together to promote technical issues as well as the joint construction and management of projects for the CMAR improving management strategies between the five MPAs. The CMAR mechanism has great potential to facilitate the upscaling of best practices identified during projects undertaken.

These five updated lists of NIS for each MPA will allow the creation of a web-based portal, modelled after the National Estuarine and Marine Exotic Species Information System (NEMESIS), which was developed by SERC in the United States **(https://invasions.si.edu/nemesis/).** This platform will allow data from the five MPAs in the region to facilitate rapid information exchange. Coordination between the representatives from the Ministry of Environment from each country, CMAR, COMBINA and academia will be needed to achieve this output.

At the end of this activities, the following outputs are expected:

- Five web-based portals modelled after the National Estuarine and Marine Exotic Species Information System (NEMESIS), to upload the updated lists of NIS in the ETP region
- One Early Detection and Rapid Response (EDRR) protocol for marine invasive species is created for the GMR.
- 20 risk assessments conducted to determine the main pathways for marine invasions into the ETP by modelling dispersal mechanisms of potential invasive species considering variables such as climatic events and oceanographic circulation.
- Twenty risk assessments conducted to determine the main pathways for marine invasions into the ETP by modelling dispersal mechanisms of potential invasive species considering variables such as climatic events and oceanographic circulation.
- One NIS dashboard will be created to facilitate dynamic queries and rapid information exchange in the GMR.

Sub-activity 1.2. Develop and implement an Alert System for incursions of NIS in the GMR.

Early Detection and Rapid Response (EDRR) protocols for NIS will be created for the GMR in close collaboration with the GNPD and ABG. Risk assessments will be conducted by CDF to determine the possible pathways for marine invasions and by modelling dispersal mechanisms of potential invasive species (Table 7), considering variables such as climatic events and oceanographic circulation. A marine NIS dashboard will be created and uploaded to the web-based platform, that will allow dynamic queries and rapid information exchange. This dashboard will be hosted in the CDF DataZone web-based portal and managed by CDFs knowledge management team in collaboration with CDF scientists, GNPD park rangers and ABG technicians. Information generated in the dashboard will put in motion the EDRR protocols and management strategies for NIS that the GNPD and ABG will implement. This sub-activity aims to work in close collaboration with the local stakeholders to build capacity within the institutions (Activity 1.1.4), that will improve biosecurity in the GMR, that can then be replicated in the other MPAs in the region through the networks mentioned in sub activity 1.1.

Table 7: Examples of potential invasive species for the GMR

Potential Invasive Species	Distribution
Pterois volitans	Indo-Pacific, Australia, Atlantic coasts of USA and Caribbean.
Carijoa riisei	Iran, Mozambique, Western Atlantic and Caribbean from Florida to Brazil, Hawaii, Central Indo-Pacific.
Cacinus maenas	North of Africa to Australia, South America to South Africa
Undaria pinnatifida	Australia, New Zealand, Tasmania, North Atlantic, USA, Russia, China, Japan, France, UK, Italy, Spain, Mexico and Argentina.
Chama macerophylla	Hawaii, Caribbean Sea, Colombia, Costa Rica, Cuba, Gulf of Mexico, Jamaica, Lesser Antilles, Puerto Rico, San Andres, Venezuela

The GMR will serve as a model for the rest of the ETP as it is the MPA in the region with the most advanced biosecurity system. A Rapid Response framework will be developed using a decision tree for new incursions into the GMR based on the gathered information. A NIS Alert System to mitigate the impact of NIS on marine ecosystems in the GMR will be co-created with the GNPD and ABG. The alert system will be approved by the Ministry of Environment and Water of Ecuador and implemented by the GNPD and ABG.

At the end of this activity, the following outputs are expected:

- A NIS Alert System to mitigate the impact of NIS on marine ecosystems in the GMR developed.
- A rapid response framework using a decision tree for new incursions created to mitigate the impact of NIS on marine ecosystems in the GMR, adopted by the DPNG and ABG.

Sub-activity 1.3. Adoption and implementation of improved marine biosecurity and Early Detection and Response (EDRP) protocols, by the DPNG and ABG.

The marine biosecurity protocols for the GMR will be revised and improved using information generated in activities 1.1, 1.2, 1.3. CDF and SERC will work together with ABG and DPNG to co-develop the biosecurity protocols. ABG and GNPD will socialize the protocols with the Ministry of Environment and Water of Ecuador to start the implementation of these protocols. Training and co-implementing activities will take place to ensure GNPD park rangers and ABG technicians are proficient at implementing the revised protocols and marine biosecurity skill levels are improved. Capacity building workshops and training modules will be run by CDF and SERC scientists to increase the GNPD park rangers and ABG technician's knowledge on NIS identification techniques and biosecurity protocols.

At the end of this sub activity, the following outputs are expected:

- Marine biosecurity protocols for the GMR developed.
- Capacity building workshops and training modules implemented by CDF and SERC scientists to increase the GNPD park rangers and ABG technician's knowledge on NIS identification techniques and biosecurity protocols.

Sub-activity 1.4 Implement a regional outreach campaign to showcase and promote the replica of the GMR NIS Alert System and EDRP, in other ETP region MPAs.

A regional workshop will take place with the stakeholders from each MPA in the ETP region. The aim of the workshop will be to showcase the GMR NIS Alert System and promote the neighbouring MPAs to replicate this system to expand biosecurity in the region. Regional coordination of this event will be aided by the COMBINA and CMAR platforms.

At the end of this sub activity, the following outputs are expected:

- Visual and graphic material produced to showcase the GMR NIS Alert System.
- One regional workshop to present alert system to all stakeholders in each MPA of the ETP.

5.1.4 Impact on the resilience of the Galapagos system

<u>Impact on the resilience of ecosystems:</u>

The conservation of biodiversity and uninterrupted ecosystem processes will ensure the marine ecosystems resilience against climate and human perturbations. Invasive species alter biodiversity and functional diversity, reducing the capacity of the natural system to bounce back under diverse interacting pressures, directly impacting native and endemic species. Such disturbances can cause trophic cascades and shifts in the biodiversity of entire ecosystems.

In the case of the GMR it is protected in large part through recognition of their intrinsic natural heritage value, and local communities depend upon those resources for artisanal fisheries and nature-based tourism. If the biodiversity capital is diminished, the Islands become more attractive to traditional development concerns that do not prioritize on nature conservation and sustainable livelihood for local communities.

Marine invasive species can potentially increase with a shift in environmental conditions. A reduction in suspension feeders such as barnacles that proliferate in cold productive water would open space for invasion of novel species. Figures S3 and S4 show the predictions of temperature variation during the warmer months in the GMR under RPCs 4.5 and 8.5 with the largest increase in average temperature over the 20 years being in March, with an increase of over 3.5°C and with the next largest being May with just under 3°C warming. The rate of spread of marine invasive species will have a much greater magnitude of what is expected under these scenarios, which could cause devastating changes to the marine ecosystem structure and functioning. 2

This module will contribute to the Convention on Biological Diversity (CBD) Strategic Goal B: "Reduce the direct pressures on biodiversity and promote sustainable use" The project will update the biodiversity lists of species and endangered species and create risk assessment tools for anthropogenic threats (CBD Art 7), with the aim of establish a warning system and regional plan (CBD Art 6). The project will prevent the introduction of marine invasive species and control their impacts (CBD Art 8h), with a direct benefit for the local sustainable livelihood (CBD Arts 8i and 8j). Local authorities' staff will be trained and integrated in the project (CBD Art 12) in close collaboration with international experts and its technical resources (CBD Arts 16 and 18). The project's outreach program will inform and encourage local community participation (CBD Art 13). Web based portal for databases will be created and updated and available for information exchange (CBD Art 17).

This project will address SDG 14 (Conserve and sustainably use the oceans, seas and marine resources for sustainable development), SDG 13 (Take urgent action to combat climate change and its impacts), SDG 15 (introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on water ecosystems and promote initiatives focusing specifically on empowering women in coastal areas and the scientific community (SDG 5) as well as working towards global partnership (SDG 17).

The prevention of invasive species entering Galapagos and other protected areas will have significant benefits to habitats, ecosystems, and species across the Galapagos the ETP region. It is difficult to quantify or qualify these benefits as impacts would depend upon which invasive species were introduced. However, we do know that invasive species have caused ecosystem and fisheries collapses elsewhere (e.g., lionfish, zebra mussels). Through an exchange of information and knowledge amongst practitioners from the GNPD and ABG and by creating a network of science and management professionals, we will address the critical emerging concerns related to marine invasive species for the conservation and preservation of marine resources in Galapagos. The team will use risk assessments to inform the creation of protocols for Early Detection and Rapid Response (EDRR) strategies, including coordinated international alerts to announce new incursions. This will include species distribution models, focusing on selected target species of concern. A revised version of the ABG's Biosecurity Plan related to climate change incursions will be produced as well as revised protocols that will incorporate lessons learnt globally from other MPAs, and will be co-designed with representatives from ABG, GNPD. Critically, the team seeks to place regional bioinvasion networks and EDRR protocols in a world-wide context that can be replicated by other MPAs in the region to make the region more resilient to NIS and climate change.

<u>Impact on the resilience of Galapagos livelihoods:</u>

Healthy, well-functioning ecosystems enhance natural resilience to the adverse impacts of climate change and reduce the vulnerability of people. The GMR is the only MPA in the ETP region that has a resident population of 35,000 inhabitants that directly depend upon the ecosystem services provided by natural biodiversity to support their livelihoods (i.e., nature-based tourism and artisanal fisheries). This module proposes to use biodiversity and ecosystem services as part of an overall adaptation strategy to help people and communities adapt to the negative effects of climate change.

The Galapagos Islands are one of the best conserved archipelagos in the world and its effective conservation depends on sensible and sustained governance and management, ideally coupled to relevant applied research and robust monitoring. The conservation of the natural system is directly linked to a well-managed and implemented marine biosecurity program. The proposed module will work on preventing the arrival, establishment and spread of existing and new invasive species and as a result, the ecological integrity of the marine ecosystems in the GMR and their capacity to generate services for the local and global community would be maintained. This intervention will build capacity amongst stakeholders and increase awareness of the local community to protect the marine ecosystems from the introduction of NIS that can lower the resilience and affect livelihoods. Additionally, it will strengthen regional cooperation amongst the countries in the ETP region.

Preventing the settlement and spread of NIS in the GMR will protect the marine ecosystems from invasions and maintaining the health of the ecosystem making it more resilient to climate change. Rocky reefs are important for biological processes such as recruitment of key commercial species for fisheries that in turn are important for food security of the population of the Galapagos. Similarly, rocky reefs are important because they provide habitat for many species of fish, turtles (EBA 5.4) and algae making them highly productive. The diversity of fish and invertebrates attract tourists from around the world making it an important source of income for the local population of the islands. If climate driven NIS were to arrive to the rocky reefs of the archipelago the nature-based tourism and artisanal fisheries that are the two main livelihoods of the islands could be seriously affected. A clear example is the potential arrival of Cobia (*Rachycentron canadum)* or the lionfish (*Pterois volitans)* due to climate change, both these species could compete and predate on species that are of commercial value and benefit people's livelihoods. Similarly, if an invasion occurred and native species were displaced the cultural (tourism) benefits of visiting the rocky reefs could be eliminated. If the disturbances are persistent or of great magnitude, the result can end in a restructuring of the communities changing the functioning and the rates of diversity

Thanks to the intervention of this EBA the management of marine invasive species is improved in the GMR and the region to protect biodiversity and the sustainable use and improve resilience of the GMR against climate change. This intervention will also enhance the protection of coral reefs in the GMR by preventing the introduction of alien species allowing EBA 5.2 "Restore selected coral reef areas through coral planting and exclusion areas" to be successful. Additionally, the intervention proposed for the GMR will act as a model for other MPAs in the region to follow to improve resilience in the entire ETP region. Through the exchange of knowledge and capacity through workshops with stakeholders from the other MPAs in the region the importance of healthy ecosystems and natural resilience against climate change can be enhanced.

5.1.5 Description of the species that make up the module.

The module aims to control and mitigate the negative impacts of marine invasive species on Galapagos marine ecosystems. It is currently known that there are at least 53 marine introduced species in the GMR (Carlton, Keith and Ruiz, 2019). Here, we propose to add an additional layer of measures, leveraging existing activities to explicitly evaluate spill-over and occurrences of non-native species in natural habitats, selecting high-profile and high-impact target species of concern that include both established invaders and potential future invaders. Already present, the large Indo-Pacific seasquirt *Halocynthia hispida* now also occurs in Galapagos habitats and is of critical concern. Also present is the green algae *Caulerpa chemnitzia* found growing extensively on coral reefs on the northern island of Darwin. Species of the genus Caulerpa, are known as widespread and persistent marine invaders (Lowe et al. 2000; Schaffelke et al. 2006). Similarly, potential invaders also include the previously mentioned Indo-Pacific lionfish (*Pterois volitans*) and the snowflake coral (*Carijoa riisei*).

5.1.6 Technologies to be promoted through the module.

Remote Operated Vehicles (ROVs) are used by the ABG to inspect hulls of vessels that enter the GMR, however the models they have lack the power and agility to inspect the hull in more detail and to collect samples for further analysis in the laboratory. This module proposes the use of modern ROVs to facilitate the inspection conducted by ABG technicians and improve the detection of biofouling organisms on the vessels that enter the GMR (activity 1.1.1). This equipment will be used only by ABG trained technicians.

Similarly, there are ROVs that can be used to clean vessels hulls to reduce the biosecurity risks of vessels dispersing biofouling organisms. This technology can form part of a proactive biofouling management program to reduce the accumulation of organisms on the vessel or be applied to remove biofouling growth from unmanaged vessels (activity 1.1.1). This equipment will be used only by ABG trained technicians.

Temperature loggers will be installed in strategic places around the GMR including ports where vessels enter to measure temperature on a yearly basis to understand the processes that occur within the water column with climate change scenarios (activity 1.1.1). CDF will oversee deploying and recovering these devices.

5.2 EBA measure 2. Restore high ecological value coral reef areas through coral planting and exclusion area.

TARGET INDICATORS	
At the end of the project, at least 10 km^2 of corals will be protected and effective instruments to reduce coral mortality are implemented	
At the end of the project, at least one degraded site in each island (Darwin, Wolf and Floreana) will be under restoration schemes through transplanted corals in collaboration with the GNPD	
BENEFICIARIES	
Direct	40% technical staff of the Marine Department of the GNPD will be trained on techniques and methodologies to grow and transplant corals 80% technical staff of the and Marine and Tourism/recreation Departments of the GNPD are trained in improved monitoring and coral conservation techniques 80% technical staff of the Marine and Tourism/recreation Departments of the GNPD will participate in workshops to create improved coral conservation regulations 40% technical staff of the Ecuadorian Navy will participate in workshops to create improved coral conservation regulations 40% technical staff of the Oceanographic Institute of the Ecuadorian Navy – INOCAR will participate in workshops to create improved coral conservation regulations 40% technical staff of the ministry of tourism will participate in workshops to create improved coral conservation regulations 60% staff members of the Galapagos Governing Council CGREG will receive scientific information of the improved coral conservation plan in order to create new regulations
Indirect	100% of active tour and dive operators in the GMR are trained in improved monitoring and coral conservation techniques. 100% active Galapagos Naturalist and Dive guides are trained in improved monitoring and coral conservation techniques. 100% active small-scale fishermen are trained in improved monitoring and coral conservation techniques

	100% of active small-scale will benefit from coral reefs being restored and protected, species of commercial value will be able to complete their recruitment which in turn benefits livelihoods. 100% of the community will benefit from coral reefs being restored and protected due to increasing tourism which benefits livelihoods. 100% of local schools will receive environmental education regarding the importance protecting coral reefs. 100% tourists will benefit from coral reefs being protected as the cultural value of the visiting sites will increase

2. Restore high ecological value coral reefs through coral planting and exclusion areas, to enhance their ecological role in the GMR.	2.1 Produce one update assessment of the abundance and distribution of coral reefs and their associated biodiversity in the GMR considering current and future climate scenarios.	
	2.2 Transplant corals from the nursery developed in collaboration with the GNPD, to at least 1 degraded site in each island (Darwin, Wolf and Floreana)	
	2.3 Design and implement a removal program for sea urchins to assess vulnerability by conducting experiments	
	2.4 Mainstream the participation of the tourism sector in conservation and restoration programs carried out by the DPNG, in key touristic coral reef sites. 2.5 Monitor ongoing efforts and restoration needs of the areas that has been intervened with restoration techniques as well as control sites	- Eight coral assessment to evaluate the health of the reefs at the intervened sites and control sites - Develop a long-term monitoring plan with the GNPD to identify priority areas to implement active and passive restoration

		actions under current and future climate scenarios

5.2.1 Description of the current situation and baseline

Coral reefs are recognized among the most biodiverse and productive ecosystems in the world (Hoegh-Guldberg, 1999; Spalding et al., 2001; Roberts et al., 2002; Hoegh-Guldberg et al., 2007; Coles et al., 2008). Their complex structures provide habitat, shelter, and food for hundreds of species (Paulay, 1997). They also provide benefits to human beings because they serve as protection against storms and promote livelihoods in coastal communities, whose income depends on fishing and tourism generated by the reef (Birkeland, 1997; Edwards, 2010; Spalding, 2017). However, there is evidence of a growing deterioration of coral reefs globally as a result of natural and anthropogenic impacts such as: climate change, acidification, invasive species, overfishing, destructive fishing practices, pollution, coastal development, sedimentation, irresponsible tourism and diseases (De'ath et al., 2012; Hughes et al., 2007; Pandolfi et al., 2003).

Corals are key species because they are habitat builders, thus, their importance in ecosystems and tourism is high in the GMR (Banks et al., 2016). Differences in coral reef development and coral population dynamics have been evaluated throughout the GMR by monitoring populations and environmental parameters since the 70s. It has been found that the northern Galapagos Islands (Darwin and Wolf) have higher coral cover and richness and recover more rapidly that central and southern islands after disturbances in the region. The northern islands are of critical conservation importance as key reservoirs of regional coral biodiversity as well as source of larvae (Riegl et al., 2019b).

There has been a dramatic reduction in corals during bioerosion and bleaching events since El Niño 1982-1983, which resulted in extensive loss and fragmentation of coral habitat in the archipelago. Coral reefs were reduced by 97% after 1983 and by 26.2% during the 1997-1998 El Niño (Glynn et al., 2018). The slow natural recovery of new recruits and the growing concern of the potential risks to corals from global climate change raise important conservation questions, while urging appropriate protection within the GMR. In 2007 the largest communities of corals were evaluated on the islands of Darwin, Wolf and Marchena in order to provide information on their condition on a comprehensive baseline, and as a basis for future evaluations. The main results from these evaluations showed that the lobe coral (*Porites lobata*) showed the greatest population resilience at the central and northern islands of Marchena, Darwin and Wolf. The greatest frequency of large, old corals was found in Darwin and Wolf Islands. These colonies have survived strong ENSO events (1982-83 and 1997-98) and all showed good recruitment except for Devils Crown on Floreana Island (Glynn, 1990, 1994; Glynn et al., 2015). A cold-water shock was observed in the northern Islands in 2007, which caused coral bleaching and some tissue mortality (Banks et al., 2009; Glynn et al., 2017). During the evaluation, a notably high incidence of coral health anomalies was recorded (e.g., trematodiasis, tissue discoloration, uncharacterized diseases; Vera and Banks, 2009). The observed impacts could be a result of a tendency towards more frequent warm-water and cold-shock bleaching events.

Coral reefs have been affected by bleaching as a result of sustained high temperatures and physical damage caused by excessive surf. Of the 22 species recorded in the northern islands, none are endemic and are widely distributed in the region from Ecuador to Mexico. However, following the loss of> 95% of corals between the two last strong El Niño events, the little that survived on the northern islands now supports the largest proportion of the archipelago's macrofauna biodiversity associated with the provinces of Panama and the Indo-Pacific. These populations face several threats, including a high rate of disease among their reduced populations (~ 20%) and damage from anchors dragged over their colonies. Corals are the first to be impacted by the effects of ocean acidification, which prevents the normal growth of their aragonite skeletons (Glynn et al., 2018).

The Ecuadorian government started several measures through the GNPD and the CDF to safeguard corals in the GMR by performing comprehensive baseline surveys of the occurrence and condition of coral communities and monitor the health of coral ecosystems across the GMR (Danulat and Edgar, 2002; Banks et al., 2016; Riegl et al., 2019a). These surveys are essential to continue, in order to allow for quick recognition and migration of potentially damaging stresses such as coral bleaching, invasive species, diseases, bioerosion and overfishing (Glynn et al., 2018). Long-term marine monitoring works as a valuable tool to assess how communities naturally develop, as well as the how effective management measures work to mitigate any undesirable negative impacts between years (Banks et al., 2016).

The GMR is a multi-use protected area, where, to improve the management of the protected area the GNPD implemented a dynamic and adaptive management tool that divides the protected area into zones of different use. The first zoning plan of the GMR was declared in 2000 following a consensus of the Participatory Management Board, the aim of this plan was to reduce conflicts between uses, protect marine biodiversity, and promote sustainable uses (Castrejón and Charles, 2013; Heylings et al., 2002). The area surrounding the coastline of the islands, inlets and rocks of the archipelago are extremely important for ecological processes and represent many of the relevant habitats in the archipelago, coral reefs, rocky reefs, mangroves, and beaches, as many marine and marine-related species inhabit those areas (Banks et al., 2009). Some coral reefs of the Galapagos are protected under the zoning plan, however, currently there is a lack of protection and implementation of management and conservation measures for the coral ecosystems of Galapagos; this could affect their long-term survival if not acted in a timely manner. The deterioration of coral ecosystems as a result of inadequate management in the face of climate change would not only cause the loss of biodiversity, but would also affect tourism and artisanal fisheries, causing millions in losses. Well-informed actions such as impact mitigation methods, improved policies and implementation of zoning rules that regulate uses need to be applied to the GMR (Dawson et al., 2009).

Among the strongest impacts of climate change are the high sea temperatures recorded during recurrent El Niño events, which have caused coral bleaching and the loss of many reefs around the world (Glynn, 1984, 1993; Obura, 2004; Palumbi et al., 2014). Faced with this threat and given the recognized value of coral ecosystems globally, a series of management and mitigation strategies have emerged focused on the rehabilitation and restoration of impacted coral reefs, using coral transplantation (Guzmán, 1991; Edwards & Clark, 1999; Naughton & Jokiel, 2001). At the same time, it has been discovered that among coral communities, there are some species that show a much higher tolerance than others to climate change and bleaching (Hughes et al., 2003; Oliver and Palumbi, 2011). This resilience enables communities to withstand disturbances and regain their functions and dominance in the environment (Hughes, 2007, Glynn et al., 2009).

Coral transplantation is an increasingly used approach to restoring impacted coral reefs (Forrester et al., 2012). Coral transplant investigations in Hawaii indicate that when corals are transplanted to areas protected from the waves, which present conditions like those of their place of origin, they can have a high survival rate (Rodgers et al., 2017). The transplantation of corals in degraded reefs has yielded successful results in the Philippines, where fragments of corals attached to the substrate have doubled in size and the diversity of reef fish has increased at the transplant sites in a year and a half (Gómez, 2009). Coral transplantation is a tool that has also been used in the ETP region with good results in Costa Rica (Guzmán, 1991).

5.2.2 Objective and justification of the proposed module

The objective of this module is to increase the resilience of coral reef ecosystems by restoring corals and strengthening the controls of bioerosion and coral bleaching in critical High-Ecological Value areas (HEVAS) of the GMR.

Since corals are very sensitive to changes in temperature, climate change poses a great threat, particularly to these important communities (Banks et al., 2016). Recent changes in climate have turned many coral reefs into highly endangered ecosystems, reducing their resilience (Riegl et al., 2019b). Persistent temperature increase of only 1-2 ^{o}C can result in coral bleaching and mortality. Reduction of corals is widely known to be detrimental for their associated communities (Denkinger and Vinueza, 2014). Therefore, promoting the conservation of coral reefs is fundamental for all marine life but also for people's livelihoods (i. e. income, food and protection; Imtiyaz et al., 2011; Barbier, 2017).

A coral restoration plan will begin with experiments in the marine biology department of CDF determining the feasibility of planting coral and conduct experiments to increase survival rate and reduce mortality rate. Different experimental conditions will be used to measure the optimal temperature, light, and substrate for corals to grow on. Temperature and light can determine the makeup of the initial colonizers while sediment that accumulates on artificial substrate and affect settlement of coral (Spieler, Gilliam & Sherman, 2001). This will be done in close collaboration with technicians from the GNPD and coral experts from the Nova Southeastern University (NSU) in the USA. NSU is one of the leading universities researching coral ecosystems worldwide in order to understand species ecology, improving coral conservation methods, and promoting coral reef restoration and species recovery. NSU has laboratories and coral nurseries which are used to repopulate affected areas in Florida. Knowledge on different techniques and methodologies used by this institution can be applied in the GMR. After initial experiments have been validated using aquariums and a nursery area (1 year), we propose to transplant resilient corals to areas where corals have been degraded in coordination with the GNPD. The area that will be restored will be calculated during the initial assessment of degraded areas (Floreana, Darwin and Wolf). Rearing of coral fragments in nurseries prior to transplantation makes much better use of a given amount of coral source material and provides an opportunity to establish the transplants on substrates that can be readily attached at a degraded reef site. The corals that will be transplanted will be well-adapted to survive at the site as they will be reared under similar environmental conditions. Additionally, control areas will be identified where no active restoration has been attempted in order to provide a clear baseline to be able to evaluate the effectiveness of the transplantation. The rehabilitation of corals will increase the diversity of fish, macroinvertebrates and species functional to the health of the reef. We propose to carry out the proposed EBA, using the *Pocillopora*, *Porites* and *Pavona* corals, which lives naturally in the area where the rehabilitation of the reef patch will be carried out. These species are predominant in the ETP region (Baker, 2004). Furthermore, sea urchins are important herbivores on coral reefs, however, urchins can also have negative impacts on coral reefs where urchin populations reach outbreak densities. Urchins feeding can remove coral recruits, reduce cover of important coralline algae and lead to unsustainable bio-erosion. In order to measure ecological processes that promote resilience this EBA proposes to remove areas of urchins that feed on corals in areas identified during reef assessments to increase survival rates and colonization rates of certain species of coral and use exclusion caged experiments to minimize reef damage and assist recovery of the degraded areas delimited by the GNPD. According to studies conducted in the Seychelles, coral recruitment can increase up to two-fold at sites where urchins have been removed (McClanahan, 1999).

The transplant and rehabilitation actions proposed by this project will promote the conservation of the reef and its biodiversity, on which livelihoods depend on. The areas that will be restored in Floreana, Darwin and Wolf will be identified during the initial reef assessments. This information will be presented to the GNPD who will make the decision on the amount of degraded area the GNPD is comfortable restoring. To avoid degradation and protection of the coral reefs this module will go hand by hand with EBA 5.3 to adopt better diving practices.

In the face of the recovery response of these corals to the increase in sea temperature, finding coral communities that can be resilient to bleaching are increasingly important conservation priorities (Palumbi, et al., 2014). Coral transplants offer us the opportunity to carry out a management intervention and mitigation of impacted areas, using fragments of their colonies through transplantation. For this reason, we propose resilience-based management approach that seeks the conservation of coral environments and the sustainability of the services they offer in a changing global scenario (Hughes et al., 2007).

Restoring degraded coral areas will increase their ability to recover from a disturbance and move towards a coral-rich state, and/or to maintain morphological diversity as opposed to shifting to an algal-dominated state or a single coral morphology. Some of the indicators that show a healthy and resilient reef include, strong coral recruitment, low human impacts and healthy herbivore populations. By intervening on the degraded areas of coral reefs and by monitoring and improving coral conservation programs the coral reefs of the GMR will become more resilient in the face of climate change.

5.2.3 Description of sub-activities and outputs

To achieve the proposed objective, the following sub activities and outputs are proposed:

Sub activity 2.1. Produce one update assessment of the abundance and distribution of coral reefs and their associated biodiversity in the GMR considering current and future climate scenarios.

Conduct one coral biodiversity assessments in each of the islands (Darwin, Wolf and Floreana Islands) in the two initial years of implementation. An inventory of coral species and their conservation status will be carried out as well as an inventory of the species associated to the coral ecosystem. This will be done twice a year during the warm and cold season in Galapagos. This will be in addition to the yearly subtidal ecological monitoring conducted by CDF, as this assessment will be looking for degraded sites that are necessarily covered.

Dives will be carried out in the coral areas of each island, photos of the coral species will be taken in each site, and sensitive areas of degraded coral reefs identified and mapped. These affected areas will be identified for potential sites of coral transplants. At least 3 potential sites in each island will be identified over two years. This assessment will be conducted with GNPD technicians and park rangers will be trained in coral identification techniques by CDF and Nova Southeastern University. During the first two years a particle tracking model will be created to model coral dispersion under current and future climatic scenarios (RCP 4.5

and 8.5) in order to validate the effectiveness of transplanting corals to the selected areas creating a habitat suitability model (map) for coral transplantation/restoration in the GMR.

The following outputs are expected at the end of this sub activity:

- One coral biodiversity assessment in each of the islands (Darwin, Wolf and Floreana).
- Sensitive areas of degraded coral reefs identified and mapped.
- At least two potential sites for coral transplant in each island identified and a control site selected.
- One particle tracking model created to model the coral dispersion under current and future climatic scenarios (RCP 4.5 and 8.5) to validate the effectiveness of transplanting corals to the selected areas.

Sub activity 2.2 Transplant corals from the nursery developed in collaboration with the GNPD, to at least 1 degraded site in each island (Darwin, Wolf and Floreana)

During the first year of the project a knowledge exchange between Nova Southeastern University (NSU), the GNPD and CDF will take place to learn techniques and methodologies to grow and transplant coral. NSU farms coral to repopulate areas of coral degradation in Florida and CDF has a long-standing collaboration with this institution. Using the skills acquired during the exchange, we will develop a coral nursery in coordination in with the GNPD and conduct experiments using different environmental conditions to assess resilience using the CDF aquariums and a site designated by the GNPD during the first two years of the project. Corals grown in the nursery will then be transplanted to the identified degraded areas in the three islands.

GNPD technicians will be trained on coral identification, restoration techniques and monitoring techniques. Training and co-implementing activities will occur to ensure staff are proficient in all coral restoration to replicate the techniques in other selected sites in the future.

The following outputs are expected at the end of this sub activity:

- Knowledge exchange implemented between Nova South Eastern University (NSU), the GNPD and CDF on techniques and methodologies to grow and transplant coral. (NSU) farms coral to repopulate areas of coral degradation in Florida.
- Experiments using different environmental conditions to assess resilience using the CDF aquariums during the first two years of the project, developed.
- Coral nurseries implement in a site (in-situ) approved by the GNPD to grow new corals that will be transplanted to degraded areas.
- At least one degraded site in each island (Darwin, Wolf and Floreana) will be under restoration schemes through transplanted corals from the nursery developed in collaboration with the GNPD.

Sub activity 2.3 Design and implement a removal program for sea urchins to assess vulnerability by conducting experiments.

A sea urchin removal program will be designed as a pilot initiative to increase survival rates and colonization rates of coral transplanted to degraded areas. This will be done using exclusion caged experiments and a small-scale removal plan to minimize reef damage and assist recovery. Permanent transects will be established in designated sites. There will be transects where urchins will be removed whilst there will be transects where urchins will not be removed (control). This will allow us to increase our knowledge of the impacts of bioeroders in corals and assess vulnerability.

The following outputs are expected at the end of this sub activity:

- At least one small-scale sea urchin removal plan implemented to minimize reef damage and assist recovery of coral reefs.

Sub activity 2.4. Mainstream the participation of the tourism sector in conservation and restoration programs carried out by the DPNG, in key touristic coral reef sites.

The involvement of visitors in these restoration initiatives will be implemented through an initial pilot initiative at the end of the project, once the DPNG and FCD consolidate the restoration techniques and processes. A first step suggested by the DPNG Tourism department's managers would be to include the participation of tour guides and diving tour operators in coral reefs' transplant activities. This pilot can serve as a tool to expand coral reefs' knowledge in the tourism sector and as a good opportunity to engage this sector in conservation. Diffusion of the pilot to visitors and the local community will complement this awareness initiative.

The following outputs are expected at the end of this sub activity:

> At least one pilot project implemented with the tourism sector to mainstream their participation in coral restoration processes.

Sub activity 2.5. Monitor ongoing efforts and restoration needs of the intervened areas with restoration techniques as well as control sites

Eight assessments over 4 years will be conducted of the natural and restored coral ecosystems and their relationship with oceanographic and climatic parameters in the GMR. This will be done over in the warm and cold seasons each year of the project. For the monitoring of coral communities linear transects will be installed to characterize the benthic structure of the area and collect information on the health of the colonies, permanent plots will be established that allow the replication of monitoring over time on a section of the same community. Although the focus of this activity is on the health status of corals, the fish, invertebrates and algae associated with them will be monitored as well because these can be indicators of changes in the coral reef assemblage.

The following outputs are expected at the end of this sub activity:

- At least eight coral assessment to evaluate the health of the reefs at the intervened sites and control sites

- Develop a long-term monitoring plan with the GNPD to identify priority areas to implement active and passive restoration actions under current and future climate scenarios

5.2.4 Impact on the resilience of the Galapagos system

Impact on the resilience of Galapagos ecosystems:

The proposed module would aid increasing and maintaining the resilience of coral ecosystems in the GMR, which, in turn, contributes to the sustainability of the GMR. Coral populations in the GMR have undergone large reductions and tremendously negative changes since the early 1980's. Out of the 17 known coral reefs in the GMR back in 1976, all but one at Darwin Island, have completely disappeared or been highly degraded thanks to the 82/83 El Niño event (Glynn et al., 2018). However, the coral recovery in the northern islands has been robust whereas in the central and southern islands it has been low (Glynn et al., 2015). This has inspired researchers into using the GMR case to help assess species resistance and resilience in order to understand ecosystem responses to long-term climate change scenarios (Denkinger and Vinueza, 2014).

Biological processes such as predation, herbivory, and competition (which have now been studied by relatively few taxonomic groups in the Galapagos) exert their effect on the structuring of communities, particularly at the local scale, and their influence depends largely on measurement of large-scale oceanographic processes (Wellington 1975, Vinueza et al., 2006, Witman and Smith 2003).

The degree of ecological complexity and the current state of subtidal communities are the result of a multitude of interactions between species and their environment. Such interactions are influenced by disturbances, which demand pressures on components and processes of the ecosystem. If the disturbances are persistent or of great magnitude, the result can end in a restructuring of the communities changing the functioning and the rates of diversity. The ENSO cycle has sculpted the islands' natural environment for thousands of years but other impacting factors, in more recent decades, come from the increase in anthropogenic use of the coastal zone. In reality, it is the interaction between different factors - such as abrupt changes in climate, fishing extraction scenarios, the entry of invasive species facilitated by man and the wide range of coastal use modalities - that must be better understood for the adequate management and conservation of the RMG.

This module will contribute with coral restoration processes in HEVAS of the GMR to increase the resilience of benthic communities in the selected sites. The restoration success will enhance reef functions leading to improved ecosystem services in the GMR. The restoration processes will be conducted in three HEVAS of the GMR (Darwin, Wolf and Floreana). Sites will be chosen in the three islands for coral transplants in order and two stations will be chosen in each site (impact and control). In each station four replicates will be established for monitoring purposes. The five ecological indicators that will be measured will be hard coral cover, structural complexity, coral diversity, coral juveniles and coral health. Additionally, a small-scale sea urchin removal plan will be implemented to evaluate its effect on recruitment and mortality rates as well as the particle model. These indicators will allow the GNPD and the CDF to work together in improving the coral habitat, preventing the loss of corals and their habitat, enhancing coral population resilience to climate change and improve coral health and survival.

Impact on the resilience of Galapagos livelihoods:

Healthy and resilient coral ecosystems maintain their capacity to generate goods and services on which people depend. Tourism in the Galapagos is almost exclusively nature-based, and well conserved sites are more attractive and ensure a constant flux of visitors. Conservation of coral ecosystems will support the tourism livelihoods of the local population as is explained in EBA 5.3. Raising awareness with the local population and improving stewardship of ecosystem services increases the value of the ecosystem which in turn provides resilience.

Coral reefs are particularly important for fishing and tourism in the GMR, but they also contribute to coastal protection and are associated with high aesthetic values and, in places, high cultural values. Coral reefs provide the spawning and nursery grounds that economically important fish populations need to thrive. Coral reefs provide jobs to local people through tourism, fishing, and recreational activities. In the GMR tourism and recreation activities related to the coral reefs attract hundreds of visitors a year through diving tours, recreational fishing trips, cruises, hotels and restaurants.

The high vulnerability of coral reefs to climate change induced stress can lead to substantial coral mortality. Such climate change impacts have the potential to lead to declines in marine fish production and compromise the livelihoods of fisheries dependent communities as well as those that depend on tourism. Without reefs many species would suffer, people's food security would decline and the economies would be affected.

While international action on climate change is crucial for ensuring a future for coral-dominated reefs, effective management is also critical to sustaining reefs to sustain the livelihoods people depend on (Cinner et al., 2020). In the case of the coral reefs of the GMR it is critical to increase the resilience of these ecosystems both for the biological importance and the economic importance (Banks et al., 2016). It is important to act now before coral reefs in the GMR reach a high degree or degradation and the restoration efforts needed are high in cost and peoples' livelihoods are affected.

This module will contribute with coral restoration processes in HEVAS of the GMR to increase the resilience of benthic communities in the selected sites. The restoration success will enhance reef functions leading to improved ecosystem services in the GMR and livelihoods for the local community. The restoration processes will be conducted in three HEVAS of the GMR (Darwin, Wolf and Floreana). Sites will be chosen in the three islands for coral transplants in order and two stations will be chosen in each site (impact and control). In each station four replicates will be established for monitoring purposes. The five ecological indicators that will be measured will be hard coral cover, structural complexity, coral diversity, coral juveniles and coral health. Additionally, a small-scale sea urchin removal plan will be implemented to evaluate its effect on recruitment and mortality rates as well as the particle model. These indicators will allow the GNPD and the CDF to work together in improving the coral habitat, preventing the loss of corals and their habitat, enhancing coral population resilience to climate change and improve coral health and survival.

5.2.5 Description of the species that make up the module

The species that make up the module are three reef framework builders of the GMR: *Porites lobata, Pavona gigantea* and *Pocillopora* spp. (Riegl et al., 2019b).

5.2.6 Technologies to be promoted through the module.

Coral mapping and photogrammetric mapping of coral reefs in the GMR (using photography and drones):

- Launch the drone to fly an automated path over a section of reef (200m x 200m is a normal size) in the morning or evening. Flight is in a "lawn mower" pattern, usually at about 100 meters altitude.
- Similarly, specific segments of reef or specific corals can be photographed from all angles using SCUBA.
- Images are stitched together into 3D maps using Agisoft metashape. 3D map is converted to orthomosaic.
- Images are processed under machine learning algorithms to categorize benthic cover.

Instruments (smart moorings, temperature loggers) in key sites in the GMR:

- These instruments can provide temperature, current, wave, wind and tide data that can be transmitted to servers that can then be downloaded and the data can be used to validate data used in the particle tracking model.

Coral nurseries:

- Using the aquariums in the CDF and sites designated by the GNPD coral will be grown to a suitable size and out planted back to the natural reef. There are 4 cement aquariums that are 1.31m wide, 2.81m long, 0.82m high, 3.018502m^3 and hold 3018.502 litters. The in-situ nurseries in the aquariums will serve as a stock supply of corals that can be used for future population enhancement projects if needed.
- Block nursery structures or frame nursery structures will be used in the designated site to grow corals on cement slabs or frames anchored to the seafloor. Coral transplantation will be done in an area that is protected from wave action and easy to monitor and maintain.

Particle Tracking Model:

- To continue producing the particle tracking model a renewed subscription to MATLAB is required. The validation of the models would also be assisted by transects performed during tourist cruises using an ADCP (Acoustic Doppler Current Profiler).

Sea urchin removal:

- Mesh wire cages will be used to conduct sea urchin exclusion experiments. Three experimental treatments will be used 1. Closed cage with urchins 2. Open cage control and 3. Uncaged control. 9 replicates of each treatment will be used. The cages measure 0.5m wide and 0.2m high with a 0.2m overhanging edge made of 2cm mesh wire.

5.3. <u>EBA measure 3.</u> Reduce the impact of diving, anchoring and pollution related to tourism operations in selected marine HEVAS

TARGET INDICATORS	
At the end of the project, one agreement by diving operators to apply diving tourism Best Practices At the end of the project, one pollution monitoring system implemented at visitor sites. At the end of the project one agreement adopted between tourism stakeholders as a mechanism to enable future co-responsibility in the use of the buoys. At the end of the project 3 to 4 diving cruises operating in Galapagos to implement the adoption of DPS systems.	
BENEFICIARIES	
Direct	80% technical staff of marine and tourism and recreation departments of the GNPD 40% Navy INOCAR's technical staff 50% technical staff of the Ministry of Tourism 40% of the technical staff of the Galapagos Governing Council CGREG 100% active small scale artisanal fishers 100% active naturalist guides 100% tourism operators with diving and other activities in the GMR
Indirect	100% of local schools 100% tourists and visitors to the Galapagos 100% local population with increased natural experience 80% local residents that are beneficiaries of tourism industry (hotels and restaurants)

Logic Framework for EBA 3

Activity	Sub-activity	Deliverables
1. Reduce impacts of diving in marine visitor sites	1.1 Design and implement a conservation categorization system and management protocols for diving visitor sites.	- Dive sites categorized and mapped according to conservation levels. - Agenda and protocols for Best Diving

		Practices approved by all stakeholder parties.
	1.2 Strengthen monitoring of the DiveStat system with new indicators of impacts on the ecosystem, monitoring of climate change and new data portal to support decision making.	-Develop indicators to assess the impacting tipping points on corals, other fragile species and selected megafauna species resulting from inappropriate diving behaviours (manipulative experiments). -Identify diving impact indicator species to monitor diving impacts in the long term. -Monitor the impacts of climate change and tourists on corals and other fragile species, including the installation of oceanographic sensors in situ and remotely sensed data at visitor sites. -Adopt a fully digital survey system to ease data collection and management and develop a data portal based on current dashboard system to integrate all diving tourism indicators.
	1.3. Development and adoption of Diving Tourism Best Practices Toolkit co-created with dive tourism stakeholders.	- Diving best practices toolkit developed, including visual and graphic material to promote its adequate implementation. - Capacity building activities for dive guides and GNP rangers implemented. - Voluntary agreement by diving operators to apply the diving tourism Best Practices, designed.

		- Monitoring system implemented for underwater diver behaviour and the associate impacts as well as naturalist guides compliance to the best practices. - Diving operators and diving guides trained and feeding the monitoring system
	1.4 Reinforce the control and monitoring of pollution levels from boats	- Pollution monitoring system implemented at visitor sites. - Control mechanism for pollution levels from the boats, reinforced.
	1.5. Develop a Decision Support System (DSS) portal for policymakers, with information regarding marine tourism, including impacts from the tourism activities and the health of sites.	- Decision Support System (DSS) portal for policymakers, implemented.

2. Reduce the impacts from anchoring at visitor sites	2.1 Implement agreements with tourism stakeholders for replacing anchoring procedures and technologies with fixed-mooring buoys signalling and the Digital Positioning Systems (DPS).	- Participatory design of a fixed-mooring buoys solution, that guarantees its implementation and finds solutions to their maintenance costs. - At least one agreement adopted between tourism stakeholders as a mechanism to enable future co-responsibility in the use of the buoys. - Training workshops

		implemented to cruises operating in the Galapagos for understanding and awareness of the operation, benefits, and opportunities to adopt DPS systems. - Agreed plans between DPNG and at least one third (3-4) of diving cruises operating in the Galapagos implemented for the adoption of DPS systems. - Lessons learnt disseminated to promote replica.

5.3.1 Description of the current situation and baseline

The outstanding marine ecosystems of the GMR are the main attraction to SCUBA diving tourism in Galapagos, which is evidenced by the approximately 18 000 divers coming to the islands every year (Izurieta & Moity, 2018). Galapagos is consistently classified as one of the top ten diving destinations in the world (Scuba Diving, 2020), particularly for seeing marine megafauna. The unique diving conditions offered by the archipelago are a result of the different currents that converge in the Galapagos, the isolation and the bathymetry surrounding the islands and the unique ecosystems that support a rich marine life: mangroves, beaches, seamounts, rocky and coral reefs. Coral reefs support high fish biodiversity (Jones et al, 2004), where fish abundance and diversity are known to attract divers to the Galapagos (Moity & Izurieta, 2017). However, corals in Galapagos have suffered due to bleaching events as a result from El Niño 1982-83 and 1997-98 (Glynn et al., 2018). The slow recovery of these coral reefs is particularly alarming since climate change impacts are expected to exacerbate coral habitat loss in the GMR due to thermal stress. Hence, non-harmful tourism practices on marine ecosystems, and particularly on corals, need to be implemented in order to increase the resilience of coral reefs to natural and anthropogenic impacts.

Although snorkelling and diving has a long history in the GMR, the Galapagos National Park (GNP) has historically lacked the information needed to assess marine tourism and guide policy, particularly in an era of climate change. Consequently, the effects of marine tourism on the Galapagos social-ecological systems have remained unknown. To fill this knowledge gap, the DiveStat monitoring program was created (Moity et al., 2019). The program developed a standard monitoring methodology to evaluate diving marine tourism using a holistic approach, understanding the marine tourism activity in the Galapagos as a social-ecological system. DiveStat identified eleven indicators to evaluate the ecological impacts associated with the activity, the ecological state of the sites, as well as indicators related to the visitor, its demographic, trip and diving profile, perceptions, and satisfaction levels (Moity, 2017d; Moity & Izurieta, 2017, 2018a, 2018b). Other aspects of the activity, such as those related to the security of the diving operation and good practices recommendations based on empirical data, were also initiated (Moity, 2017b, 2017a, 2017c). Nature-based tourism is the economic motor of the Galapagos upon which other important livelihoods, like fisheries, are highly dependent. It is estimated that 80% of the economic activity on the islands depends on nature-based tourism (Pizzitutti et al., 2017). Tourist entry fee to the GNP alone, accounts for 45% of the annual budget of the National Park and it is estimated that a tourist in the Galapagos spends on average, US$ 1 310,50 in its journey on the islands (Observatorio de Turismo de Galápagos, 2019). Nature-based tourism has the potential to substantially contribute to livelihoods while, if well managed, being ecologically sustainable. However, although the Galapagos are a worldwide example of good tourism management, this holds true only for the terrestrial areas. Marine tourism has consistently been forgotten from monitoring and evaluation programs from the GNP. Diving tourism is an important and ever-growing sector of marine tourism (Cisneros-Montemayor et al., 2013; O'Malley et al., 2013). It has been widely demonstrated that diving tourism impacts coral reefs and other temperate rocky reefs formations (Betti et al., 2019; Giglio et al., 2020; Renfro & Chadwick, 2017). Similar impacts were found in Galapagos after it was found, through monitoring of divers' behaviour, that most divers (~80%) had some sort of contact with the substrate with either parts of their equipment or their body (Moity et al., 2019). Most importantly, 12% of these incidents involved contact with coral species that were hit by the fins or touched directly with the hands of divers. Repeated direct or indirect injury to coral reef by divers occurs through fracture of the rigid skeletal structures or abrasion of the soft tissues. This type of damage is especially problematic for hard corals because of their role as foundational species on tropical reefs. Damage created by divers can increase the susceptibility of corals to predation (Guzner et al., 2010), disease (Lamb et al., 2014), and impair their growth (Guzner et al., 2010), as well as reducing reef complexity (Lyons et al., 2015). These impacts and corals' increasing vulnerability are the result of bad tourism practices and act synergistically with natural and anthropogenic impacts, intensifying the degradation and bioerosion of corals product of El Niño events, increase in sea temperature and acidification of the oceans. Overall, these impacts diminish their resilience against climate change.

Tourism in the Galapagos involves the use of boats to get to the visitor sites either on day trips or multi-day cruises. Currently there are 78 cruises in the Galapagos (9 of which are diving liveaboards) (Observatorio de Turismo de Galápagos, 2019), which anchor at the visitor sites on each of their visits. In addition, there are 103 small boats that are also used for daily tours and anchor occasionally depending on the site, boat type and the sea conditions. Anchoring is a widely recognized factor impacting reefs (e.g. Flynn & Forrester, 2019) through physical damage or destruction of the coral structures (especially hard corals). Anchoring effects on corals can take years to recover (Rogers & Garrison, 2001) and, like the impact of divers, it can increase the susceptibility of coral reefs to thermal changes due to climate variability as well as debilitation due to bioerosion processes and acidification. In spite of the long periods needed to recover from anchoring damage and the decreasing resilience of ecosystems to stressors, coral reefs and coral communities would greatly benefit from coral restoration programmes.

There was an initiative to provide 70 fixed mooring buoys at ten of the most visited sites of the archipelago with the aim to transform the Galapagos as a "Zero anchoring" MPA. The project was implemented by the Oceanographic Institute of the Army (INOCAR) in 2011 with pilot studies starting in 2008 (Acuña-Marrero & Keith, 2011). However, the project was deemed unsuccessful since most of the buoys were seldom used due to errors in their placement, and a lack of participation from the major stakeholders (tourism sector and boat captains) in the process. Nowadays the majority of the buoys are unusable or have disappeared due to a lack of maintenance and populate the coasts of the archipelago.

Furthermore, other forms of impacts from the marine tourism activities come from pollution caused by touristic vessels. Owing to the Ecuadorian Environmental Organic Code (COA), each multi-day cruise must possess an environmental licence to be able to operate. This licence is approved upon positive semestral environmental quality monitoring of the boat's grey, black and bilge waters, which are also regulated by international MARPOL normative. This regulation is effectively implemented in the GMR ensuring, at least in theory, that pollution from the marine tourism activity is very low. However, non-liveaboard boats, such as those used in day tours, are not eligible to have an environmental licence and only MARPOL normative apply. For these boats no semestral water quality monitoring is required and there is no control of MARPOL application. On the other hand, monitoring is focused at the cruise boat level but there is no knowledge on long-term pollution levels or accumulation through years at the visitor sites nor at the species level. Other pollutants, like heavy metals, other organic compounds associated with tourism activities (such as sunscreens) or micro plastic generation, are not targeted by current environmental quality monitoring measures. Presence and concentration of those pollutants is currently unknown.

5.3.2 Objective and justification of the proposed module

The objective of the present module is to increase the resilience of marine coastal ecosystems to climate change by reducing the environmental impacts associated with marine tourism. Activities will be centred at minimizing impacts from the diving activity, anchoring and pollution associated to tourism activities.

This EBA supports the stability, resilience, connectivity, and multiple roles of ecosystems as part of larger seascapes. It encompasses measures such as ecosystem management and management of threats associated with the effects of climate change or human activities like those associated with marine tourism in the archipelago. Because climate change can force changes in ecosystem composition and structure, and marine tourism activities can exacerbate those changes by adding stress and by damaging the ecosystem, it is important that the health and stability of ecosystem services are maintained and monitored. In the Galapagos, marine tourism is still impacting ecosystems locally threatening their conservation and resilience. Anchoring and diving tourism are directly impacting the structure of ecosystems while the pollution levels from tourism and potential effects are currently unknown. In the face of global climate change there needs to be an urgent intervention to monitor ecosystem services and promote sustainable tourism practices.

Because ecosystem services are the basis of the archipelago's attractiveness and central to its main economic activity, tourism, the intervention will be centred at including stakeholders in capacity building, monitoring, and promoting the conservation of marine ecosystems.

5.3.3 Description of sub-activities and outputs

Sub activity 3.1: Design and implement a conservation categorization system and management protocols for diving visitor sites.

Dive sites will be categorized according to conservation levels and management recommendations will be issued accordingly. To categorize the sites, these will be monitored ecologically and mapped to identify fragile species and areas (e.g. areas with high coral cover). The monitoring will include fish and other macrofauna (sea lions, marine turtles, etc.), macroinvertebrates and benthic cover components. Fixed plots at visitor sites and control sites will be monitored over time for change detection. The sites will be monitored during the duration of the project, but data will be compared before and after the implementation of Diving Best Practices Toolkit, to detect possible changes due to the intervention.

Experience has demonstrated that the implementation of top-down management measures can generate conflicts, refusal and create a detachment of the stakeholders from the conservation agenda. Thus, a series of workshops will be planned to include dive tourism stakeholders' representatives to co-create the agenda of Best Diving Practices that should be implemented in the GMR. At the end of the workshops, an official agenda and protocols for the diving Best Practices will be approved by all stakeholder parties for later compliance.

The following outputs are expected at the end of this sub activity:

- Dive sites categorized and mapped according to conservation levels.
- Agenda and protocols for Best Diving Practices approved by all stakeholder parties.

Sub activity 3.2. Development and adoption of Diving Tourism Best Practices Toolkit co-created with dive tourism stakeholders.

Visual and graphic material will be produced to be exposed at dive centres, boats, live aboard cruises, etc., to help dive guides to perform their *dive briefings* thoroughly, which is a critical step in Best Practices education and appliance. Thorough dive briefings prior to diving significantly reduce diver impacts once underwater (Giglio et al., 2018; Toyoshima & Nadaoka, 2015). In addition, an underwater 360º promotional video will be developed for the most charismatic dive sites, including diving Best Practices recommendations, for a double purpose, to promote the dive sites and be of use to the local diving tourism industry, but also to educate in diving best practices especially at those diving sites. Once created, the diving best practices toolkit will be promoted through Facebook, Twitter and You Tube campaigns as well as radial interviews and local presentations with the participation of dive guides to connect with and impact the local population.

Capacity building activities for dive guides and GNP rangers will be implemented to help them gain marine conservation awareness and understanding, interpretation insights of marine seascapes, responsible diving practices with the environment, and climate change impacts in the oceans and the GMR. This will have lasting impacts in their education and employability. These aspects will be reinforced with Community Outreach activities, that will be implemented in component 3 of the programme.

To support the GNPD to implement the Diving Tourism Best Practices in the GMR we will assist the co-development of a voluntary agreement by diving operators to apply the diving tourism Best Practices. A workshop will be held with the tourism stakeholders (GNPD, operators and guides' representatives) to co-develop the terms of a voluntary agreement scheme by which the diving operators agree to comply to the Best Practices and agree to be monitored in this regard on at least a yearly basis. In return, we will evaluate with the GNPD, the creation of an "eco-friendly dive operation" certification, renewable yearly, endowed to those diving operations that agree to comply with the Best Practices and prove to do so upon a monitoring of their diving operation. On the other hand, we will also evaluate with the GNPD the creation of a monetary incentive in which some of the current mandatory taxes due by the diving operations to operate in the GMR could be partially alleviated if the eco-friendly dive operation certification is awarded. In addition, this certification will be used by the diving agencies to promote their diving operation as friendly with the environment. Since long-term changes towards Best Practices application are partially dependant on education of the tourism stakeholders, the GNPD will agree to include the Diving Best Practices agenda in all the mandatory guides courses (including the guides refresher courses). To complement the implementation of the Best Practices, and to ensure the success of the certification scheme, the program will include capacity building of park rangers in marine monitoring knowledge and abilities and promote park rangers and dive guides training in Best Practices compliance monitoring.

Finally, to corroborate that the Diving Best Practices Toolkit is positively impacting the way diving tourism operates in the GMR, we will monitor underwater diver behaviour and the associate impacts of diving tourists as well as naturalist guides compliance to the best practices before and after the implementation of the Diving Best Practices Toolkit. We will also compare after data to referential, base-line data to evaluate time series changes. If changes are not detected and Diving Best Practices are not respected, data will allow to detect the precise changes to be made to correct this (e.g. the implementation of on-site correction measures by the guides on diving tourists with bad underwater behaviour).

To promote involvement of the tourism sector regarding climate change impacts on corals and the importance of the adoption of best practices in diving tourism to avoid damaging these systems, monitoring of the dive sites will be implemented with a citizen science approach. Diving operator and diving guides will be trained in marine ecological monitoring techniques on the same components of the previous activity and provided with underwater cameras to take footage of the dive sites. The images obtained will be analysed with deep learning workflows to alleviate the processing and annotation time. Data will be used to complement the monitoring and categorization of diving sites.

The following outputs are expected at the end of this sub activity:

- Diving best practices toolkit developed, including visual and graphic material to promote its adequate implementation.
- Capacity building activities for dive guides and GNP rangers implemented.
- Voluntary agreement by diving operators to apply the diving tourism Best Practices, designed.
- Monitoring system implemented for underwater diver behaviour and the associate impacts as well as naturalist guides compliance to the best practices.
- Diving operators and diving guides trained and feeding the monitoring system.

Sub activity 3.4: Reinforce the control and monitoring of pollution levels from boats.

Pollution from tourism activities can exacerbate climate change impacts, forcing changes to the marine ecosystem's composition and structure, adding stress, and affecting the resilience of the species. It has been demonstrated that UV-filter components found in most solar screens can have toxic pathological effects on corals, fish and jellyfish affecting reproduction and larvae (Coronado et al., 2008; Downs et al., 2016; Fitt & Hofmann, 2020). Furthermore, hydrocarbons and heavy metals commonly found in fuel leakages from boats, bioaccumulate in corals (Han et al., 2020; Yang et al., 2019) and can alter reproductive success, degenerate symbiotic zooxanthellae, provoke tissue loss, and alter mucus secretion, impacting overall coral resilience (Burns and Knap, 1989; White et al., 2012; Turner & Renegar, 2017). Anthropogenic microplastics, for which the marine tourism activity could be a source at visitor sites, since plastic is ubiquitous in dingies, carpets, fins, wetsuits, lycras, etc., can impact coral physiology, energetics, growth, and health (Huang et al., 2020); while microplastic ingestion in fish (Tanaka & Takada, 2016) and invertebrates has a consistent negative effect on the consumption of natural prey, affecting growth, reproduction, and survival (Foley et al., 2018). These pollutants would adversely affect corals, other invertebrates, and fish, and greatly increase their sensitivity to climate change related stresses as well as the physical damage produced by anchoring and harmful diving behaviour. In addition, the impact could cascade to other components of the ecosystem, which are dependent on them for substrate or food. Thus, it is of paramount importance to implement a pollution monitoring plan at visitor sites. To achieve this, visitor and control sites will be monitored to quantify the magnitude of the presence of pollutants (heavy metals, organic compounds (hydrocarbons, Benzophenone-2 and 3, micro plastics). Pollutants presence and quantity will be compared between visitor and control sites and relationships between site use and pollutants concentration will be analysed. Each site will be sampled for water, sediment, and representatives of the food chain (fish, gastropods, sea urchins, algae and corals, three species each). Metals and micro plastics will be analysed in at least 30 sites, organic compounds in 15 sites and organic pollutants (e.g. coliforms) in ten sites. Visitor sites will be chosen by level of use so as to have at least sites with very high and low use (plus control sites with no tourism at all). This sampling design will allow to establish a baseline in pollutants from tourism and evaluate the levels of pollution by comparison between highly visited sites, sites with low visitation and control sites. Also, the degree of impact from pollutants across the marine food chain will be established.

Upon analysis and interpretation of information gathered through the environmental pollution monitoring plan of the tourism sites, meetings will be held with the GNPD and marine tourism operators to inform of the results and reinforce control mechanisms for pollution levels from the boats.

The following outputs are expected at the end of this sub activity:

- Pollution monitoring system implemented at visitor sites.
- Control mechanism for pollution levels from the boats, reinforced.

Sub activity 3.5 Develop a Decision Support System (DSS) portal for policymakers, with information regarding marine tourism, including impacts from the tourism activities and the health of sites.

A DSS portal with a front end available on the Internet will be constructed. The portal will allow a seamless workflow from information integration and archival to analysis and communication with policy makers, relevant stakeholders, and the general public (with different levels of access rights). The DSS will make use of dashboards to facilitate the analysis, interpretation, and summarization of the information to be displayed in the front end. All the information generated from this EBA and the DiveStat program regarding the social-ecological marine tourism system will be integrated in the DSS. The Charles Darwin Foundation will administer the DSS, in close collaboration with the GNPD.

The following outputs are expected at the end of this sub activity:

- Decision Support System (DSS) portal for policymakers, implemented.

Sub activity 3.6: Implement agreements with tourism stakeholders for replacing anchoring procedures and technologies with fixed-mooring buoys signalling and the Digital Positioning Systems (DPS).

The lack of discussion spaces between tourism stakeholders and the poor representation of boat captains working locally are some of the reasons of failure of past essays to reduce the impacts from anchoring via mooring buoys. Thus, we will create those spaces for discussion ensuring the inclusion of the relevant stakeholders and with the help of a conflict solving expert. Bottlenecks of the anchoring problem in the GMR will be identified and diagnosed. The outcome of these discussions will result in a design for fixed-mooring buoys solution overcoming past experiences, that guarantees their implementation and finds solutions to their maintenance costs.

At the end of the discussion exercise described in the previous activity, following workshops will be held to conclude with at least one agreement adopted between tourism stakeholders as a mechanism to enable future co-responsibility in the use of the buoys and to guarantee an economically sustainable long-term maintenance scheme for the fixed-mooring buoys.

The Dynamic Positioning System is a novel system that few boats have implemented at present. Thus, the first step will be to bring DPS experts to deliver training workshops in the Galapagos on its use, benefits, and technical matters. We will ask for participation of the cruise and diving operation key personnel (especially the captains) of the company that have already installed DPS systems, so they can provide a review of the pros and cons of the DPS and its use in the Galapagos. They will be important promotors of the system with on-site experience. The workshops will deal with the functioning of the technology, its technical specifications, costs, installation requirements, ecological benefits, etc. so that all stakeholders are on the same page regarding this future-looking conservation approach to anchoring. The workshops will be especially targeted to diving live aboard cruises and will derive in an installation plan agreed with DPNG and one third (3-4) of diving cruises operating in the Galapagos selected based on their willingness to engage, DPS specifications and DPS expert advice.

Based on the installation plan agreed with DPNG and abroad cruises the program will assist cruise companies in the access to low interest credits to acquire the technology and will provide technical assistance for the adequate installation of the DPS.

After at least six months after installation, an identification of the strengths, weaknesses, opportunities and threats (SWOT) related to the DPS use in the GMR will be developed with the cruise and diving operation key personnel. The analysis will be presented and discussed with relevant tourism and government stakeholders, to promote adoption 100% of operating cruises.

The following outputs are expected at the end of this sub activity:

- Participatory design of a fixed-mooring buoys solution, that guarantees its implementation and finds solutions to their maintenance costs.
- At least one agreement adopted between tourism stakeholders as a mechanism to enable future co-responsibility in the use of the buoys.

- Training workshops implemented to cruises operating in the Galapagos for understanding and awareness of the operation, benefits, and opportunities to adopt DPS systems.
- Agreed plans between DPNG and at least one third (3-4) of diving cruises operating in the Galapagos implemented for the adoption of DPS systems.
- Lessons learnt disseminated to promote replica.

5.3.4 Impact on the resilience of the Galapagos system

Thanks to the intervention proposed in this EBA, the marine environment will be better conserved, and its resilience to climate change, improved. The intervention will result in more ecologically friendly marine tourism practices, decreasing their impact on key ecosystems such as coral reefs, significantly reducing their vulnerability to climate change and at the same time preserving their natural resilience. Diving and marine tourism will be better managed; impacts from divers, anchors, and pollution from boats to the marine habitats and, particularly to coral reefs, will be greatly reduced. Tourists, naturalist guides and, in general, the tourism stakeholders, will have a better understanding of the dangers and consequences arising from unsustainable tourism practices. This will result in a change in behaviour and a better management of tourism activities, which will contribute to protect marine habitats and increase coral reef resilience from expected climate change impacts.

The activities proposed in this module aim first towards the monitoring of the marine tourism activities and the ecological monitoring of the visitor sites. They will allow for the (1) detection of impacting behaviours within divers, (2) the identification, mapping and monitoring of fragile species and the assessment of conservation levels within the visitor sites, including anchoring damage monitoring, (3) the establishment of thresholds or tipping points regarding impacting behaviours from divers on selected species, (4) the identification of indicator species to monitor diving impacts in the long term, (5) the monitoring of changes with regard to baseline ecological information, (6) the establishment of baseline information regarding pollution levels at the environmental scale of visitor sites and control sites regarding heavy metals, organic compounds including hydrocarbons and those found in sun-screens with proven negative effects on marine biota and corals (Coronado et al., 2008; Downs et al., 2016; Fitt & Hofmann, 2020), and microplastics and (7) the monitoring of climate change oceanographic parameters (temperature, pH, dissolved oxygen, salinity, chlorophyll). All the information gathered will allow the precise establishment of baseline values and monitoring of conservation levels at visitor sites and the monitoring of changes that result from the intervention (EBA). At the same time, environmental parameters will be continuously measured to monitor the oceanographic changes associated with climate change.

In a scenario without intervention, marine diving tourism sites will not see a reduction of the impacts related to tourism activities, accelerating the expected impacts from climate change (coral bleaching, low recruitment, bioerosion) and decreasing the natural resilience of impacted species to climate change (such as coral reefs). Diving tourism stakeholders will not have the tools to understand and promote Best Practices, and current, damaging diving practices will remain. Tourists will be unaware of their damaging underwater behaviours. Anchoring will continue to be performed as usual, perpetrating the damaging practices that have been occurring since the 1980s. No spaces and opportunities for discussion will be created for the stakeholders to discuss and imagine solutions to the anchoring problem. New technologies to avoid anchoring at all (such as the DPS) will not be evaluated nor implemented in diving cruises. The ecosystem conditions of the marine tourism sites, baselines with regards to pollutants and responses of the ecosystems to the diving tourism activities and practices will remain unknown. Finally, policy makers will not have access to a Decision Support System portal that aggregates all the information around the marine tourism social-ecological system in the Galapagos.

The adaptation scenario will be fostered by several interventions that will set the conditions needed to promote the conservation of marine ecosystems. First, the facilitation of discussion spaces for stakeholders to consider anchoring alternatives will provide an ecological solution to widely recognized anchor associated impacts on corals and other fragile organisms (Flynn & Forrester, 2019; Jameson et al., 2007; Rogers & Garrison, 2001). This will include the potential co-creation of a self-managed and self-financed fixed-mooring buoy system at selected sites in which the cruise operators could oversee their installation and maintenance as well as the promotion of pioneering solutions using Dynamic Positioning Systems (DPS) on a selected group of insignia live aboard boats that others could adopt with the help of soft financing. DPS is a next-generation non-anchoring system in which the boat automatically corrects its position with the help of GPS positioning, current and wave detection and the help of an array of thrusters that maintain the boat at the desired place without the need to anchor, thus providing a complete solution to anchoring damage. Second, the establishment of baseline pollution levels will allow for the identification of potential pollution-related impacts from the tourism sector to the marine ecosystems and will foster the adoption of management measures by policy makers to reduce pollution levels. Third, the co-creation of a diving Best Practices Toolkit aimed at tourists and naturalist guides, and capacity building of marine tourism stakeholders and the community in good environmental tourism practices, marine sites interpretation, conservation and the role of marine ecosystem services in the benefits for the society, are expected to significantly increase the adoption of best practices in diving and marine tourism at large and to decrease current impacting behaviours, increasing the resilience of the rocky and coral reefs. Fourth, the monitoring of diving sites to identify and map fragile species and habitats and to determine impacting thresholds will provide the necessary information to guarantee a correct management of the sites and diving tourism practices to ensure a more sustainable and managed marine tourism activity by the reduction of its impacts. To this end, the inclusion of the tourism sector and other stakeholders as citizen scientists in the ecological monitoring of the sites aided by the use of artificial intelligence to be able to process the large volumes of information gathered using technological resources, has the potential to revolutionize the way marine monitoring has been performed in the Galapagos. Finally, policy makers will have access to the information generated in this EBA through a Decision Support System. This system will facilitate and guide management decisions based on empirical information. The implementation of the intervention will ultimately have a substantial and long-lasting impact on the resilience of the GMR and its key reef habitats and the ecological sustainability of tourism practices.

Impact on the resilience of Galapagos livelihoods:

Galapagos is known for being one of the best conserved and managed tropical archipelagos in the world. Indeed, its main livelihoods, nature-based tourism and artisanal fisheries are totally dependent on ecosystem services. The maintenance of these services depends on their conservation and resilience to global impacts such as climate change as well as local pressures such as direct damage to the ecosystems and pollution. By promoting low-impact tourism practices and the recuperation of the most impacted and fragile areas, the resilience of marine ecosystems will be increased, ensuring that healthy and highly diverse habitats will better resist climate change impacts. At the same time, healthy reefs are more productive and can keep providing the ecosystem services to which nature-based tourism and the fisheries depend.

The recent COVID-19 pandemic showed the overwhelming contribution of tourism to the local economy in the Galapagos and makes it difficult to find, in the short term, other economic activity that takes over the role of tourism as driver of the economy. As the tourism sector has strong backward linkages with other sectors of the Galapagos economy, when tourism grows, it buys inputs from other economic sectors, such as the artisanal fisheries and agricultural sectors, propelling the growth of these. Thus, a well promoted, well managed, nature-based and conservation focused tourism sector will have many social benefits to the local economies and a considerable contribution to nation-wide economies. In this regard, the intervention includes the development of 360º promotional videos of the main diving sites that include best practices messages. The objectives are twofold, first promote diving tourism in the Galapagos as a destination with high conservation standards, especially aimed at local diving agencies which have less capacities than live aboard operations; and second, send a message to potential tourists that diving tourism in the Galapagos is responsible, allied to conservation and dependent on the ecosystem services provided by nature.

Implementing adaptation policy can become a bottleneck where resources are limited. Therefore, the private sector (such as tourism) should be considered as part of an EBA strategy and incentivized to be involved in adaptation measures. This EBA includes a big component in the co-creation of best practices and the promotion of discussion spaces which allows for the involvement of all stakeholders since the beginning of the implementation. The social benefits will be the shared responsibility, active involvement, and appropriation of the stakeholders in the future of nature-based tourism in the Galapagos. This desired outcome is opposed to a reactive behaviour resulting from the imposition of rules from the policy makers. This would avoid repeating the negative outcome from the fixed-mooring buoys project carried out in the past, which failed at being inclusive with stakeholders.

In addition, the intervention has a strong component of capacity building of the stakeholders and general community outreach. This will play an important role and contribution of the project to conservation education and promotion but will also have lasting benefits to the people involved in its citizen science component. Capacity building in ecological monitoring using a highly technological set up will constitute transferable skills and knowledge beyond the scope of this project and nature-based tourism, largely impacting the local community.

Our intervention aims to build resilience in the tourism sector through promoting cooperation, dialogue, formulating innovative strategies to increase environmental value and prevent unsustainable tourism practices. Ultimately, the coordination of EBA activities, from planning through to implementation and monitoring, across different levels of government, and with different sectors and actors, will be needed to achieve the objectives of adaptation.

Thanks to the implementation of the EBA the resilience of the Galapagos system will be enhanced. The intervention will promote best practices in diving tourism that will reduce the impacts from the tourism activity in the GMR and establish the pollutants baseline associated to the tourism activity. This program can provide important inputs and support to the SIMAVIS GNP tourism management program in relation to marine tourism management. Currently the SIMAVIS does not have identified the marine tourist site use impacts thresholds. The implementation of this EBA will provide a better understanding of the impact thresholds according to different use intensities of the sites. Thus, this EBA will provide important contributions to GNP's SIMAVIS that will eventually be translated to management towards a more resilient marine tourism. The monitoring of the sites will allow for micro zoning schemes to be developed, which, in combination to use regulations and best practices, will guide policy making. In addition, alternatives to traditional anchoring will be evaluated for the first time, establishing the ground for future, low-impact marine tourism in the Galapagos.

5.3.5 Description of the species that make up the module.

Emphasis will be posed to (1) fragile benthic sessile species found at visitor sites, e.g. reef-building corals (mainly species of *Pocillopora, Pavona* and *Porites*) and non-reef building corals (Tubastraea), black corals, gorgonians, hydroids, sponges, sea anemones, zoantids and ascidians; (2) focal fish species, i.e fish species targeted by the artisanal fisheries like groupers, snappers, scorpion fish, whitspotted sand bass, tuna, wahoo and other big pelagic species, and ecologically important fish like cleaners; (3) important megafauna for tourism and ecological processes like sharks, dolphins, rays, mantas, sea-lions, penguins, flightless cormorants, green sea turtles, marine iguanas); and (4) mobile macroinvertebrates with ecological and fisheries importance, i.e. sea-urchins, sea-stars, sea-cucumbers, lobsters, gasteropods and octopus.

5.3.6 Technologies to be promoted through the module.

The module promotes the use of technology as an asset to achieve its goals. Technologies promoted include the pilot use Dynamic Positioning Systems (DPS) for a selected number of live aboard cruises to test its viability as an alternative to anchoring in the Galapagos; the use of drones, ROVs, GPS, SONAR and satellite imagery to aid in the high resolution mapping and characterisation of visitor sites; 3-D mapping by means of photogrammetry techniques through digital underwater photography, also used for ground-truthing; the use of deep learning to aid in the annotation and processing of large amounts of photographic and video graphic output from citizen science-aided monitoring; the use of tablets to perform surveys; 3-D videography of the visitor sites as a means of community engagement, outreach and marine tourism best practices promotion; the technological development of a data shuttle device to retrieve temperature data underwater from the loggers; multi-parameter instruments and temperature, salinity, pH, dissolved oxygen, chlorophyll loggers; the use of dashboards and a decision support system to analyse, visualize, evaluate, and share information with policy-makers and to engage with marine tourism stakeholders; and the creation of graphic content (video, photo, design) as part of the Best Practices Toolkit.

5.4. <u>EBA measure 4.</u> Improve surveillance and control measures to promote adequate green sea turtle nesting and foraging sites in the GMR.

TARGET INDICATORS	
At the end of the project, more than 7000 nests at two main nesting beaches will be protected of the effects of flooding due to climate change	
At the end of this project, more than 10.000 green sea turtles arriving at the three main nesting sites will be protected from boat collisions	
At the end of this project, more than 1.000 green sea turtles present at more important feeding grounds that represent iconic touristic will be protected from boat collisions	
BENEFICIARIES	
Direct	80% technical staff members of the Marine Department of the GNPD will be trained on techniques of nests handling and translocation. 80% technical staff members of the Marine Department of the GNPD will be trained on techniques of sea turtles tracking. 80% technical staff members of the Marine Department of the GNPD will be trained on techniques of monitoring beach profile and flooding changes. 100% technical staff members of the Control and Surveillance of the GNPD will be trained to monitor the compliance of the approved marine traffic regulations, adopted by the GNPD. 40% technical staff of the Ecuadorian Navy will be trained to monitor the compliance of the approved marine traffic regulations, adopted by the GNPD. 50% of technical staff members of the Sub-secretariat of Ports and Maritime and River Transport will be participating in workshops to discuss new marine traffic regulations. 50% of technical staff members of the Ministry of Tourism will be participate in workshops to discuss new marine traffic regulations. 50% of technical staff members of the Tourism and Recreation Department of the GNPD will be participate in workshops to discuss new marine traffic regulations. 40% technical staff members of the Galapagos Governing Council will receive scientific information related to boat strikes on sea turtles and strategies to avoid collisions in order to create new marine traffic regulations.
Indirect	100% active tourist operators with diving and other activities in the GMR are trained in how to compliance new marine regulations.

	100% Galapagos active Naturalist and Dive guides are trained in how to compliance new marine regulations. 100% small-scale active fishermen are trained in how to compliance new marine regulations 100% local schools are involved in outreach activities to learn the importance of protecting sea turtles from climate change and anthropogenic impacts

Logic Framework for EBA 4

Activity	Sub-activity	Deliverables
4. Improve surveillance and control measures for adequate sea turtle nesting and foraging in the GMR, to counteract potential effects of climate change in their reproductive success.	4.1 Translocation of nests from current flooding areas to safer zones.	4.1.1. Three models including maps of main nesting beaches that include the areas with the lowest risk of flooding and erosion ("safer zones) with their thermal conditions and density of nests per/zone per beach. 4.1.2. One protocol for handling and translocation of nest site-specific for different nesting beaches of Galapagos 4.1.3. One assessment of hatching and emergence success at beaches where nest's translocation protocols are implemented 4.1.4. One sex-ratio of hatchling production assessment per site, where nest translocation is implemented
	4.2 Design and implement marine traffic regulations to avoid boat strikes at nesting and foraging sites	4.2.1. At least three new simulations using the collision risk model updated to include key areas where male green turtles are present. 4.2.2. One detailed map highlighting overlapping zones of sea turtle movements around feeding areas and marine traffic.

		4.2.3. One technical document detailing regulations proposal to avoid boat strikes in turtle nesting and feeding sites, developed by the GNPD with the participation of stakeholders. 4.2.4. Proposal of control mechanisms to monitor the compliance of the approved marine traffic regulations, adopted by the GNPD. 4.2.5. Outreach material and activities to increasing awareness of compliance with the new marine regulation.
	4.3. Monitoring the impact of climate change on Galapagos sea turtles and the effectiveness of adaptation measurements applied	4.3.1. One full assessment of four sea turtle's feeding sites of the archipelago, including turtle abundance, sex-ratios, feeding habitat conditions and boat strikes incidence. 4.3.2. Assessment of the thermal condition during the incubation period of at least two beaches, that could present a different thermal range that current monitored beaches.

5.4.1 Description of the current situation and baseline

Climate change is expected to impact sea turtles (Hawkes et al 2007; Mazaris et al 2008; Poloczanska et al 2009, Fuentes et al 2012) as environmental temperature plays a crucial role in the sex determination of hatchlings. The increase in temperature during the incubation period results in a female-skewed sex ratio (Yntema and Mrosovsky 1982; Glen and Mrosovsky 2004), and high temperatures can ultimately lead to egg mortality (Tomillo & Spotila 2020). This effect has already been reported in several species and populations around the world, with nesting beaches increasingly producing a major proportion of females (Broderick et al 2000, Godley et al 2001, Jensen et al. 2018). The effects of climate change also affect reproductive success, due to the intensification of climatic events such as hurricanes and tidal waves, that provoke extreme flooding and erosion of the nesting habitat leading to the corresponding loss of nests. Projections suggest this situation is expected to worsen with sea-level rise (Gill et al. 2005; Calvillo et al. 2015).

Galapagos is one of the most important nesting areas for the East Pacific (EP) green turtle (*Chelonia mydas*). Nesting of green turtles occurs on more than a hundred beaches in the archipelago located on several islands influenced by different ocean currents (Pritchard 1975, CDF database 2020). Four of these nesting sites are considered index beaches and have been monitored to understand the nesting trends for green turtles of the Galapagos islands. Quinta Playa in Southern Isabela Island, monitored since 2002, is one of the most utilized turtle nesting beaches in the archipelago (with ~2000-3000 nests per year) and located approximately 15 km from the populated area of Puerto Villamil. The beach area of Quinta Playa is currently a protected site without public access; however, the marine zone has intense traffic as it is open to local fishers and tourists, the latter arriving on speed boat to a feeding and resting site located west of Quinta playa (Parra *et al* 2013). At Las Bachas, a beach in northern Santa Cruz Island, approximately 400 ~ 500 nests are laid every season. This beach has the peculiarity of being a tourist destination, visited by more than 100 tourists per day potentially disturbing nesting turtles and trampling nests. This beach is a good example of the many other secondary nesting sites throughout the GMR where there is overlap between sea turtles and human use due to the easy landing on the beaches.

Effects of climate change such as sea-level rise, strengthening of storms and tides significantly increase the risk of flooding at coastal areas (Muis et al. 2020). These effects threaten sea turtles that depend on coastal areas, more specifically sandy beaches, to lay their eggs and maintain population levels (Limpus et al., 2020). A study conducted at the main nesting beach for the green turtle in the Eastern Pacific (EP) predicted that a sea-level rise of 5 m, would lead to the loss of 54% of the nesting beach, resulting in a decrease in nesting success (Calvillo et al 2015). The effect of waves, especially during spring tides, has been observed in main Galapagos green turtles nesting beaches. A pilot study conducted during 2012-13 nesting season at Quinta Playa, revealed that the beach profile changed in elevation and width during January to May, period that correspond with the nesting season of green turtles in the archipelago. Some areas of the beach are eroded during spring tides, causing a setback of the beach in a range of 2 to 9 meters and increasing the angle of the slope (Fig. 13a & b). On the other hand, another area of the beach showed a different dynamic. Here, the tides deposit sediments, increasing the width of the beach by 10 meters and the elevation or height of the dune by 0.65 meters, producing mortality of the nests deposited in that area due to over-burial, which reduces the passage of oxygen from the environment to the interior of the eggs (Fig. 13c). During that nesting season, 30% of the nests (n=702) were in the berm zone of the beach (Parra et al, unpublished data). Nests located in this risky zone were vulnerable to flooding events and erosion during high tides, especially spring tides and to over-burying in areas where the tide deposited more sediment.

Sex-determination in sea turtles depends on the temperature of incubation (Spotila et at 1987). Recently, researchers have been combining data from green turtles feeding grounds with data from beaches from the Great Barrier Reef area, which hosts the largest green turtle population in the world and in Australia. The study has revealed that beaches from the Great Barrier Reef have been producing primarily females for more than two decades. The proportion of females at the studied sites is currently prominent, and that the complete feminization of this population is possible in the near future (Jensen et al. 2018). The last assessment to understand the sex composition of Galapagos green sea turtles in four feeding sites, revealed that females are more abundant than males at the proportion of 1:7 (males/females) (Zarate & Carrion 2007). However, only 2% of the monitored turtles could be classified as male or female since marine turtles do not display sexually dimorphic external characteristics until adulthood and the majority of the turtles monitored at feeding sites corresponded to juveniles (Fuentes et al 2017). Seminoff et al (2008) described the green turtle nesting colony as partially resident in the GMR, meaning that, despite being a migratory species, part of the nesting colony stays within the GMR at feeding sites all round year. According to this and considering sea turtle philopatry behaviour (hypothesis that turtles return to beaches in their natal region during breeding seasons as adults), it could be inferred, from the sex ratios of turtle at feeding sites in Galápagos, that the nesting beaches of the archipelago could be producing more proportion of females.

Despite strict protection in the National Park and Marine Reserve, several important threats to sea turtles remain. Feral cats feed on hatchlings, illegal long line and gill net fisheries in the Marine Reserve can cause high levels of by-catch mortality (40% of strandings in 2009/10 were due to fisheries (Zárate 2009). The high connectivity of Galapagos green turtles to feeding areas without any legal protection throughout Central and South America leaves them at risk of by-catch and intentional harvest (Nichols, 2003, Koch et al. 2006, Seminoff et al. 2008). Finally, evidence of increased seasonal oceanographic extremes in the Galapagos El Niño Southern Oscillation region (analysis of temperatures 1965-2010; Banks et al. 2011) may have repercussions upon food availability, nesting behaviours, nesting habitat structure and possibly hatchling gender ratios (Hawkes et al. 2007).

Nature-based tourism is an important economic activity for exploiting wildlife resources in a non-consumptive way under a wildlife-oriented recreation scheme that can help the conservation of wildlife and ecosystems when well managed (Wilson and Tisdell 2001). However, disturbance of wildlife by touristic activities has become a major concern in the last decades, due to the substantial and fast increase of recreational activities, especially in marine protected areas (Monti et al., 2018). Nature-based tourism in Galapagos is done either on-board, where visitors spend their visit on a cruise ship on established itineraries around the islands, or on-land, where visitors stay in accommodation on one of the islands and visit the others on daily tours. The 50% increase in tourist numbers in the Galapagos Archipelago in the last decade (Dirección del Parque Nacional Galápagos & Observatorio de Turismo 2018) is due to an increase in on land visitors (Dirección del Parque Nacional Galápagos & Observatorio de Turismo 2018), with only 32% of the tourism now cruise ship based. The increase in daily tours, island hoping, diving and snorkelling tours have resulted in a rise in marine traffic (Dirección del Parque Nacional Galápagos & Observatorio de Turismo 2016), mainly from small speedboats, which increase the likelihood of lethal boat strikes and exposure to sub-lethal stressors such as underwater noise pollution.

Injuries from boat strikes have been observed in more than 19% of sea turtles at some feeding areas close to ports throughout the Galapagos (Denkinger, *et al*. 2013). Likewise, an initial assessment of mortality events between 2002 and 2008 showed that 20.8% of the dead turtles found (n=120) at monitored nesting and feeding grounds were attributed to boat strikes (Zárate 2009). In a follow up study, Parra *et al*. (2011) recorded 53 stranded green turtles on the main two nesting beaches during the 2009-2010 breeding season, of which 13% of the mortalities were due to boat strikes. Given that most dead sea turtles will not wash ashore, it is likely that boat-strike mortalities are actually far higher than is reported, changing the nature of the problem from the welfare of individuals, to an emergent population level threat.

From 2000 to 2015, the Charles Darwin Foundation (CDF) established and maintained a nesting monitoring program of green turtles in the main nesting beaches of the Galapagos. This allowed us to monitor the abundance of nesting females to assess, in the long term, the population trend for green turtles in the Eastern Tropical Pacific. From 2009 to 2015 CDF shared skills and expertise with the Galapagos National Park for them to be able to run the nesting monitoring directly (which is conducted by the GNP to the present), while in parallel, CDF started to focus on the main threat to sea turtles within the Galapagos Marine Reserve, as boat strike incidence previously described. Currently CDF in collaboration with the GNP and Queen's University Belfast, is working in produce a scientific tool, a collision risk model, which will be used to simulate different management measures that could be applied within the GMR to avoid boat collision on sea turtles. In the first instance, the model will be tested using data gathered from one nesting beach, but it can be fed with data collected from different zones of the archipelago, to simulate different management measures or marine traffic regulation, applicable to different zones of the GMR (more details in section 5.3.3.)

Additionally, four foraging grounds were monitored by the CDF between December 2000 and December 2008, which has allowed us to identify species present, determination of their population abundance, size structure and growth rates, the evaluation of health status and movement patterns at different levels, assess the hatching and emergence success, describe habitat conditions and the early identification of threats coming from non-climatic stressors that could affect the population resilience. The monitoring and research on marine turtles over the last decades have helped us to understand population trends and identity non-climatic stressors. Here we propose to support the GNP to design management plans and apply adaptation measures to climate change to protect sea turtles at nesting and feeding sites. At nesting beaches, adaptation measures will lead to protect nests from climate change effects such as habitat loss (flooding and erosion of beach) to increase hatching and emergence success. Management plans at feeding sites, will be addressed to protect sea turtles at marine areas to avoid sea turtle mortality related with anthropogenic activities (e.g. marine traffic). We expect that by increasing the protection of both, nests and adults, resilience to climate change of Galapagos sea turtle population will increase, ensuring its long-term conservation.

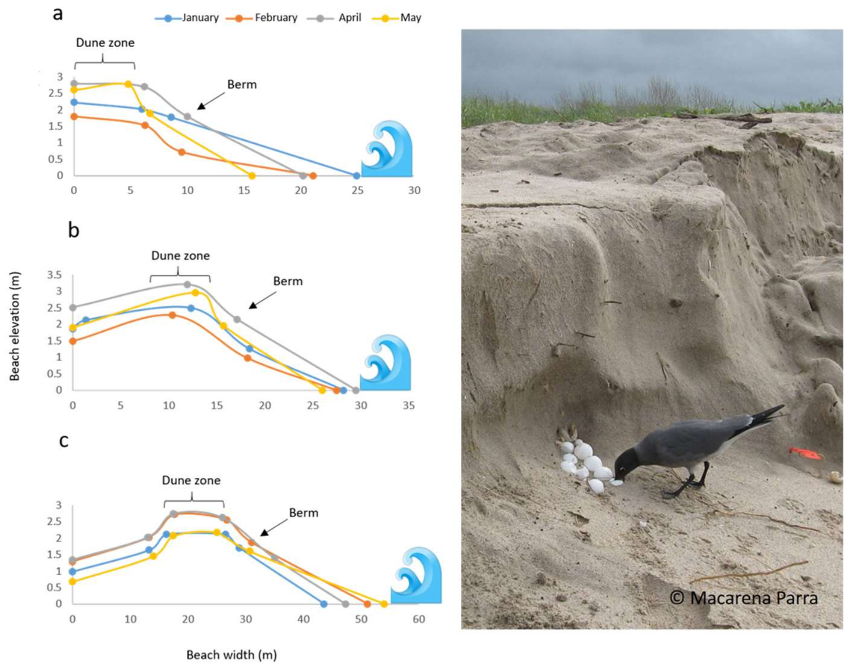

Figure 13. Beach profiles of three different areas (a, b and c) of Quinta Playa beach (Isabela Island), during the nesting season of green turtle, season 2012-13.

5.4.2 Objective and justification of the proposed module

The main objective of this module is to apply mitigation strategies to alleviate climate change impacts on the population of green turtles in Galapagos, by protecting their nests from direct impacts of climate change and reducing other threats of anthropogenic origin that increase the vulnerability of the population.

The vulnerability of sea turtles to potential impacts of climate change has alerted researchers, conservationists and decision-makers all around the world to design strategies to alleviate climate change impacts on their populations. These strategies ranging from (1) directly manipulate nests and habitat to reduce site-specific impacts, (2) increasing their resilience by minimizing mortality due anthropogenic impacts, (3) protecting representative samples of their important habitats, and (4) monitor, management and assess to adequate geographic and temporal scales (Esteban et al., 2018; Hamann et al., 2010). This EBA proposes tackle effects of climate change by (1) directly manipulate turtle's nests to protect them from the direct impacts of erosion and flooding at most important nesting sites of the archipelago, (2) reduce sea turtle mortality due to anthropogenic causes, more specifically boat strikes, and (3) monitor and assess key habitats within the GMR in order to assess the success of the measurements applied.

The proportion of monitored nests at Galapagos nesting beaches affected by wave action and flooding increased from 1.6% during nesting seasons 2002 – 2007 (Zarate et al 2013) to 8.94% during the period 2009 – 2013 (Parra, unpublished data). It is important to highlight, that this number of affected nests correspond to monitored nests and not to the total number of nests laid per season/beach. As was mentioned in the previous section, the total number of nests located in the flooding zone is higher. The reason for this difference is explained for the fact that only a sample of nests laid per season, randomly distributed in different areas and zones of the beach is tagged and monitored. This protocol has been applied due to the density of nests in some areas is high then the presence of tags in the nesting area represents obstacles to the nesting females seeking for a site to dig the nest and laid the eggs. Concerning current nests loss, measures can be applied to protect nests located in flooding areas of the beach, by translocating them to areas and zones less exposed to tide effects. To reach this, is crucial to implement a systematic methodology to measure the beach profile, to identify currently safer areas within the beaches that can be used for translocation. It is also important to produce data that can be used in advanced modelling to quantify long term nesting habitat loss under extreme scenarios of sea-level rise that could require more drastic interventions. Additionally, consider the thermal conditions of the nesting beaches will be crucial when designing protocols of nests intervention, to avoid sex-ratio biased of nests translocated.

Current sea turtle species have been adapted to historical climate change events that occurred at geological level. However, current acceleration of climate change process due to the human activities and their impacts, change turtles habitats and their environmental conditions at faster rates than species can adapt (Esteban et al., 2018). In addition to changes in their habitats, direct impacts of human activities on sea turtles such a bycatch, direct hunting, collection of eggs and boat strikes, make population more vulnerable to climate change (Hamann et al., 2010). Therefore, this EBA will address the boat strikes issue reported in Galapagos (Denkinger et al. 2013; Parra et al. 2013; Zarate 2009), by supporting the GNP authorities and the Galapagos Governing Council to design and implement management measurements to reduce sea turtle mortality within the GMR due to boat strikes. By reducing this direct anthropogenic impact, we expect to increase sea turtle population resilience at local and regional due the migratory condition of the species.

Additionally, after 13 years we need to re-assess the feeding sites to detect changes in the sex-ratio composition, identify which sites present a major proportion of males and to extreme protection measures in these sites in order to conserve the male sea turtle population. A constant shortage of males prolonged in time has the potential to eventually cause population extinction, therefore it is crucial to improve conservation efforts to this part of the population at different levels of their life state to ensure a sufficient number of males to maintain populations (Hays et al 2010, Blechschmidt et al 2020). Considering that Galapagos represent the second most important site for the green turtle of the EP, is urgent to understand how climate change is affecting the stability of green turtle key habitat within the GMR as well as the sex ratio of its population to design strategies of conservation and climate change adaptation to assure the conservation of the species at local and regional level.

Sea turtles provide invaluable ecosystem services and by conserving sea turtles, we ensure ecosystem health that is important for local population livelihoods, that directly depend on the ecosystem services obtained through artisanal fisheries and more significantly thought tourism activities. (see section 5.3.8 for full details). For example, sea turtles are important in the trophic chain, as a prey at various life history stages (Heithaus 2013). In the Galapagos the nesting beaches are important food resource of native species ranging from small invertebrates such as beetles (*Omorgus suberosus*) and ghost crabs (*Ocypode gaudichaudii*) (Zarate et al 2013), to native seabirds such as frigates (*Fregata minor*, *F. magnificens*), herons (*Ardea herodias*, *Nyctanassa violacea*), gulls (*Larus fuliginosus, Larus pipixcan*) feeding on eggs and emerging hatchlings (Figure 13) (Zarate 2009) and top predators including tiger sharks (*Galeocerdo cuvier*) which feed on juveniles and adults specially during the breeding season (Acuña et al 2017). Under this context, given the important ecological role of sea turtles, their protection and conservation within the GMR, it is important to enhance the resilience of key ecosystems of the archipelago such as sandy beaches and coastal ecosystems used by the turtles at nesting and feeding areas during their different life stages.

5.4.3 Description of sub-activities and outputs

Sub activity 4.1: Translocation of nests from current flooding areas to safer zones.

Beach profiles models will be built to simulate flooding and nesting habitat loss under different scenarios of sea-level rise to identify safe zones of beaches to translocate turtles' nests from flooding and erosion areas. Using unnamed aerial vehicles beach profiles will be measured periodically during the nesting season at three main nesting sites Quinta Playa, Bahia Barahona and Las Bachas. The beach profiles will be used to determine the current dynamic of beach erosion within the nesting season and in consequence the nests loss. Furthermore, following the methodology described by Varela et al (2018) and Drews & Fonseca (2009) that combines beach profiles and oceanographic data we will produce a model to simulate nesting habitat loss and flooding events under different future sea-level rises scenarios. The model will include nesting beach profiles and nests locations to calculate percentages of nests loss because of flooding and erosion.

The model will be used not only to identify flooding and erosion zones but also to identify zones of the beaches more stable that can be consider safer zones to translocate nests coming from the flooding zones. Once the model is finished, the project will work with the Galapagos National Park to define a certain range of nests loss that can be used as a trigger to start implementing protocols of massive translocation of nests from vulnerable zones to safer areas within the same beach.

Successful nests translocation involves choosing zones of the nesting beach that do not experiment drastic erosion or flooding events within the nesting season, but also is needed to identify areas of the beach with favourable thermal conditions. Here, two main criteria will be used to define areas with favourable thermal conditions. (1) areas of the beach where the temperature of the sand remains below temperature ranges that are lethal for turtle eggs and embryos of 33°-35°C (Howard et al (2014) and Bladow et al (2019)), and (2) areas of the beach that do not induce biased male or female hatchling production.

For this purpose, temperature data loggers will be deployed inside nests at different areas of the three main nesting beaches of the archipelago (Quinta Playa, Bahia Barahona and Las Bachas). Data gathered from Galapagos nesting beaches, will be compared with available data of pivotal temperatures (the incubation temperature that produces 50/50 sex ratio) for other green turtle populations as a reference, to estimate sex ratios of the hatchling produced in the currently nesting beaches monitored in Galapagos.

With the information generated, in combination with data of location of nests collected during the nesting monitoring performed by the Galapagos National Park, the project will produce maps of the nesting beaches that include the areas with the lowest risk of flooding and erosion ("safer zones) with their thermal conditions and density of nests per/zone per beach. Finally, these maps will be used to define zones to translocate nests that need to be moved from flooding and erosion areas.

Once safer zones within the monitored nesting beaches have been identified, a capacity building program will be implemented to strengthen the GNPD in techniques and methodologies of nests handling and translocations. The first translocation activity will take place in at least one nesting beach selected by the GNPD. Nests translocated will be permanently monitored until hatchlings emergence occurs. After emergence, following the current nesting monitoring protocol (Parra 2013), nests will be exhumed to calculate hatching and emergence success. Nests translocation will be considered successful when hatching and emergence success remain within the reported ranges for Galapagos of 46.0 ± 33.4 and 45.6 ± 33.4%, respectively (Zarate et al 2013). Additionally, temperature data loggers will be deployed inside of translocated nests to determine their sex-ratio of the hatchlings produced.

The following outputs are expected at the end of this sub activity:

- Maps of the nesting beaches that include the areas with the lowest risk of flooding and erosion ("safer zones) with their thermal conditions and density of nests per/zone per beach.
- Capacity building program implemented to strengthen the GNPD in techniques and methodologies of nests handling and translocations.
- Translocation in at least one nesting beach selected by the GNPD, implemented.
- Monitoring system for translocation effects and impacts, implemented.

Sub activity 4.2: Design and impleme0nt marine traffic regulations to avoid boat strikes at nesting and foraging sites.

As have been mentioned previously in this document, boat strikes represent a serious threat for sea turtles within the GMR, due to the overlap of key green turtles' habitat (feeding and nesting sites) and current marine routes used mainly for touristic activities. Currently CDF in partnership with the GNP and other collaborators are working to collect the scientific evidence that can inform management plans to mitigate this issue. We will implement a collision risk model based on the distribution and at surface behaviours of nesting females combined with data from the vessel monitoring system (VMS) and automatic identification system (AIS) managed by the GNP, to simulate different scenarios of marine traffic regulation.

By combining these sources of information, we will simulate the following scenarios:

1) At present rates of travel (recorded by VMS and AIS) what are the likely rates of sea turtle boat strikes over a diel period at Las Bachas (nesting site).
2) By manipulating boat speeds (but maintaining existing routes) is it possible to identify a given speed whereby boat strikes reach a minimum asymptote (akin to speed limits on land). In this simulation we will assume that boat captains are not taking evasive action, but that at a boat speed of <4 knots sea turtles are able to detect vessels and dive to avoid collision (following Hazel et al. 2007).
3) Based on the sea turtle surface abundance and distribution data from the drone surveys at Las Bachas, we will determine the collision risk for alternative boat routes through these sensitive habitats.

In complement, during the project the implementation phase of the model will take place, which involves workshops with the GNP and other local stakeholders. During these workshops, different marine traffic regulation scenarios will be presented, to discus and ultimately decide which regulation will be the most feasible and applicable for the GMR.

The collision risk model is currently based on nesting females of green turtles, but under a scenario of climate change, it would be crucial to gather some essential data from male turtles, such as movement and distribution within the GMR, to address the marine regulations not only where nesting females are present but also where males aggregate. Therefore, we propose to deploy satellite transmitters with depth sensors built-in, in at least ten male green turtles, during the nesting season to track their movement, to determine their time spent at the surface and know their post-reproductive season migration. This information will be incorporated in the model to assure that marine traffic regulations include key areas where male green turtles are present.

To design marine traffic regulation to avoid collision at feeding sites, data from main feeding sites will be collected to feed the collision risk model with information from key habitats. For this purpose, we will assess four feeding sites. The assessment of these feeding sites will provide data of turtle abundance, sex-ratios, and feeding habitat conditions. This information combined with data from distribution and movement of sea turtles, that will be collected by tracking at least ten individuals from feeding sites, we be will used to identify sea turtles' corridors between different feeding and resting sites. Integrating these results with AIS and VMS data provided by the GNP, it will be possible assess overlaps between marine traffic routes, touristic and fishing sites, and sea turtles' corridors, and to identify zones where marine traffic regulations are needed. Additionally, as males become invaluable objects of conservation to assure the stability of the population under climate change scenarios, feeding sites and marine corridors with major presence of males will be priority areas to implement marine traffic regulations.

The project will provide technical support to the GNP to present the formal request of a new marine traffic regulation at near marine areas to nesting beaches, to the Galapagos Governing Council (Consejo de Gobierno para el Regimen Especial de Galapagos, Spanish name). The Galapagos Council is the institution of promulgating this type of regulations in the archipelago, in coordination with the Sub-secretariat of Ports and Maritime and River Transport (Subsecretaria de Puertos y Transporte Marítimo y Fluvial, Spanish name) and the GNP. This support includes participation and discussion with fishers and the tourism sector for the preparation and presentation of a technical feasibility document for the Galapagos Governing Council, justifying the need of a marine traffic regulations, including a list of suggested regulations to avoid boat strikes on sea turtles. Accompany the GNPD and GGC in the discussions, additional consultations, and verification until the final emission of regulations.

Finally, the project will support the GNPD to design and implement control mechanisms to monitor the compliance of the approved marine traffic regulations. This will be accompanied by outreach activities aimed at involving the local community in sea turtle conservation and increasing awareness of compliance with the new marine regulation.

The following outputs are expected at the end of this sub activity:

- Collision risk model improved to include key areas where male green turtles are present.
- Regulations proposal to avoid boat strikes in turtle nesting and feeding sites, developed by the GNPD with the participation of stakeholders.
- Regulations to avoid boat strikes in turtle nesting and feeding sites, approved by the GGC.
- Control mechanisms to monitor the compliance of the approved marine traffic regulations, adopted by the GNPD.
- Outreach material and activities to increasing awareness of compliance with the new marine regulation.

Sub activity 4.3: Monitoring the impact of climate change on Galapagos sea turtles and the effectiveness of adaptation measurements applied

Conduct monitoring of green turtle feeding sites

Sexual dimorphism in sea turtles is only evident on adults. The last assessment was done in 2008 in main four feeding sites for green turtles in Galapagos and revealed a major proportion of females, but with a considerable number of juveniles that at that time could not be classified as male or females. After 12 years, these juveniles should have now reached the size and age to be distinguished as a male or female and a re-assessment of the sexual structure can be conducted. The results from this activity will inform adaptation measures to climate change, for example, if a trend to feminization of sea turtles is observed at feeding sites, the temperature of nests could be manipulated. This assessment will also provide an update on the boat strike incidence on sea turtles at feeding sites. Annual monitoring of the feeding sites will help to monitor the success of the implementation of marine traffic regulation, which is expected to lower injury and mortality to sea turtles from boat strikes.

Monitor incubation temperatures in others nesting beaches of the archipelago

Green sea turtles nest in more than hundred beaches, located on different islands, influenced by different currents and with different type of vegetation (Pritchard 1975, Parra et al. 2013). Therefore, temperature data loggers will be used to monitor sand temperature during the nesting season in two beaches with a potentially different thermal condition. The first one is “Caleta Tortuga Negra” (CTN) located west of Isabela Island, in an area influenced by Cromwell current (cold current), and the second is “Espumilla beach” (EB) in

Santiago Island, where the nesting zone is dominated by trees providing shade to the nesting area. These two beaches will be monitored in case there is need to apply extreme protocols of moving nest to other beaches, and improve the protection of that zone of the archipelago, anticipating a female biased production in the current monitored beaches, or high density of nests in the safer zone that could make translocation of nests not viable. It is important to highlight that translocation within the same nesting beach is the priority alternative.

The following outputs are expected at the end of this sub activity:

- One full assessment of four sea turtle's feeding sites of the archipelago, including turtle abundance, sex-ratios, feeding habitat conditions and boat strikes incidence.
- Assessment of the thermal condition during the incubation period of at least two beaches, that could present a different thermal range that current monitored nesting beaches.

5.4.4 Impact on the resilience of the Galapagos system

<u>Impact on the resilience of ecosystems:</u>

With more than 3000 nests of green turtles laid in the main three nesting sites of the Galapagos Islands (monitored sites) (Seminoff, 2004), an annual hatchling production over 120,000 neonates are estimated (Zarate et al. 2007). Besides, green turtle nesting activity has been recorded in more than 100 other beaches around the archipelago (Pritchard, 1975; Zarate 2009b, Parra et al. 2013). Given the importance of Galapagos as a nesting site at regional level, due to the significant contribution of hatchlings to the Eastern Pacific population, this component aims to understand the proportion of hatchlings males that Galapagos beaches are producing and implement protocols to avoid a bias in female production under a climate change scenario. By avoiding sex biases in the hatchling production at nesting sites, the measures proposed here, can contribute to reach a population with sex ratios as balanced as possible, that will assure reproduction in the long term. With implementation of protocols for the protection of nests due extreme flooding and nesting habitat loss due to sea-level rise, proposed in this model, we expect to maintain the hatchling and emergence success (46.0 ± 33.4 and 45.6 ± 33.4%, respectively, Zarate et al. 2013), to assure the hatchling production and contribution with new individuals to the population.

By implementing a marine traffic regulation to avoid boat strikes in key habitat of sea turtles within the GMR, we expect to increase the protection of over 1500 nesting females that arrive annually to the main nesting beaches. By improving protection of nesting females, which can a safely arrive to the beaches to lay the eggs, reproduction season success will increase. Furthermore, by applying marine traffic regulation at feeding sites where there is overlap with marine routes, we expect to see a decrease in the rate of incidence of boat strikes, which is currently 20% at feeding sites near ports (Denkinger et al, 2013), and as consequence a reduction on sea turtle mortality due to anthropogenic activities, especially nesting females, that by laying eggs increase the production of hatchling and therefore the resilience of the population to climate change. Additionally, by understanding the distribution and movement of adult males within the GMR, marine traffic regulation could be intensified in these areas in order to protect a segment of the population extremely important to preserve a healthy sea turtle population in a global warming scenario.

Sea turtles play an important ecological role helping to maintain resilience both terrestrial and marine ecosystems due to their complex life cycle (Heithaus, 2013). Their ecological services begin in their reproductive habitats, the nesting beaches, whereby laying the eggs, they move important amount of organic material, nitrogen, phosphorus, calcium carbonate, and energy from the ocean to the beaches, crucial in environments like islands, as the Galapagos, where the health of terrestrial systems decisively depends on ocean-land exchanges (Bjorndal, 2003). This contribution of nutrients to the beaches promotes the growth of vegetation needed for the stability of beach by protecting the beach from erosion, which is crucial to maintain the habitats of many other organisms, as many macros as microscopic (Madden et al. 2008, Bouchard and Bjorndal, 2000; Hannan et al. 2007).

Nutrients coming from the nesting of turtles in beaches of the Galapagos benefits the native and endemic vegetation such as mangroves including buttonwood (*Conocarpus erectus*), black (*Avicennia germinanswhite*), white (*Laguncularia racemosa*) and red mangroves (*Rhizophora mangle*) (Zarate et al. 2013). Mangrove ecosystems in Galapagos serve as crucial habitats for some land birds species including the critically endangered Mangrove Finch (*Camarhynchus heliobates*) that is a habitat specialist restricted to mangroves (Feels et al 2011).The dune vegetation of the green turtles nesting beaches consist of sea purslane (*Sesuvium portulacastrum*), beach morning glory (*Ipomoea pescaprae*), saltworts (*Batis maritima*), saltbushes (*Cryptocarpus pyriformis*), sea purslanes, and quail plants (*Heliotropium curassavicum*) (Zarate et al 2013), that provide habitat for several invertebrates and small land birds such as the iconic yellow warbler (*Setophaga petechia*) that feed on seeds and insect present in the coastal vegetation (Guerrero and Tye 2011).

Some studies also show that green turtles help enhance coral reef resilience in their feeding sites by helping maintain low algal cover even foraging on introduced species (Wabnitz et al. 2010). This particular situation has been reported in Galapagos, where green turtles have been observed feeding on a species of invasive algae (*Caulerpa* spp.) in several feeding sites around the GMR (Carrion-Cortez et al 2010). Given that green sea turtles provide important ecosystem services to the habitats they use at different stages of their life, promoting adaptation measurements for sea turtles within the GMR, will maintain the well-functioning of the natural socio-ecosystems of the Galapagos Islands. By protecting key habitats for sea turtles, we can help to reduce their vulnerability to the negative impacts of climate change. Indirectly, several other species depending on sea turtle's ecosystem services will benefit from this, for example those species directly involved in predator-prey interactions with sea turtles. The Galapagos Archipelago is known as a global biodiversity hotspot and is inhabited by several migratory species of cetaceans, sharks and other sea turtle's species coming from different areas of the region. These migratory species depend on Galapagos unique ecosystems during crucial part of their life such as reproductive periods, as a feeding seasons or as an intermediate point during migration between different habitats within the region (Shillinger et al. 2008; Whiteheat et al. 2008; Bessudo et al. 2011; Ketchum et al. 2014; Hearn et al. 2016).

<u>Impact on the resilience of Galapagos livelihoods:</u>

As was described previously, sea turtles play an important ecological role in maintaining ecosystem health. However, the role of the turtles is not limited to the ecological level but also, to ecosystem services that turtles provide which benefit people's livelihoods. For example, by foraging on sea grass and algae, sea turtles contribute to community succession, that is crucial to other species including fisheries resources (Bjorndal and Jackson 2003; Heithaus, 2013; Stadler et al., 2015). In Galapagos, the rocky bottoms and coral reefs where green turtles forage represent the main habitats for fisheries resources such as lobsters, sea cucumbers, cod and other rocky fishes (Banks et al. 2016). Therefore, the prevention of sea turtle mortality due to boat strikes proposed in this EBA, will ensure that sea turtles remain in their role of maintaining the habitat for fisheries species, that are important for the local economy of the archipelago. In addition, green sea turtles in

Galapagos are feeding on a species of invasive algae in several feeding sites around the GMR (*Caulerpa* chemnitzia) (Carrion-Cortez et al 2010), especially at corals reefs of Darwin Island where this species could threaten the health of corals under climate change scenarios (Study case, EBA 5.1). This invasive alga can be associated with warming-related range shifts (Riegl et al., 2019) and causes damage to corals (Keith et al. 2016). In this regard, by mitigating sea turtle mortality through reducing boat strikes within the GMR, the consequential cascade effect through the ecosystem could contribute to the control of this invasive species, directly supporting EBA 5.1 and EBA 5.2.

Worldwide, nature-based tourism is an important economic activity for exploiting wildlife resources in a non-consumptive way under a wildlife-oriented recreation scheme (Wilson and Tisdell 2001). Especially in Galapagos, the local economy mainly depends on nature-based tourism and derived activities such as the artisanal fisheries and local agriculture which provides food security for an increasing resident population (~35,000 inhabitants) and to a large number of visitors that reach over the 200,000 per year in recent years. Tourism in Galapagos constitutes the first productive activity, with 66% contribution to the GDP (according to data from the Ministry of Tourism), and 3,000 families that depend directly on it for their livelihoods (Galapagos National Park 2020, unpublished data).

Sea turtles are the second most sighted species during recreational diving activities within the GMR (DiveStat, Observatorio de Turismo 2021) and are recognized as a key species for tourism (Cardenas et al 2016). Several sea turtles nesting beaches around the archipelago where landing is possible are included in tourist itineraries. Nest protection measures proposed in this EBA will not only help mitigate sea turtle egg and embryo mortality from flooding and erosion due to climate change, but they will also contribute to maintaining beach ecosystems for tourist activities. Combining the importance of sea turtles in the trophic chain with their role in maintaining beach stability (i.e., as ecosystem engineers, for more details see previous section) will safeguard the tropic chain: Sea turtle hatchlings for example are an important prey item for the survival of sea birds that also represent iconic touristic species.

Tourism represents the most important economic activity for the local community and therefore maintaining the ecosystem health of the Galapagos Archipelago is crucial to continue to market this unique and well-conserved ecosystem for tourism and travel. To maintain the socio-economic benefits derived from tourism activities for the residents of the

Archipelago, it is necessary to maintain a high quality of tourism services. Applying regulation to marine traffic within the GMR proposed by this EBA will not only reduce sea turtle mortality (directly protecting a tourist resource) but it will contribute to improving navigation and touristic practices. Currently, speedboats in Galapagos are unregulated, travelling at recorded speeds over 30 knots (Parra 2021, unpublished data) which represents a risk for sea turtles and marine wildlife in general. Similarly, these excessive speeds represent a risk for passengers' safety and could be considered a negative experience for passengers experimenting discomfort during navigation. Furthermore, promoting marine traffic regulations will align with EBA 5.3, to increase the marketing of services supplied by local tourism operators and increase local community livelihoods. Maintaining the economic flow derived from nature-based tourism in the islands has strong repercussions at both the social level and social benefits, which depend on the profits of tourism to improve overall well-being and access to health, housing and education services.

5.4.5 Description of the species that make up the module.

The green turtle (*Chelonia mydas*) has been a species of global concern for decades. It is estimated that worldwide populations have declined 50% - 80% since the 1990's (National Marine Fisheries Service & US Fish and Wildlife Service 1998; Seminoff, 2004). The causes of this decline are harvesting of eggs and adult females at nesting beaches and juveniles and adults in foraging areas, incidental mortality relating to marine fisheries and degradation of marine and nesting habitats (Baillie & Groombridge 1996, Hilton-Taylor 2000, Lewison 2004). The species is therefore listed by IUCN as Endangered (Seminoff 2004; IUCN 2020). The green turtle is the most common and abundant sea turtle species in Galapagos and the only species that nests in the archipelago (Seminoff, 2004; Zarate et al. 2013).

The green turtle life cycle is characterized by their utilization of various habitats and has been described as following: after their eggs hatch, the neonates direct themselves toward the ocean and are passively transported by oceanic currents and gyres. This is perhaps the least understood stage, named by some authors "the lost years." The individuals that reach the juvenile stage will recruit in developed coastal areas, estuaries, and reefs, and when they reach sexual maturity they move to habitats with food for adults, which may or may not overlap with eight different habitats of juveniles. Every two to five years, depending on the population and on the quality of feeding areas, individuals migrate long distances to nesting beaches to reproduce and lay eggs (Carr et al 1978; Meylan and Meylan 2000; Reich et al 2007).

The range of incubation temperature for sea turtles for a successful development of the eggs varies from 25 and 35°C (Ackerman 1997), lower and higher temperatures due to global warming can leads to eggs and embryos mortality (Hawkes et al. 2007; Poloczanska et at 2009). Sex determination in sea turtles depends on incubation temperature (Yntema and Mrosovsky, 1982) and the 'pivotal' temperature for green turtle, at which a 50:50 sex ratio is produced, is around 29°C (Spotila et al 1987; Broderick et al 2000). Due to the role that temperature plays in the sexual determinations of sea turtles' embryos during the incubation process as well as their dependence on a wide variety and interconnected habitats over their complex life cycle, sea turtles are used as flagships species to assess effects of climate change on coastal ecosystems (Hawkes et al 2009; Fish and Drews 2009; Fuentes et al 2012; Jensen et at 2018).

5.4.6 Technologies to be promoted through the module.

Deployment of temperature loggers at nesting and feeding sites: Data loggers will be used to record the incubation temperature in green turtle's nests at key nesting sites (both currently monitored sites and new sites with potential different ranges of sand temperature). Temperature data loggers will also be installed in key green turtle feeding sites to monitor the water temperature at a small geographic scale around the year.

Using Unmanned Aerial Vehicle (UAV) Technology: Using Unmanned Aerial Vehicle (UAV) Technology: UAV will be used to collect digital information of the beach profile, to produce models of the nesting habitat loss at the nesting beaches. The UAV will be also helpful at feeding grounds to get aerial images that allow us to map the algae coverage in shallow waters.

Satellite tracking devices: satellite tags will be used to track the movements and distribution of the most valuable individuals in the population in terms of climate change effects, that is, male green turtles both inside and outside the GMR.

Advanced computational and data analysis technology for model- building: Using new software and computational technology we will build models to assess marine traffic regulations, simulate protocols of translocation the nests versus beach erosion and flooding to select best protocols of nests protection.

Improvement of the boat tracking system of the GNP: Implement new settings or complementary applications to the current boat tracking system to incorporate "warning alerts" when new marine traffic regulations are being infringed.

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