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Restoring Scalesia forests and highland areas of high ecological value to secure environmental services in the face of climate change

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1. SUMMARY

In Galapagos, agricultural practices in the inhabited highlands of Isabela, San Cristóbal, Floreana and Santa Cruz islands since the early 1900s resulted in significant land cover transformation and increased incidence of exotic plant invasion. As a result, the remaining forest fragments of the humid zones across the different islands are disconnected and highly threatened due to the combined effects of exotic species invasions and increased tree mortality because of the augmented frequency of strong ENSO events driven by warmer ocean conditions. Climate change projections suggest that this threat will become more severe as rainfall events increase in frequency and intensity, augmenting hazards on agricultural lands and the local human population.

To mitigate this threat, we need to increase ecosystem resilience and the adaptive capacity of agricultural livelihoods through implementing strategic restoration at a landscape scale, integrating the agricultural and Galapagos National Park areas in a single common vision. Furthermore, there is a pressing need to determine how to best restore these areas and to which aim, considering the synergistic effects of climate change and exotic species invasions.

The proposed intervention seeks to increase the resilience of key terrestrial ecosystems through rehabilitation and restoration approaches, while strengthening the ongoing invasive species control program lead by the Galapagos National Park Directorate. For this, the spread of an invasive plant species (*Psidium guajava*) in the highlands of the inhabited islands of Galapagos was projected under two Representative Concentration Pathways scenarios for 2030. Based on these results and a project intervention alternative that takes into account ongoing restauration efforts and prior knowledge of the Galapagos systems, this program proposes three ecosystem-based Adaptation Measures to increase the resilience capacity of the ecosystems of the humid highlands of the inhabited islands of the Galapagos Archipelago. First, we will strengthen control programs for invasive plant species, especially blackberry, in protected and agricultural areas, based on projected dynamics of their expansion under climate change scenarios. Second, we will restore key remnant forest fragments in protected and agricultural areas to enhance ecosystems adaptive capacity and

provision of environmental services. Finally, we will establish a monitoring program to assess the success and impacts of invasive species control and restoration measures on the resilience and recovery of the key terrestrial ecosystems.

As a result of the implementation of the proposed adaptation measures, this program will: (1) Restore 1500 ha of Scalesia forest in the highlands of Santa Cruz, Isabela and San Cristóbal, (2) Increase the connectivity of 750 ha of Scalesia forest fragments within the agricultural area, (3) Strengthen the Terrestrial Invasive Species Program of the Galapagos National Park Directorate for long term control under climate change scenarios; (4) Establish economic incentives for farmers to implement restoration actions; (5) Consolidate a data management and information system to inform restoration measures and control of invasive species; and (6) Prioritize areas of high conservation value for mitigating greenhouse gas emissions.

2. INTRODUCTION

The very me attributes that promoted evolutionary speciation on oceanic islands, like geographic isolation and niche vacancies, leave endemic species on islands highly vulnerable to human impacts. The majority of documented human-driven extinctions have been exacted upon island endemics and reasons for this include land use change and invasive species (Fordman and Brook 2008; Harter et al. 2015). Land transformation, either indirect, through the introduction of invasive species and their subsequent establishment, or direct, through habitat obliteration, is the primary cause of the decline of tropical island biota (Harter et al. 2015). In the Galapagos Islands, agricultural practices in the inhabited highlands of the islands of Isabela, San Cristóbal, Floreana and Santa Cruz since the early 1900s, have resulted in significant land cover transformation and increased incidence of plant invasions (Gardener et al. 2013). For example, the extent of the native forest in the humid zone of Santa Cruz (the forest formed by *Scalesia pedunculata*) is now only 1% (ca. 100 ha) of its historical distribution, due to land use change in the past and more recently, to invasions of non-native plant species (Mauchamp and Atkinson 2010). As a result, the remaining forest fragments of the humid zones across the different islands are disconnected and highly threatened, due to the combined effects of non-native species invasions (Rentería et al. 2012, Rivas-Torres et al. 2018a) and increased mortality of *Scalesia pedunculata* because of augmented frequency and intensity of ENSO events driven by warmer ocean conditions (Itow and Mueller-Dombois 1988, Mauchamp and Atkinson 2010). Furthermore, the encroachment of forest fragments by invasive species is worsened by ENSO events, which increase the forest vulnerability to invasions by plants due to the formation of forest gaps, as a consequence of tree death and excess of rainfall (Trueman et al. 2010). Climate change projections suggest that this threat will become more severe as rainfall events increase in frequency and intensity (Cai et al. 2015).

Forests sequester and store more carbon than any other terrestrial ecosystem and therefore are important to curb adverse effects of climate change (Gibbs et al. 2007). The carbon cycle of forests closely related to the different environmental services and values that forests provide, like biodiversity, carbon sequestration, climate regulation, watershed protection and aesthetic benefits (Herrero and Bravo 2012). However, due to human activities, many forests nowadays are rather carbon sources than carbon sinks (Csillik et al. 2019). In Galapagos, a large proportion of the Galapagos ecosystems, especially the forests, have already been altered, making them less of a carbon sink. Therefore, strategic restoration needs to be implemented at a landscape scale, integrating the agricultural and Galapagos National Park (GNP) areas in a single common vision. Furthermore, it is key to determine how to best restore these areas and to which aim, considering the synergistic effects of climate change and exotic species invasions. Identifying the dynamics of the spread of invasive species, over both agricultural and protected areas in Galapagos, is important to prevent invasions of endangered terrestrial ecosystems and to promote the integration of production and conservation within complex multifunctional landscapes. Control and eradication of invasive species represent one of the most difficult challenges in Galapagos. There are many successful examples of combating introduced species in Galapagos but also many failures (Shackleton et al. 2020, Appendix 2). A better understanding of invasive species distributions and their responses to climate change will provide new ways of understanding invasive species dynamics, which will lead to more effective management programs.

The proposed intervention seeks to increase the resilience of key terrestrial ecosystems through rehabilitation and restoration approaches, while strengthening the ongoing invasive species control program lead by the Galapagos National Park Directorate (GNPD). In the following sections, a case study is presented, in which climatic and biological variables are used to estimate the spread of an invasive plant species (*Psidium guajava*) in the highlands of the inhabited islands of Galapagos under different climate change scenarios (see section 4). This modelling can be used as a proxy for the spread of other invasive plant species in the Galapagos highlands, like blackberry (*Rubus niveus*). Then, based on the modelling outcomes, with ongoing restauration efforts and prior knowledge of the Galapagos systems (Shackleton et al. 2020, Appendix 2), this program proposes three ecosystem-based Adaptation Measures (EBA) to increase the resilience capacity of the ecosystems of the humid highlands of the inhabited islands of the Galapagos Archipelago (see section 5).

3. PROJECT IMPLEMENTATION AREA

This proposal focusses on the areas of the humid highlands of Santa Cruz, San Cristóbal and Isabela[1] that are of high ecological value and are currently invaded by introduced plant species, mainly by guava (*Psidium guajava*) and blackberry (*Rubus niveus*). The minimum areas that both species are covering is 1371 ha on Santa Cruz, 1731 ha on Isabela and 175 ha on San Cristóbal, a total of of about 3277 ha (Fig. 1, data only shown for guava, Rivas-Torres et al. 2018b; Carrión, unpubl. data). Since these are areas of deeper soil and optimal growing conditions, they coincide with the remnants of the last Scalesia forest patches (Rentería et al. 2012; Rivas-Torres et al. 2018a). The selected areas include agricultural zones and the adjacent protected areas of the Galapagos National Park (GNP).

Precipitation along the elevation gradient is the primary driver of terrestrial biological productivity in Galapagos (Nieuwolt 1991). Thus, the humid highlands are the islands' most biologically productive regions, both in biomass accumulation and soil fertility (Trueman et al. 2014, Laso et al. 2020). Soils are up to 1 m deep, with high organic matter contents, well-weathered and a texture of sandy loam (Laruelle 1966). Additionally, this region is characterized by the *garúa*, which is heavy fog being intercepted by the vegetation and benefitting growth of all plant species during the cool season (Lawesson 1988; Pryet et al. 2012). However, these conditions do not only favor growth of native and endemic species, but also agricultural production and the area expansion of invasive plant species. Currently, the biotic conditions in these areas are changing due to shifts in climate conditions and have become more favorable for the spread of invasive plants (Di Carlo et al. 2010).

Given the future climate variability and its direct and indirect influence on the dispersion of invasive species, local governance seeks to incentivize restoration strategies aimed at conserving the last remnants of the Scalesia forests, through control of invasive plants in native ecosystems and securing provision of

[1] Floreana was not considered due to lack of information about invasive species processes and the inability to collect data in the field, due the COVID19 pandemic.

ecosystem services (e.g. water regulation), while simultaneously contributing to local food security.

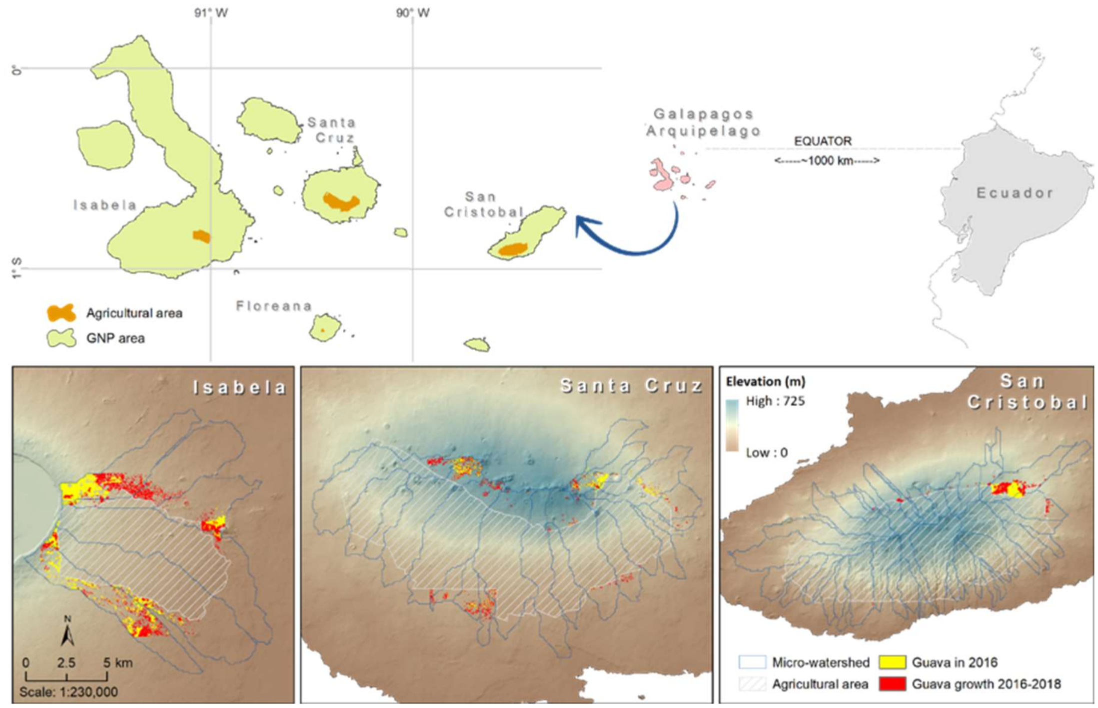

Figure 1. Study area (landscapes of the humid highlands of Santa Cruz, San Cristóbal and Isabela) showing the guava (*Psidium guajava*) dispersion and distribution from 2016 to 2018. Note agricultural areas indicated in hatched white lines.

4. PROBLEM CONTEXT AND ANALYSES

The unique humid highland ecosystems of the Galapagos Islands have undergone massive losses of their original distribution and biodiversity due to their transformation into pastures and agricultural lands in the past (Watson et al. 2009). The remaining fragments are exposed to progressive degradation due to the synergistic effects of the invasion of alien species and climate change (Trueman et al. 2010). Below, we provide an overview of each of these drivers of change and present a case study for the spread of the highly invasive guava under climate change scenarios in the highlands of Santa Cruz, San Cristóbal and Isabela, which serves as a proxy for the anticipated spread of other invasive plants, especially that of blackberry.

The analysis of Watson et al. (2009) revealed that 5% (37,833 ha) of the Galapagos Archipelago’s main inhabited (or previously inhabited) islands had been disturbed by human activities. While this disturbed land represents a small fraction of the total land area, it has experienced a substantial human impact over the last 100 years (Watson et al. 2009). The total area of degraded land per vegetation zone shows that the naturally bare, the littoral and arid vegetation zones have been subject to minimal human impact (~ 1% modification), whereas 29 and 45% of the humid and very humid zones have been altered, respectively (Table 1). Degradation of vegetation zones is not evenly distributed among inhabited islands. For example, 94 and 100% of the humid and very humid zones have been degraded on San Cristóbal, and 88 and 76% of the humid and very humid zones on Santa Cruz. Overall, the humid and very humid vegetation zones of the main islands have been heavily impacted by land conversion and invasions by four of the most prevalent alien plant species (*Psidium guajava*, *Rubus niveus*, *Cinchona pubescens* and *Syzygium jambos*), with major effects on Santa Cruz, San Cristóbal and Isabela (Table 1).

Table 1. Total area (ha) and percentage of degraded land (in parenthesis) of the six vegetation zones on the five inhabited or formerly inhabited (Santiago) islands of the Galapagos Archipelago.

Vegetation zone	Florena	Isabela	San Cristóbal	Santa Cruz	Santiago	Total
Naturally bare	0	406 (0.4)	15 (0.5)	0	0	421 (0.2)
Littoral	0	8 (0.4)	NDA	0	NDA	8 (0.3)
Arid	54 (0.5)	162 (0.2)	888 (2)	319 (0.4)	0	1,423 (0.4)
Transition	72 (2)	2,185 (4)	1,015 (24)	3,121 (25)	10 (0.2)	6,403 (5)
Humid	1,170 (38)	8,173 (21)	5,552 (94)	8,381 (88)	23 (0.5)	23,299 (29)
Very humid	NA	2,460 (29)	2,078 (100)	1,765 (76)	13 (1)	6,316 (45)
Total	1,296 (8)	13,394 (5)	9,548 (17)	13,586 (14)	46 (0.1)	37,870 (4.4)

Source: adapted from Watson et al. (2009)

NDA = No data available

One ecosystem type that is severely being affected by land-use change (conversion to agricultural areas) and invasive species is the Scalesia forest. *Scalesia* is one of the seven endemic plant genera (15 species with 21 taxa) of the Galapagos Islands (Eliasson 1974). Some species occur on several islands while others are endemic to a single island. Most are shrubs that established in the arid and transition zone, but three species: *S. pedunculata*, *S. cordata* and *S. microcephala* are trees that used to occur in the highlands and used to form dense forests as the dominant species in the past (Eliasson 1974; Hamann 2001).

On Santa Cruz, San Cristóbal, Floreana, and Santiago, this forest is comprised of the giant endemic and vulnerable daisy-tree, *Scalesia pedunculata*. Today, remnants of this forest can only be found in the protected areas and hardly any *Scalesia* trees are left on San Cristóbal (Mauchamp and Atkinson 2010). The forest on Santa Cruz is now estimated to cover an area less than 1% of its original extent (Mauchamp and Atkinson 2010) and remnants are invaded by non-native plants, especially by blackberry and guava (Rentería et al. 2012, Rivas-Torres et al. 2018a). Ironically, agriculture has proved to be only marginally viable as an economic activity and hence much of this land now lies fallow and increasingly infested with non-native species (Watson et al. 2009). On Isabela, it is estimated that only about 300 trees of the endangered *Scalesia cordata* remain at Cerro Azul and Sierra Negra volcanoes (Jaramillo and Chávez 2002; Jäger, unpubl. data). All Scalesia forests are very species-rich and house many endemic species, like the Darwin's finches, which are currently in dramatic decline (Dvorak et al. 2012). There are eleven endemic invertebrate species registered for *Scalesia pedunculata* (Boada 2005), some of them feeding exclusively on *Scalesia*, especially some Lepidoptera species (Roque 2006). Together with the *Scalesia*, loosing these species species would result in a drastic decline of the local biodiversity. Biodiversity-poor ecosystems are more vulnerable to the establishment of invasive species and less resilient to climate change (Trueman et al. 2010). For example, in forest fragments where the understory is dominated by blackberry, mortality rates of adult *Scalesia* trees is high and recruitment of saplings and young trees is limited, leading to forest degradation (Rentería et al. 2012, Jäger et al. 2017). In addition, being an evergreen endemic tree in the otherwise naturally treeless highlands (Jäger et al. 2007), *Scalesia pedunculata* offers a permanent surface to capture additional water from the characteristic mist (*garúa*) of the highlands in the cool season (Pryet et al. 2012). Studies in Hawaii have shown that the canopy water storage capacity was twice as much at the native site compared to the site invaded by the introduced strawberry guava (*Psidium cattleianum*, Takahashi et al. 2011) Thus, conserving the last fragments of this critically endangered ecosystem, and implementing restoration efforts so that it can eventually recover, will enhance the resilience of terrestrial ecosystems in Galapagos to climate change, while supporting the livelihoods of the local farmers..

The terrestrial ecosystems of Galapagos have evolved within the unique climate of the archipelago and are therefore susceptible to changes in the climatic regime (Di Carlo et al. 2010). Due to the natural rainfall variability associated with ENSO events, there is some intrinsic resilience in terrestrial organisms and communities (Trueman et al. 2010, Restrepo et al. 2012). However, the two strong El Niño events in 1982–83 and 1997–98, marked by anomalous warming of the sea surface temperature, air temperature and extreme precipitation, resulted in substantial impacts in the terrestrial ecosystems, like increased growth of herbaceous plants (proxy for increase in invasive species growth) and mortality of arboreal plants (Escobar-Camacho et al. 2021). These observations help us understand the vulnerability of species and ecosystems to potential future changes to the climate in Galapagos. These insights are key to be able to develop and apply management measures to increase the resilience of threatened species and ecosystems to climate change, like the different *Scalesia* species that form these unique forests. *Scalesia pedunculata* may be particularly affected by ENSO, since it exhibits a natural stand-level dieback and regeneration that appears to be linked with El Niño and La Niña events (Hamann 1985). Scalesia forests are highly susceptible to extreme precipitation events, leading to high tree mortality, since these get water-logged (Hamann 1985). In the past, the initial high tree mortality triggered by El Niño was usually followed by a mass recruitment of *Scalesia* through seed germination during the following La Niña event (Hamann 1979). However, due to the invasion of the understory by blackberry, the light-demanding *Scalesia* seeds cannot germinate in the dense thicket and the forest is not able to regenerate as it used to (Rentería et al. 2012; Jäger et al. 2017). Higher precipitation, as predicted for Galapagos, could threaten the humid zone ecosystems by changing vegetation growth rates and forest structure (Trueman et al. 2010). Additionally, increasing temperatures could cause species, like the *Scalesia* species, to shift their ranges to higher elevations (Larrea and Di Carlo 2011). This, combined with the short life expectancy of the *Scalesia* species (an estimated 15 years, Hamann (2001)), makes them more vulnerable to long-term disturbances (Hamann 2001) and to invasive species (Jäger et al. 2017). Climate change impacts, including warming temperatures and changes in CO_2 concentrations, are likely to increase opportunities for invasive alien species because of their adaptability to disturbance and to a broader range of biogeographic conditions (Burgiel and Muir 2010).

The mean annual temperature in Galapagos has increased by ~0.6°C over the last four decades across the islands (Escobar-Camacho et al. 2021). Future scenarios detected by General Circulation Models (GCMs) suggest warmer and wetter trends for the Galapagos Islands. Annual precipitation is projected to increase between 20-70%, with major changes in the highlands, while mean annual temperature is expected to rise between ~1.1 and 2.0 °C (Paltan, unpubl. data). Under these new climatic conditions, the increase, distribution and impacts of invasive species may directly or indirectly be accelerated (Hulme et al. 2017, Essl et al. 2020). Many invasive species are pre-adapted to take advantage of disturbed areas (e.g. native ecosystems stressed by climate change), mainly by extreme events such as ENSO, creating new opportunities for introduced species to establish and thrive (Beaury et al. 2020, Shackleton et al. 2020). A good example is the case of the guava (*Psidium guajava*) and blackberry (*Rubus niveus*), the most invasive plants in Galapagos (Jäger et al. 2017, Shackleton et al. 2020, Appendix 2). Preliminary evidence suggests that guava is drought and shade tolerant, resistant to temporary water-logging, grows well in a wide range of soil pH and has the capacity to intercept fog water via stemflow (Walsh et al. 2008, Takahashi et al. 2011). These characteristics, coupled with the high rainfall and several droughts associated with El Niño and La Niña respectively, is expected to facilitate the spread of guava and blackberry after dieback of native species (e.g. *Scalesia spp.*) and the progressive degradation of agroecosystems in Galapagos (Tye 2006, Jäger et al. 2019, Schmitt et al. 2018, Laso et al. 2020).

In addition, residents from the farming zone migrate to coastal towns to work on tourism related activities, which leads to the abandonment of agriculture and cattle ranching. The proportion of the population residing in rural areas has decreased from 42% in 1974 to just 17% in 2010 (Sampedro et al. 2018). This leaves the lands vulnerable to the invasion of alien species (Barona and Mena 2014) and further exacerbates the desertion of the highlands and a low food production. According to the Agricultural Census, the total productive area had been reduced from 23,426 ha in 2000 to 19,010 ha in 2014, representing a decrease of 19% (Sampedro et al. 2018). According to Laso et al. (2020), guava is the most common invasive plant inside the agricultural area, covering about 6,836 ha (27%) of the area, of which 73% corresponds to areas dominated by guava and the rest corresponds to areas covered by mixed forest, which is a mixture of native vegetation and invasive species (mainly blackberry). However, in a representative survey of 20% of the farmers on Santa Cruz, 85% of interviewees said that blackberry was the most problematic invasive species on their land, followed by guava with 67% (Jäger et al. 2019). Moreover, previous studies carried out in the GNP suggested that about 2-5% of the protected area had been severely modified by the spread of invasive species from the adjacent agricultural area (Rivas-Torres et al. 2018b). Current studies indicate that almost USD 3,000,000 are invested in Galapagos annually to fight invasive species in the agricultural area, of which about USD 1,000,000 correspond to investments in family labor force (Viteri and Vergara 2017). This represents a substantial investment by local farmers that consequently leads to higher costs for agricultural and livestock production. This increased costs discourage farmers from agricultural production, which leads to an increase in the likelihood of abandonment of the activity, when farmers are not able to recover the investment due to droughts, pests, and diseases.

Invasive species do not only have to be controlled in the agricultural areas. Over more than 20 years, the GNPD has been controlling alien plants by applying manual and chemical control (Toral-Granda et al. 2017). Results from an experimental removal of blackberry in the Scalesia forest showed a spectacular natural regeneration of *Scalesia*. Only 5 months after the last herbicide application, up to 280 *Scalesia* seedlings were encountered in an area of 10 m × 10 m. In the adjacent, blackberry-invaded area, not a single seedling emerged from seeds during that same time (Jäger et al. 2017). The study showed that without blackberry control, the Scalesia forest will not be able to regenerate on its own. However, an initial reduction in the number of invertebrates and breeding success of the green warbler finch (*Certhidea olivacea*) was also observed right after control measures were applied, but only two years later, these where not detectable anymore in the subsequent monitoring (Cimadom et al. 2019).

Therefore, anticipated negative impacts from control actions have to be counteracted by a subsequent restoration approach to increase the number of native and endemic species and the species' cover, as well as suppressing the regeneration of invasive plants. Given the current trend of abandonment in the agricultural sector in Galapagos (Laso et al. 2020) and the ability of guava and blackberry to persist under ENSO conditions, which will likely become more frequent and extreme under future climate change (Cai et al. 2015), guava and blackberry propagation could be faster than ever before (Schmitt et al. 2018). Studies have shown that restoration of plant diversity may greatly increase carbon capture of degraded agricultural lands (Yang et al. 2019). Thus, integrating invasive species management into the Galapagos climate change mitigation and adaptation programs, will help to maintain and restore native ecosystem integrity, safeguards livelihood benefits and thereby increase resilience of the protected and agricultural ecosystems to climate change.

The development of models that capture the future spatial distribution of invasive species is essential to facilitate effective management actions, such as prevention of spread and opportunities for eradication (Bellard et al. 2013). For this analysis, a Cellular automata-Markov chain (CAMK) simulation model was implemented to understand the current distribution pattern and quantify the dispersion of invasive plant species under different climate change scenarios in Galapagos by 2030. Understanding the role of plant invaders in an ecosystem, as well as interactions between and among species, is important and can significantly affect the outcome of restoration programs (D'Antonio and Meyerson 2002).

This case study aims at identifying areas that would be highly susceptible to the expansion of invasive plant species under climate change. The modelling focuses on the guava invasion in ecologically important areas that have to be protected, preserved and restored and serves as a proxy for other invasive plant species, like blackberry. The reason we are using guava as the model species is the fact that we have more and also more reliable data for guava for Santa Cruz, Isabela and San Cristóbal than we have for blackberry. As a mainly understory shrub, blackberry is hard to distinguish from shrubby or arboreal vegetation in satellite or drone images, so that an accurate modelling of its distribution would be difficult. However, we know from experimental plots that guava and blackberry are similar in their invasion behavior and that that they often occur together in invaded areas (Jäger et al. 2009, Jäger, unbubl. data). Thus, we feel confident that the modeling of the guava invasion gives us a reliable proxy for the blackberry invasion. Since blackberry forms monospecific stands that displace most species except for some fern species, whereas guava trees do not completely block the passing of light and are even seen as partially beneficial by some cattle farmers (Renteria et al. 2012, Jäger et al. 2017, Rivas-Torres et al. 2018a). Consequently, the target species to control in the proposed intervention is mainly blackberry, with guava being controlled where it occurs together with blackberry. It is important to mention that guava is seen as partially beneficial by cattle farmers but not by agricultural farmers, who mentioned guava as being the second most problematic species on their farms, with blackberry being the most problematic (Jäger et al. 2019). Based on the modeling for guava, this project contemplates supporting a restoration program over ~1,500 ha, which will provide direct impacts on the protection of natural resources.

4.1. Modelling of *Psidium guajava* spread under climate change.

5.1.1 Occurrence data

Psidium guajava or guava is an evergreen small tree (8 m tall), native to the tropical regions of America and introduced to the Galapagos Islands in the late 19th century (Walsh et al. 2008). It is now recognized as one of the most aggressive invasive plants in the archipelago, where both the agricultural area and the protected area of the GNP are seriously infested (Rivas-Torres et al. 2018b, Urquía et al. 2019). Occurrence data for guava were obtained from the most recent initiatives to map land use and land cover in Galapagos for the reference years 2016 and 2018 [(Rivas-Torres et al. 2018b, Laso et al. 2020, Carrión, unpubl. data), Table 1]. The invasion pattern of guava was analyzed in the shared area of these studies. The land cover categories selected for this analysis are those related to guava-dominated vegetation (> 50%) (Figure 1).

Table 1. Current efforts to map land cover in the Galapagos Islands.

Source	Sensor	Spatial Resolution	Years images acquired	Study area	Interest categories
Rivas-Torres et al. (2018b)	Landsat 8	15 m	2015/2016	GNP	*Psidium guajava*
	SRTM	30 m	2015		
Laso et al. (2020)	PlanetScop	3 m	2018	Agricultural area and surrounding protected area	*Psidium guajava*
	Sentinel-2	10 m	2017/2019		
	SIGTIERRAS-DTM	10 m	2009		

Carrión (unpubl. data)	Worldview 2	0.46/1.84 m	2015/2018	GNP	Guava Dominant

Based on previous studies (Jacobi and Warshauer 1992, Barona and Mena 2014), data availability and multidisciplinary experts' knowledge, a list of 15 drivers for guava invasion was compiled and analyzed. Multi-collinearity among variables was tested using Pearson's correlation and variance inflation factors (VIFs) (Sokal and Rohlf 2011). Variables with a Pearson correlation > 0.65 and VIF > 5 were dropped to reduce multicollinearity. In addition, climate variables were prioritized in the previous analysis due to their importance in the construction of growth and spread guava scenarios under future climate change. Finally, the remaining five variables: distance to guava patch, soil moisture, wetness index, precipitation, and temperature, were selected as relevant predictors to model current a future guava distribution (Table 2). These variables represent the physical characteristics of the local land (suitability) and the spatial variation in climatic conditions. Selected variables were processed and spatialized via GIS functions and gridded with a 15 m spatial resolution to match the lower resolution of the available land cover maps (Table 1). The values of all variables were standardized into a 0-1 range.

Table 2. Summary of the key driving factors for the guava growth and spread in Galapagos.

Variable	Description	Data Source
Dist_guava	Distance (meters) from the cell to guava patch inside of agricultural area, based on the least-accumulative cost over a DTM (cost surface).	Galapagos land use map 2018 (Laso et al. 2020). SIGTIERRAS orthophotos 2010 (10 m)
Soil moisture (SM)	Monthly soil-moisture storage (mm), which is the moisture retained in the soil column based on land use categories, elevation and micro-watershed.	Galapagos Water Balance 2020
Wetness Index (H)	Humidity was represented as a wetness index through the follow equation:	SIGTIERRAS orthophotos 2010 (10 m)

	$$H = \ln\left(\frac{AD}{\tan(\beta)}\right)$$ Where, AD is the drainage area and β is the slope in degrees. The index values range from 0 to 15 where values closer to 15 represent higher humidity.	Micro-watershed map
Precipitation (Pr)	Annual precipitation value of the cell (mm)	CHELSA project (1 km) (Karger et al. 2017)
Temperature (Tm)	Mean temperature value of the cell (°C)	CHELSA project (1 km) (Karger et al. 2017)

To observe the response of guava to the near-future reference period of 2030 under climate variation, we used: (i) the official downscale climate projections from four selected CMIP5 models at 10 km of resolution (CSIRO-Mk3-6-0, GISS-E2-R, IPSL-CM5A-MR, MIROC-ESM) (MAE 2017) and; (ii) the only two available GCMs (CMCC-CM, MIROC5) from CHELSA dataset (Karger et al. 2017) for this period. The CHELSA project is a high resolution (30 arc sec ≈ 1km) climate dataset for the earth land surface areas. The guava future distribution was examined under moderate and extreme climate change scenarios based on two Representative Concentration Pathway trajectories, RCP 4.5, RCP 8.5 (IPCC 2013). RCP 4.5 is a medium-low stabilization scenario that assume emissions peak around 2040, then decline. For the study area, in this scenario, the predicted temperature increases 1.1 ± 0.3°C by 2030 and the project precipitation increases by about 13% on average by 2030. On the other hand, the RCP 8.5 is a high-emission scenario in which emissions continue to rise throughout the 21st century. In this case, the temperature is predicted to increase in 1.2 ± 0.4°C and the average predicted precipitation is about 14% by 2030 for the study area (Table 3).

Table 3. Projected anomalies in Precipitation (Pr) and Temperature (Tm) under RCP 4.5 and RCP 8.5 scenarios on three islands of Galapagos.

Island	RCP 4.5	RCP 8.5
San Cristóbal	Pr: 12% | Tm: 1.1°	Pr: 14% | Tm: 1.2°

Santa Cruz	Pr: 13% | Tm: 1.1°	Pr: 15% | Tm: 1.2°
Isabela	Pr: 13% | Tm: 1.1°	Pr: 14% | Tm: 1.2°

5.1.2 Species distribution modelling

Several species distribution algorithms have been developed in the field of spatial modelling to represent and capture many complex ecological responses within the natural system (Elith et al. 2010). However, as a single modelling algorithm does not provide the best predictive accuracy, a combination of Cellular automata and Markov chain (CAMK) modelling (Keshtkar and Voigt 2016) was used to characterize the dynamic of invasive plant growth and spread in the Galapagos highlands. The hybrid model proposed combines the stochasticity provided by Markov chain technique (Iosifescu 2014) with a probabilistic synchronous from Cellular Automata (CA) approach. This model allows to predict the future status of an ecosystem based on its pre-existing status (Rimal et al. 2018).

The success of the CA model to capture the local and regional dynamic is the optimum determination of the CA transition rules. It was built and calibrated using: (i) a conventional logistic regression based on driving factors; (ii) a neighborhood model using a moving window of 5 × 5 cells (150 m × 150 m), estimated from the cumulative allocated development of the previous period; (iii) a random model that describe the inherent variation associated with the system (stochastic factor); and (iv) the growth and spread constraints (water bodies and built environments). According to the conditions of each island, different transition rules were configured to produce transition potential maps (habitat suitability) (Fig. 2), which differs in regression coefficients. Highest values represent better conditions for the development of this species.

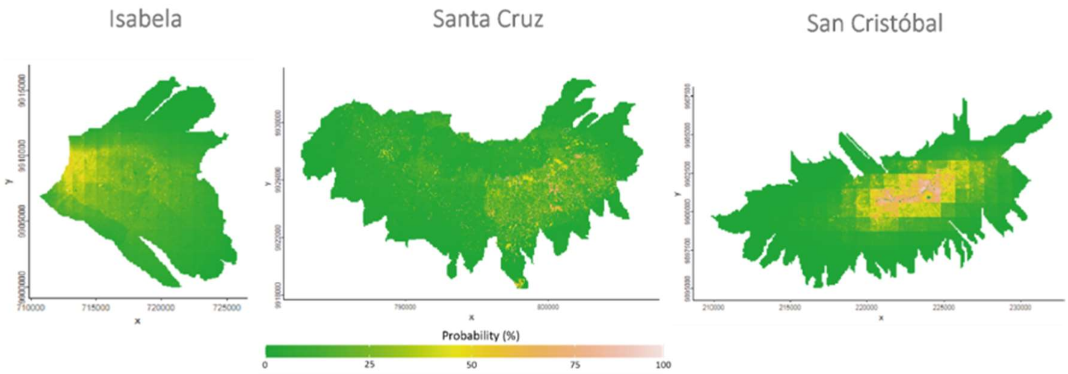

Figure 2. Potential transition maps (habitat suitability) for *Psidium guajava* development

In the absence of land cover data for a third period in the study area, landscape metrics (spatial validation) were used to evaluate the ability of the model to simulate future changes by comparing the observed *Psidium guajava* map of 2018 with the simulated map of the same year.

Finally, the map based on observed data for guava for 2018 was set as the base map and the transition probabilities (demand) of change in guava growth from 2016 to 2018, calculated through Markov chain technique, were used to forecast the guava growth map of 2030 (Figure 3). These data were used as input in the annual interactive CA modelling where, for each year, the highest potential pixels are selected and converted in guava land until de demand is filled.

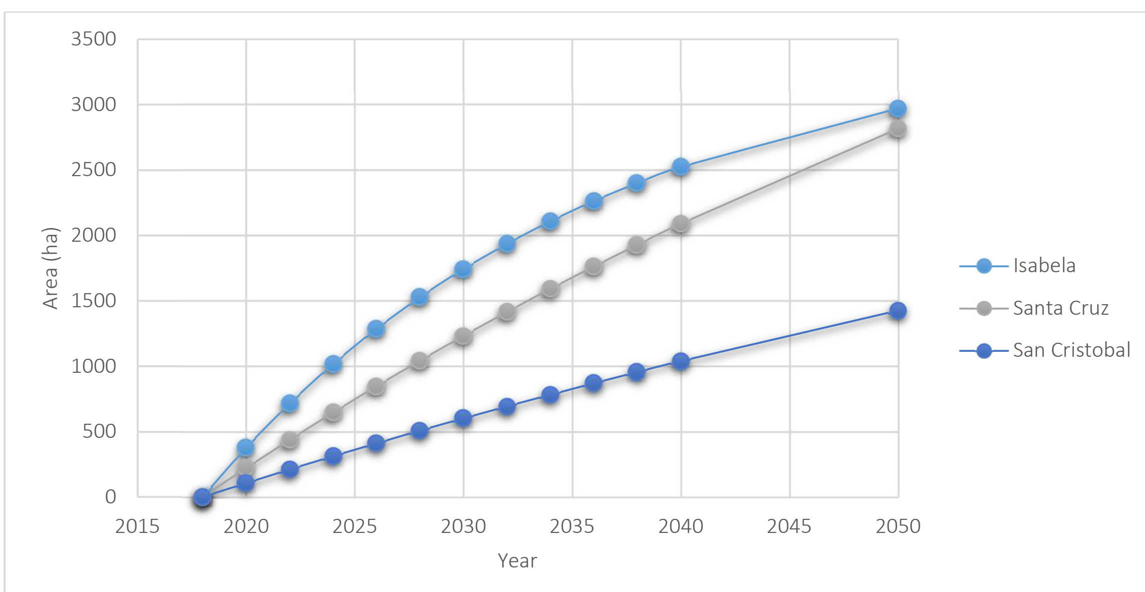

Figure 3. *Psidium guajava* growth area on the three islands, calculated based on Markov chains projections

5.1.3 Restoration/Rehabilitation criteria

A multi-criteria evaluation (MCE) was performed to define the areas with high ecological and hydrological importance in the Galapagos highlands. This method allowed us to evaluate land use based on expert knowledge in order to support land use and environmental planning and management (Feizizadeh and Blaschke 2012, Barona and Mena 2014). Expert knowledge was included in the model based on focal groups meetings with restoration scientists in Galapagos, where restoration criteria were defined. The application of MCE process involves: (i) identification of criteria or factors that contribute to identify areas with ecological and hydrological importance; (ii) determination of the relative importance (weighting) of each factor based on "*experts' opinions*"; (iii) aggregation of the criteria weights and check model consistency; and (iv) an overall evaluation of the suitability model.

In this feasibility assessment, we combined agricultural livelihoods needs with ecological and hydrological criteria for identifying intervention areas for the restoration of Scalesia forest ecosystem and rehabilitation of ecosystem services in the Galapagos highlands. These criteria included the following thematic information: (i) areas of high hydrological importance based on the baseflow (mm) of each island; (ii) the potential *Scalesia* forest distribution; and (iii) altitudinal range (m) (Figure 4).

Areas of high hydrological importance are referred to those with the highest water yield. To identify these areas, a water balance for the highlands was developed in order to determine the current water production on the three major inhabited islands (see Appendix for Output 2.1.2). The water balance analysis focused on three main flow subcomponents: (1) surface runoff, (2) interflow and (3) baseflow. In general, these three types of flows inform us about the speed of the water, the capacity of soil water regulation and water demands based on current land use (see below). Areas of high ecological importance are referred to those where the potential distribution range of the *Scalesia* forest were predicted to occur, before human intervention modified the landscape (Escobar-Camacho et al. 2021).

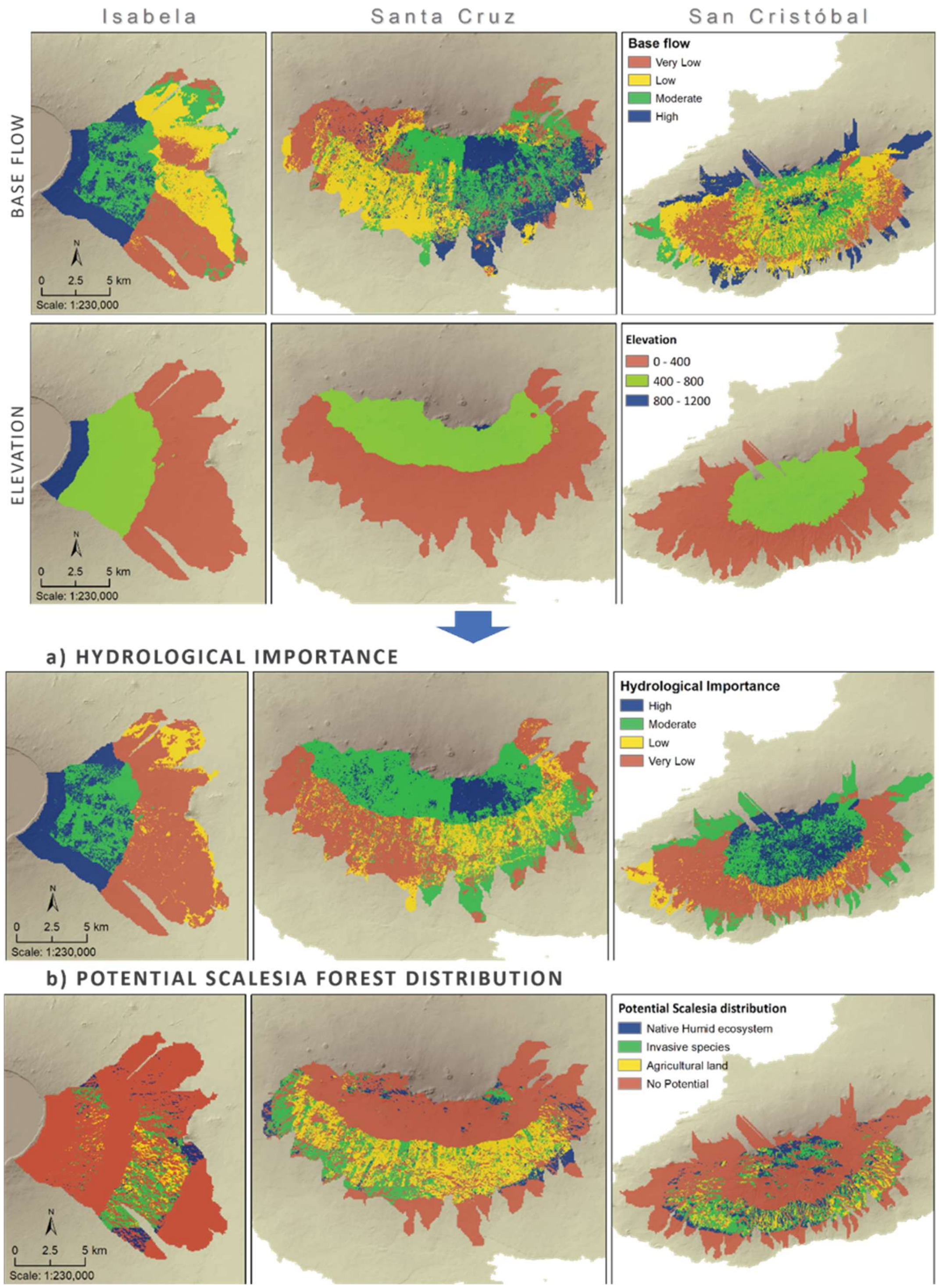

Figure 4. Thematic variables used to build sustainable areas for Scalesia forest restoration

Each thematic criterion, mentioned above, was categorized according to the degree of restoration suitability. The baseflow data was grouped into four-category quantile, elevation data was classified every 400 m intervals and the potential *Scalesia* distribution map was categorized based on their land use coverage. Each suitability classes were subsequently ranged according to their relative importance on a 1 to 4 scale, where 1 represent a very low restoration suitability and 4 a high restoration suitability. As previously mentioned, the relative importance was assigned based on expert´s opinion (see above). All variables and indicators were aggregated through a weighted overlay using GIS spatial analyses tools. A particular criterion weight was determined for each resulting combination. The details of weights used for the evaluation criteria are listened in Table 4. The weights were assigned based on restoration as a constraint to invasive plants spread, where 0 represent a high constraint to guava spread and 1 represent no-constraint to invasive spread (Fig. 5).

Table 4. Detailed weights and ranges for the criteria for restoration and invasive plant spread.

Suitability	Factor	Criterion	Weight
High	*Scalesia* potential distribution	Over agricultural areas and invasive and native vegetation	0.25
	Baseflow	Highest values (4th Quantile)	
	Altitude	Over 400 m asl	
Moderate	*Scalesia* potential distribution	Over agricultural areas and invasive and native vegetation	0.5
	Baseflow	Moderate and High values (3rd and 4th Quantiles)	
	Altitude	0 - 800 m asl	
Low	*Scalesia* potential distribution	Over agricultural areas and areas with no *Scalesia* potential distribution	0.75
	Baseflow	Low and Moderate values (2nd and 3rd Quantiles)	
	Altitude	0 - 800 m asl	
Very low	*Scalesia* potential distribution	Over agricultural areas and areas with no *Scalesia* potential distribution	1
	Baseflow	Lowest values (1st Quantile)	
	Altitude	0 - 400 m asl	

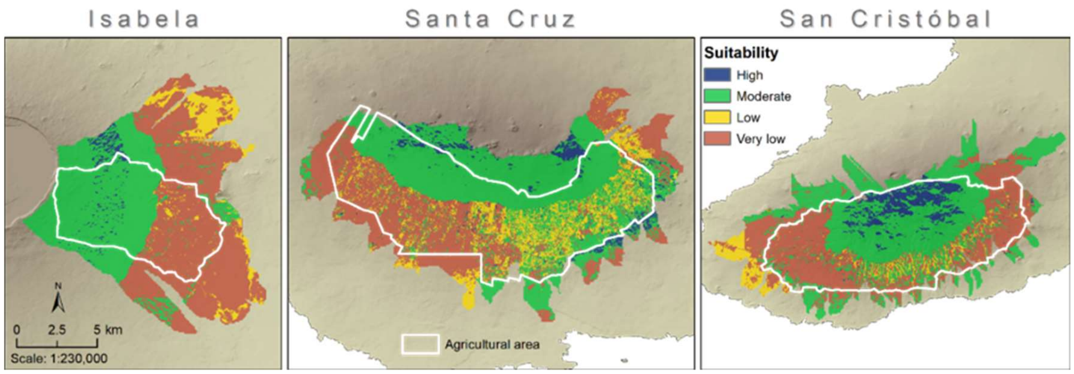

Figure 5. Suitable areas for *Scalesia* forest restoration in the Galapagos highlands

5.1.4 Driving forces of *Psidium guajava* invasion in Galapagos

In this study, a logistic regression analysis allowed us to understand and statistically quantify the relationship between guava growth and its driving factors. All the variables selected as driving forces in guava growth were significant at $\alpha < 0.001$ (Table 5).

Table 5. Cellular Automata parameters generated by logistic regression

	San Cristóbal		Santa Cruz		Isabela	
Variable	Estimate	p-value	Estimate	p-value	Estimate	p-value
Intercept	-8.83	<0.001	-8.91	<0.001	-6.81	<0.001
Dist_Guava	-7.39	<0.001	-1.03	<0.001	-7.89	<0.001
SM	1.73	<0.001	9.39	<0.001	6.02	<0.001
H	4.05	<0.001	2.89	<0.001	3.11	<0.001
Pr	7.82	<0.001	2.26	<0.001	3.62	<0.001
Tm	-6.55	<0.001	-1.75	<0.001	-2.12	<0.001

The results show that there is a positive correlation between guava growth and factors associated with water availability (i. e. precipitation, humidity, and soil moisture; Table 5). Thus, access to water plays an important role in the interaction between native and invasive species (Guo et al. 2020), where introduced plants have shown to be better competitors than native plants. For this analysis, higher values of precipitation, humidity (wet index) and soil moisture represent better conditions for guava growth and spread. Of these three variables, soil moisture showed a higher significance in the guava growth process with an estimated coefficient that ranges from 2 to 9 depending on the islands (Table 5). This means that when resources increase (high soil water storage), it will increase the probability of the invasion success of guava into a native plant community and its presence will not be affected by water scarcity due to its drought tolerance (Binggeli et al. 1998; Schmitt et al. 2018). Climate projection suggest a wetter future, promoting the increase and spread of invasive species outside of their current distribution.

Finally, the remaining two variables (distance to guava patch and temperature) showed a negative correlation with guava growth on the islands (Table 5). As was expected, guava invasion is more likely to occur in proximity of actual guava-dominated patches that currently are located within agricultural areas. This could be associated with the dispersion of seeds by local animals such as finches, giant tortoises, and lizards, because these species have included guava fruit into their diets, facilitating their establishment and spread (Blake et al. 2012, Heleno et al. 2013). Furthermore, the results show that guava is more successful in areas with low temperature, becoming a strong competitor with the native forest species in the Galapagos highlands (Table 5).

5.1.5 Future spread under Climate Change

We explore two opposing scenarios of how the *Psidium guajava* invasion will develop in the next decades under climate change based on simulation models. The first shows a “Business as usual” (BAU) scenario, where extensive areas of agricultural land are abandoned, causing the fragile Galapagos agroecosystem and the adjacent protected areas to be more vulnerable to the expansion of invasive plants (Laso et al. 2020, McCleary 2013). Currently, the agricultural area of Galapagos houses a higher number of invasive plant species, which cover 28.5% of its surface (Guézou et al. 2010; Laso et al. 2020). These exotic plants not only threaten agricultural systems but also the remaining fragments of native ecosystems that still exist within farms, as well as the native ecosystems in the adjacent GNP.

The second scenario is based on a project intervention scenario, where areas of high hydrological and ecological importance are selected to implement ecosystem-based activities. Rehabilitation and passive restoration activities will be promoted to implement agroforestry systems within active and abandoned farms, in conjunction with protection strategies that support natural succession and improve the quality of the forest fragments to enhance sustainable agroecosystems. This will be complemented through the implementation of methods to control invasive species and enrich native ecosystems by means of planting native/endemic species like *Scalesia pedunculata* in degraded areas within the GNP. To ensure the continued success of a restoration/rehabilitation project, a long-term monitoring program is necessary to evaluate the success of invasive species control methods and results, like the potential impacts on non-target species (see EBA 3).

Two possible scenarios were considered in the project intervention. For the first scenario (R1), active and passive restoration activities are implemented in about 1,500 ha inside regions with high and moderate suitability for ecological restoration (Fig. 4). The 50% (750 ha) of areas that would be restored are in protected areas and the remaining half (750 ha) within farms. The second scenario (R2) considers the reactivation and strengthening of the Galapagos agricultural sector through climate-resilient activities. These activities include forestry practices, such as bio-diversification and silvopastoral systems, which will allow the agroecosystem to control of invasive species, conserve remnants of forest fragments, protection of water resources, among others.

After process simulation, no significant difference was observed in the resulting maps under RCP4.5 and RCP8.5 scenarios. This could be explained by the minimal difference in the temperature and precipitation anomalies among both scenarios in a near-term future (Table 3) over the study area. For this reason, the results of this study are only presented under RCP 4.5 scenario.

According to the analysis, 15.7% of the study area was occupied by *Psidium guajava* in 2018 (Table 5), which will increase to 23.6% by 2030 under a BAU scenario. If restoration and rehabilitation activities were implemented in both protected and agricultural areas, this increase could be reduced to 17.5% and 16.4% under R1 and R2 scenarios, respectively. The results also showed that the rapid expansion of guava is mainly concentrated in Isabela, where the increment could range from 23.3% to 70.3% under BAU and project implementation scenarios, respectively (Table 5). The observed large expansion of guava in the highland vegetation of Sierra Negra volcano on Isabela (Fig. 5) are consistent with the agricultural abandoning process recorded since the 1980s (Laso et al. 2020), leaving the agricultural production concentrated in the lowest section of the agricultural zone.

Furthermore, we noted an important decline of guava on San Cristóbal (Table 5), if an intervention project was implemented (loss of 0.49% to 23.8%). On this island, the guava growth and spread were mainly concentrated in the agricultural area (Fig. 5), showing an effective control of invasive plants propagation under climate-resilient practices, supported by landowners and the GNPD. In addition, passive restoration practices on farms would help in the prevalence of native ecosystems within the agricultural area of San Cristóbal, where 30% of the agricultural area was categorized as native vegetation (Laso et al. 2020).

Santa Cruz has the most extensive pastures of the Galapagos agricultural area, where guava trees are used as shade trees for cattle in the silvopastures systems. Under rehabilitation activities and the protection of forest fragments, the guava spread could mainly be controlled in the protected area, where it could be reduced between 13% to 27%, compared to the BAU scenario (Table 6).

Table 6. *Psidium guajava* area (in ha) and percentage of change for 2018-2030 under Business as usual – BAU scenario and two project intervention scenarios (R1, R2).

	Initial stage, 2018	**Scenario, 2030**			**Change in Guava distribution for 2030**		
		BAU	**R1**	**R2**	**Δ% 2018-BAU**	**Δ% 2018-R1**	**Δ% 2018-R2**
Isabela	2478	4221	3556	3056	70.3	43.5	23.3
Santa Cruz	2424	3656	3183	2683	50.8	31.3	10.7
San Cristóbal	2139	2740	2128	1628	28.1	-0.5	-23.9
Total	**7041**	**10617**	**8867**	**7367**			

Considering the actual land use in the study area, the projected expansion of guava under a BAU scenario would be accompanied by an important decline of cultivated land area (loss of 21%), followed by pastures (loss of 10%) and native vegetation (loss of 6%) (Table 7). This pattern threatens food security in the islands, and the conservation and integrity of the native ecosystems will be heavily affected.

Table 7. Loses (in percentage) in land use categories (native vegetation, crop land and pastures) by *Psidium guajava* expansion by 2030 under different scenarios.

Islands		**Native Vegetation**	**Crops land**	**Pastures**
Isabela	BAU	10.9	27.4	22.3
	R1	5.8	30.4	20.2
	R2	4.3	25.1	16.0
Santa Cruz	BAU	2.0	25.5	5.3
	R1	0.4	29.8	3.6
	R2	0.5	29.4	3.9
San Cristóbal	BAU	6.6	5.9	14.5
	R1	2.9	13.7	15.2
	R2	1.7	12.4	11.7

Figure 6 illustrates the fact that guava tends to spread over agricultural areas. Although spatial patterns may be affected by the growth rate used for modelling, which is not affected by restoration/eradication efforts, it is expected to see a significant reduction in both the rate of growth and spread with the implementation of control strategies for invasive species, which will be key for improving resilience in agroecosystems.

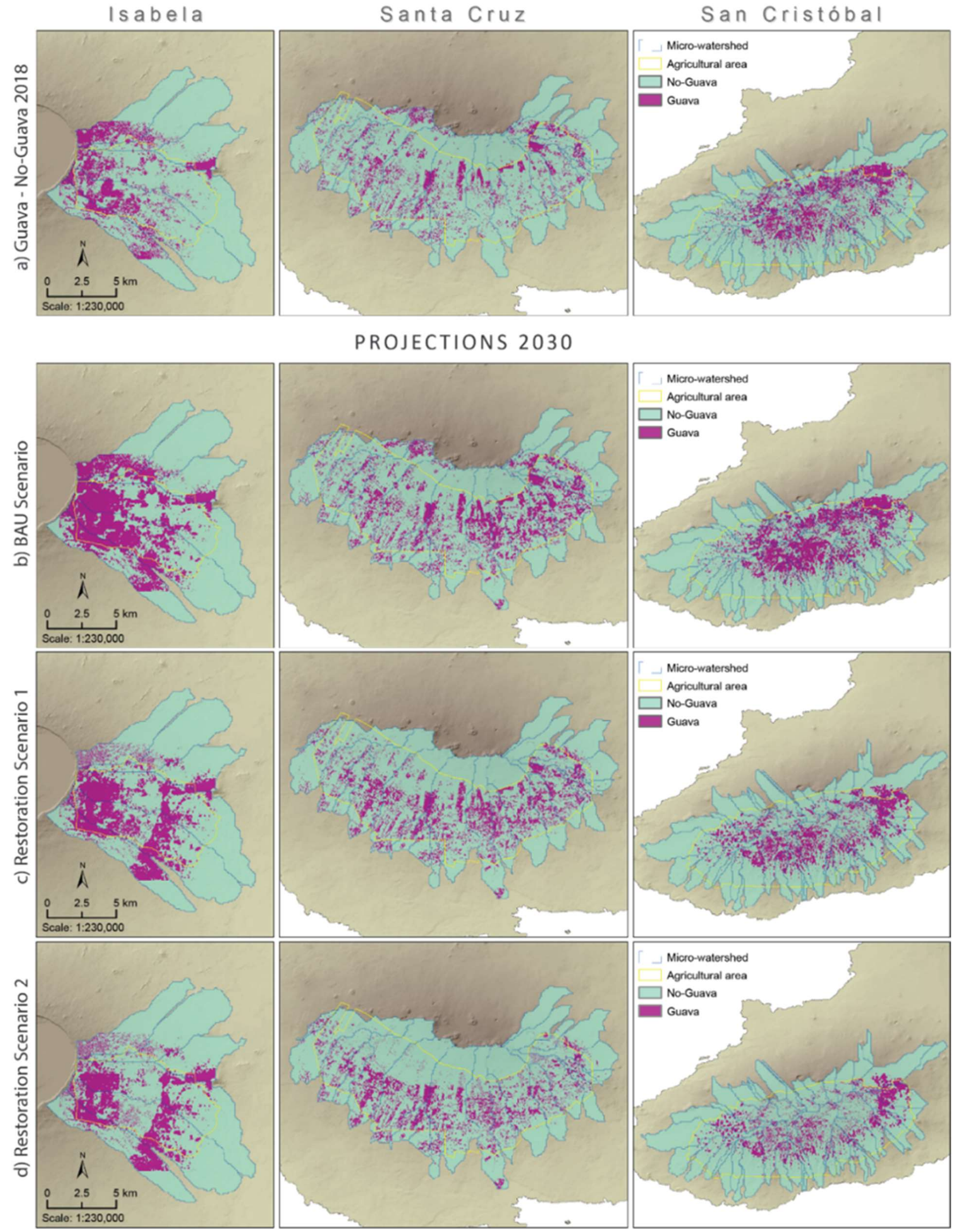

Figure 6. (a) Actual *Psidium guajava* distribution map, 2018; and simulated growth maps by 2030 under (b) BAU scenario and (c, d) Project intervention scenario (R1, R2).

5. ECOSYSTEM- BASED ADAPTATION MEASURES (EBA).

Based on the problem context and analysis (Section 4), the guava modelling outcomes, together with ongoing restoration efforts and prior knowledge of the Galapagos system (Shackleton et al. 2020, Appendix 2), this program proposes three Ecosystem-based Adaptation Measures (EBA) aimed at increasing the resilience capacity of the ecosystems of the humid highlands of the inhabited islands in the Galapagos Archipelago (Table 7). In the description of each EBA, the expected outputs for each sub-activity are included.

Table 7 summarizes activities and sub activities to be carried out for all proposed EBA measures and their related outputs.

Table 7. Integrated activities and outputs of all EBA measures.

Activity	Sub-activity	Output
1. Strengthen control programs for invasive plant species, especially blackberry, in protected and agricultural areas, based on projected dynamics of their expansion under climate change scenarios.	1.1 Strengthen control programs for invasive plant species in an area of 750 ha within the **Galapagos National Park**, with emphasis on guava and blackberry.	Guava and blackberry climate change distribution models verified and adjusted, based on ground surveys. Prioritized areas within the GNP (a total of 750 ha) under innovative control schemes. Dispersal of invasive species, mainly blackberry, contained in an area of 750 ha, with minimal impacts of control actions on the resident flora and fauna. Protocols developed to ensure successful ongoing invasive species control and to strengthen the Terrestrial Invasive Species Program of the GNPD strengthened for long term control under climate change scenarios.
	1.2 Implement invasive species management and control measures on **farms** in an area of 750 ha in the agricultural area.	Assessment of the conservation status of 750 ha of Scalesia forest fragments in the agricultural area (400 ha on Santa Cruz, 200 on San Cristóbal and 150 ha on Isabela). These are an additional 750 ha to those being controlled in 1.1. Areas freed of invasive species that are now available for agricultural production. Strengthening active agricultural practices in 750 ha to control invasive

		species in collaboration with MAG, GNPD and ongoing civil society/private restoration and sustainable production efforts. Proven and safe control of invasive plant species implemented that help preserve and promote native biodiversity, while at the same time keeping invasive species at bay.
2. Restore key remnant forest fragments in protected and agricultural areas to enhance ecosystems adaptive capacity and provision of environmental services.	2.1 Restore key remnant forest fragments in an area of 750 ha within the **Galapagos National Park.**	Assessment of the conservation status of 750 ha of Scalesia forest fragments inside the GNP. Nurseries of the GNPD on the three islands strengthened to provide native species seedlings to implement restoration activities. 300.000 native plants successfully established in key restoration areas 750 ha of key Scalesia forest fragments within the GNP under restoration schemes to protect threatened species and biodiversity.
	2.2. Conserve and restore key remnant forest fragments on **farms** in an area of 750 ha in the agricultural area.	750 ha of agricultural land restored with *Scalesia* spp. and other native tree species, totaling 300.000 planted individuals (400 ha on Santa Cruz, 200 ha in San Cristóbal and 150 ha on Isabela) on at least 10 farms (5 on Santa Cruz, 3 on San Cristóbal and 2 on Isabela). Increased connectivity between key forest fragments on farms through restoration carried out under 2.1
	2.3. Outreach activities and workshops with local community on importance of ecosystem services and how they benefit livelihoods.	Farmers trained in restoration practices to be involved in project activities as qualified labor force. Biannual meetings held with the local authorities (e.g GNPD, MAG, the Galapagos Governing Council (CGREG) and the municipalities), to discuss project progress. Publication of an annual technical report to the local authorities with recommendations based on the results of the monitoring (see EBA 3), to assure constant adjustment of project activities.

		At least two presentations each are delivered at a national and international level about the project's outcome and importance for the conservation of the Galapagos biodiversity. At least two publications in open-access peer-reviewed scientific journal, discussing the key results and outcomes of the project. Regular public posts on the project progress on social media, institutional blog posts and through press releases, to reach an even wider local, national and international audience.
3. Monitor success and impacts of invasive species control and restoration measures.	3.1 Assess ongoing efforts and restoration needs, including evaluating current control techniques for invasive plant species.	Assessment of control techniques for invasive plant species in the Galapagos highlands, including the identification of the most cost-effective techniques with the lowest environmental risk and major impacts on invasive species. Identification of priority areas to implement active and passive restoration actions, including the definition of locations to set up new permanent vegetation plots.
	3.2 Establish baselines for plant and animal species in areas under restoration, with a focus on rare species.	Consolidation of a data management and information system were all the information will be uploaded. It is envisaged the information system will inform restoration actions based on an adaptive management scheme. An open access, user-friendly, digital platform to readily access information about key species (e.g., invasive species) under a "Social-Ecological System Knowledge Node" format to inform decision-making and strengthen Galapagos local and regional governance. Assessment of plant and animal diversity in the GNP and on 40 farms to determine the status of biodiversity and to identify priority sites for future conservation activities.

	3.3 Monitor changes in plant communities in areas under restoration.	Improved understanding of the conservation status of terrestrial biodiversity and their interactions with natural (GNP) the socio-ecological (agricultural zone) systems. Updated assessment of terrestrial biodiversity and ecosystem services focused on ecological information from the highlands to support the implementation of the new zoning format (from 2016) in the GNP. Innovative management of terrestrial invasive species in the protected and agricultural areas to protect biodiversity and promote sustainable agriculture in a scientifically validated way.
	3.4 Evaluate the impact of restoration by estimating the stored carbon and CO_2 sequestration rates of the ecosystems under restoration	Better general information on the environmental quality of the ecosystem under restoration, like information on nutrient cycling, water erosion, enhanced water quality, herbicide movement, etc. Enhanced information on the amount of CO2 captured by the ecosystem under restoration. Quantification of carbon stocks and productivity in restored Scalesia forest in the Galapagos Islands. Assessment of carbon stocks and CO2 removed annually at the landscape scale. Determination of the links between soil organic carbon and water holding capacity established in restored Scalesia forests. Promotion of ecosystem resilience to climate change by increased biodiversity in restored Scalesia forests. Identification of areas of high conservation value for mitigating greenhouse gas emissions and preserving biodiversity in the face of changing climate

5.1. EBA measure 1: Strengthen control programs for invasive plant species, especially blackberry, in protected and agricultural areas, based on projected dynamics of their expansion under climate change scenarios.

TARGET INDICATORS	
• At the end of the project, 1500 ha of priority conservation area freed of invasive plant species and prepared for the restoration with *Scalesia* and other native and endemic plant species.	
• At the end of the project, conservation status of natural vegetation assessed in 1500 ha of Scalesia forest	
BENEFICIARIES	
Direct	• 80% technical staff of the GNPD working in the ecosystem department trained in innovative control techniques. • 100% farmers, from at least 10 farms, participating in this project trained in innovative control techniques. • 100% farmers, from at least 10 farms, obtain land free of invasive plants to carry out sustainable agricultural production. • 100% of technical workers of farm trained in innovative control techniques
Indirect	• ABG • Tourism operators

5.1.1. Description of the current situation and baseline

The florae of oceanic islands are under threat from results of global climate change, like increased precipitation and temperatures, which is also predicted for the Galapagos Islands (Harter et al. 2015). Here, invasive alien plant species are expected to thrive in wetter and warmer weather conditions, which would exacerbate the threats that these species already pose to vulnerable native species and degraded ecosystems such as the Scalesia forest (Trueman and d'Ozouville 2010). This is especially true for the invasive guava and blackberry (Renteria et al. 2012; Urquía et al. 2019). Research has shown that the mortality of adult *Scalesia* trees in blackberry-invaded areas is very high, which is problematic, since the blackberry thicket prevents the passing of light, required for germination of the tree seeds, which leads to further degeneration of the forest (Rentería et al. 2012, Jäger et al. 2017).

In the agricultural area, invasive plant species thrive on abandoned farms. A census in 2014 revealed that about only 45.5% (~8700 ha) of the total productive area of about 19,000 ha in Galapagos was used for agricultural production, while the remaining area was abandoned (CGREG 2014), with 21.5% of this area covered by invasive species, mainly guava and blackberry (Laso et al. 2020). The reason for the abandonment of farms is the fact that jobs are more lucrative in the tourism industry, especially for the young adults (Sampedro et al 2018). This trend has resulted in decreases in local agricultural production, reducing reliance on food produced in the islands and a decreasing food security (Sampedro et al. 2018). The abandoned land represents a source for the spread of introduced species (Laso et al 2010), which has negative impact on the surrounding agricultural land that is under production, as well as on the adjacent protected National Park areas (Sampedro et al. 2018). The most damaging species is blackberry, as it is the most problematic species on the farms, followed by guava, sauco (*Cestrum auriculatum*) and escoba (*Sida rhombifolia*) (Jäger et al. 2019). Especially blackberry and guava actively invade native vegetation (i.e. forest fragment remnants) and agriculturally productive areas in the highlands (Snell et al. 2002, Rentería and Buddenhagen 2006).

To respond to these negative impacts, the Galapagos National Park Directorate has been controlling invasive plant species over the last 50 years with a varying intensity and success (Tuoc 1983, Jäger and Kowarik 2010, Shackleton et al. 2020, Appendix 2). Control efforts are directed at areas of conservation value that host threatened endemic plant and animal species (DPNG 2021). Examples include the Scalesia forests and the *Miconia robinsona* vegetation zones on Santa Cruz, home to the threatened Galapagos petrel (*Pterodroma phaeopygia*) and Galapagos rail (*Laterallus spilonota*). Blackberry is also being controlled on San Cristóbal, Santiago and Isabela, whereas on Floreana, mainly the invasive plants *Lantana camara* and Mother-of-millions (*Bryophyllum pinnatum*) are being controlled (DPNG 2021). For the woody species, control usually consists of the '*hack-and-squirt*' method (see sub-activity 1.1). Herbaceous species are usually being sprayed with Glyphosate and the regrowth, as well as resprouts from controlled plants, are being cut down with a machete or pulled out by hand (DPNG 2021). However, all these control actions are very labor-intensive and therefore expensive and often not sustainable in the long run or possible over larger areas (FIAS 2018).

Between 2002 and 2011, the project “The control of invasive species in the Galapagos Archipelago” was directed by the Ministry of the Environment in Ecuador (Coello and Saunders 2011). This project was funded by the Global Environment Facility (a total of US$18.65 million), with counterpart or matching funding of US$32.5 million from the GNPD, the Charles Darwin Foundation, the Government of Ecuador, the German Government and other institutions (Coello and Saunders 2011). A management plan for the terrestrial and marine areas of the Galapagos National Park was implemented in 2014 (GNPD 2014), with an annual budget of about US$ 2.5 million for the control of invasive species (Shackleton et al. (2020), Appendix 2). However, challenges posed by invasive species have increased since 2014 and available funding for the control of these invaders, especially of guava and blackberry, is not sufficient for the high demand of manual labour required for this work (Toral-Granda et al. 2017). In addition, research on impacts of control actions in the fern-sedge- and *Miconia robinsoniana* vegetation showed that native vegetation can regenerate after invasive species control (Jäger et al. 2009). This research also revealed that the same or other invasive species became more abundant after control actions were carried out and can counteract restoration efforts (Jäger et al. 2009, Jäger and Kowarik 2010, Restrepo et al. 2012). Therefore, any control or eradication efforts in Galapagos should be integrated into a holistic restoration process to avoid adverse effects on the ecosystems (Zavaleta et al. 2001). To obtain this, the module proposed does not only carry out the invasive species control but also applies an immediate subsequent reforestation of the controlled area with native plant species to suppress invasive species regrowth (see EBA 2) (Kettenring and Adams 2011). This kind of holistic approach toward restoration of the ecosystem is essential (McAlpine et al. 2016), as is the subsequent long-term monitoring to evaluate the success of control methods applied and potential negative impacts on non-target species (Cheney et al. 2020).

5.1.2. Objective and justification of the proposed EBA

This EBA addresses urgent actions needed to mitigate ongoing threats to vulnerable species and ecosystems, and to minimize the additive impacts of future climate change (see section 4). Therefore, the objective of this module is to contain the spread of invasive plant species in high ecological value forest fragments in the GNP and on selected farms in the agricultural zone. Invasive plant species will be contained through the following approaches: (1) Limiting the distributions and therefore impacts of invasive species on native and endemic species and (2) Preserving remnant forest habitats from further degradation through invasive species control.

For this, priority areas, defined as areas with high hydrological and ecological importance, have been identified where invasive plant species control is proposed by this module, (see section 4) and the area controlled will be a) left to regenerate on its own, allowing ecological succession to take place (passive restoration) or b) restored with native species (active restoration, see EBA 2).

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 Strengthen control programs for invasive plant species in an area of 750 ha within the Galapagos National Park, with emphasis on guava and blackberry.

Large areas of the humid zone within the GNP are invaded by exotic plant species. In the case of Santa Cruz, this applies to more than 55% of the GNP (Trueman et al. 2014). To be able to tackle such a huge challenge, the GNPD needs to apply innovative control measures for invasive plant species. This approach will help to upscale the different restoration projects currently under execution, to increase restoration success, while at the same time reducing the costs. This includes an urgent need to apply easy-to-use and inexpensive solutions to implement restoration to protect native species and recover degraded forest fragments, while improving human livelihoods (Shackleton et al. 2020, Weidlich et al. 2020). Therefore, mapping is an important tool for the management of plant invasions, since it helps the GNPD staff to decide where to prioritize their efforts. The approach taken in this module includes the mapping of the guava distribution in different climate change model scenarios (see section 4). In addition, estimations will be carried out for the distribution of blackberry, in an area of ca. 750 ha (400 ha on Santa Cruz, 200 ha on San Cristóbal and 150 ha on Isabela). Control of invasive species will be carried out in key areas, stretching over the same 750 ha in the GNP. Blackberry bush will be cut down with a machete to ca. 5 cm off the ground and Combo will be sprayed with a backpack sprayer onto the regrowth after 2 months (Jäger et al. 2017). Combo will be used since it proved to be most effective for for the control of guava and blackberry (Yánez et al. 2004; Jäger et al. 2017, Jäger, unpubl. data). Re-growth and seedlings germinating from the seeds will be pulled out by hand.

The management of invasive blackberry requires a long-term commitment, since species resprout readily after control actions and seeds maintain viability in the soil for many years (10 years in the case of blackberry). Through capacity building within GNPD staff, invasive plant species control capacities will be strengthened by monthly meetings on-site, with evaluation of visual impressions, followed up by data-supported results from the monitoring activities (see EBA 3). This way, applied control techniques will be constantly monitored and evaluated to ensure high efficacy, while at the same time minimizing negative impacts on non-target species. In addition, an information system of invasive species will be implemented to support adaptive management of the GNPD invasive species control program (see EBA 3).

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

a. Guava and blackberry climate change distribution models verified and adjusted, based on ground surveys.
b. Prioritized areas within the GNP (a total of 750 ha) under innovative control schemes.
c. Dispersal of invasive species, mainly blackberry, contained in an area of 750 ha, with minimal impacts of control actions on the resident flora and fauna.

d. Protocols developed to ensure successful ongoing invasive species control and to strengthen the Terrestrial Invasive Species Program of the GNPD strengthened for long term control under climate change scenarios.

Sub activity 1.2: Implement invasive species management and control measures on farms in an area of 750 ha in the agricultural area.

Agricultural production in Galapagos faces a set of challenges due to the invasion of crop land by exotic plant species. The impact of invasive plant species on agricultural production has received far less attention than the risk that these poses to the protected areas (Jäger et al. 2019). Food in Galapagos is to a large extent imported from mainland Ecuador, despite recent regulations promoting the local production (Sampedro et al 2018). The local agricultural production in 2014 was 7,085 metric t/year, while the entry of products from the mainland was 19,066 metric t/year (MAGAP 2016). However, these imports facilitate the introduction of agricultural pests and invasive species, decreasing the profitability of local production, since invasive species have to be controlled (Viteri and Vergara, 2017). Sustainable farming production is key for the environmental conservation of the agroecosystems of Galapagos and for ensuring food security for the inhabitants (Sampedro and Mena 2018). These systems are crucial for food security and the control of invasive plants and therefore, this module highlights the importance of practitioners of both conservation and agriculture need to collaborate to pursue a common goal, which is the sustainable restoration and rehabilitation of the Galapagos highlands (Laso et al. 2020). Therefore, in collaboration with the GNPD, the Ministry of Agriculture and Livestock (MAG) and NGOs with ongoing activities and ample experience in improving agricultural production in Galapagos, we propose measures to sustainably control invasive species in the agricultural zone of Santa Cruz, San Cristóbal and Isabela. The GNPD will be share their knowledge and expertise on invasive species control in the GNP with the technicians carrying out the control in the agricultural zone, supported by MAG and the NGOs to assure maximum success of control measures applied.

During the first 6 months of the project, a baseline will be established in the agricultural zone on Santa Cruz, San Cristóbal and Isabela to assess the conservation status of Scalesia forest fragments and the severity of the distribution of invasive species. Since most of the introduced plant species are found in the agricultural zone (Guézou et al. 2010, Laso et al. 2020), it is key to work with the agricultural sector to improve land management practices to protect, conserve and sustain resources, like soil, water and biodiversity. A particular attention has to be paid to limiting the expansion of invasive plants into native ecosystems. Thus, 40 farms within the agricultural area will be included in the restoration process, with an emphasis on strengthening active agricultural practices to control invasive species and establish crops to compete with these. Based on the modeled expansion of guava under climate change scenarios (see section 4) and ground surveys, 750 ha will be identified in the agricultural areas of Santa Cruz, San Cristóbal and Isabela. Currently, control methods are limited to manual removal and herbicide application. The same method ("*hack-and-squirt"*) suggested for the control of invasive species within the GNP will be used here (see sub-activity 1.1).

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

a. Assessment of the conservation status of 750 ha of Scalesia forest fragments in the agricultural area (400 ha on Santa Cruz, 200 on San Cristóbal and 150 ha on Isabela). These are an additional 750 ha to those being controlled in 1.1.
b. Areas freed of invasive species that are now available for agricultural production.
c. Strengthening active agricultural practices in 750 ha to control invasive species in collaboration with MAG, GNPD and ongoing civil society/private restoration and sustainable production efforts.
d. Proven and safe control of invasive plant species implemented that help preserve and promote native biodiversity, while at the same time keeping invasive species at bay.

5.1.4 Description of the species that make up the module.

Guava (*Psidium guajava*)

The native range of guava is the tropical zone of America and it was introduced to San Cristóbal in 1869. It has spread rapidly in the humid zone of inhabited islands and since the 1950s, it is being considered invasive. Guava alters large areas of different ecosystems (Walsh et al. 2008). Guava covers about 6.836 ha in the agricultural area (27% of total area, Laso et al. 2020) and together with other invasive plant species, covers about 2-5% of the GNP area (Watson et al. 2009, Rivas-Torres et al. 2018b). Galapagos tortoises (*Chelonoidis* spp.) and other animals consume the fruit of this plant and disperse its seeds (Blake et al. 2012, Heleno et al. 2013).

Blackberry (*Rubus niveus*)

Rubus niveus is a large perennial scrambling prickly shrub; it can grow up to 5 m in height and form dense thickets of intertwining stems and displaces native vegetation and threatens native communities. It is recognized as one of the worst weeds in Galapagos, seriously impacting both biodiversity and agriculture (Rentería et al. 2012). *Rubus niveus* can invade different habitats including grass, bracken, shrub land and forest. In the remnant *Scalesia pedunculata* forest of Santa Cruz, a high cover of *R. niveus* (above 60%) was found to be associated with lower plant species richness and cover, and a simplified vegetation structure (Rentería et al. 2012). Dense stands of *R. niveus* change the usual forest microclimate, creating a dark and wet habitat that may prevent the recruitment of the dominant native shade-intolerant species. In the agricultural zone, *R. niveus* has spread aggressively and as a result, the land is now unusable for agriculture and/or livestock, which causes serious economic problems for the farmers (Jäger et al. 2019). While already a widespread and serious problem on San Cristóbal and Santa Cruz, *R. niveus* is now also spreading rapidly on Isabela, Floreana and Santiago.

5.1.5 Technologies to be promoted through the module.

a) Large-scale innovative control measures applied in protected and agricultural areas. This consist of a combination of a chemical method (hack-and-squirt), followed by mechanical (machete cuts) and manual (hand-pulling) control techniques.

b) Improved detection, identification, reporting, and response to invasive species due to large-scale on the ground work.
c) Enhanced communication between the invasive species managers and landowners due to interactive workshops organized annually.
d) Improved long-term control of invasive plant species through courses to train farmers in the correct and successful methods to do so.

5.2. EBA measure 2: Restore key remnant forest fragments in protected and agricultural areas to enhance ecosystems adaptive capacity and provision of environmental services.

<table>
<tr><td colspan="2">TARGET INDICATORS</td></tr>
<tr><td colspan="2">At the end of the project, 1500 ha of priority conservation area freed of invasive plant species restored with Scalesia and other native and endemic plant species and ecosystem services restored.</td></tr>
<tr><td colspan="2">At the end of the project conservation status assessed of Scalesia forest in1500 ha.</td></tr>
<tr><td colspan="2">BENEFICIARIES</td></tr>
<tr><td>Direct</td><td>80% technical staff of the GNPD working in the ecosystem department trained in successful planting of Scalesia and other native and endemic species.
100% farmers, from at least 10 farms, participating in this project trained in successful planting of Scalesia and other native and endemic species.
100% farmers, from at least 10 farms, benefitting from sustainable agricultural production.
20% farmers, from at least 5 farms, with improved coffee production within the Scalesia forest
100% of technical workers of farm trained in innovative control techniques</td></tr>
<tr><td>Indirect</td><td>Tourism operators from Santa Cruz, Isabela and San Cristobal.
Coffee producers</td></tr>
</table>

5.2.1. Description of the current situation and baseline

The Scalesia forest of the humid highlands on the inhabited islands (of different *Scalesia* species) is now estimated to cover less than 1% of its original extent (Mauchamp and Atkinson 2010). For example, on Santa Cruz, the *Scalesia pedunculata* forest decreased in the agricultural area from 5,737 ha in 1930 to 4,066 in 1960 to 1,614 ha in 1990, and to very few hectares today. On a finer scale, we determined that in a 1981 survey of 443 hectares in the agricultural zone of Santa Cruz, 48% was covered with *Scalesia pedunculata*. In 1993, only 16% of that area was covered with Scalesia (a 67% reduction in 12 years). Hardly any *Scalesia* trees were found in this area in 2020 (Jäger, unpubl. data). The situation in the protected area is similarly dreary. Here, the *Scalesia pedunculata* forest on Santa Cruz declined from 2,874 ha in 1930 to 1,636 ha in 1960 to 858 ha in 1990, and to only about 330 ha today (Jäger, unpubl. data). The largest remaining forest fragments on Santa Cruz are around the twin craters ‘Los Gemelos’ (Itow 1995). On Isabela, it is estimated that only about 300 individuals of *Scalesia cordata* are remaining (Jäger, unpubl. data). The are clustered in small groups rather than in forest remnants and are located at the base of the volcanoes of Sierra Negra and Cerro Azul (Mauchamp and Atkinson 2010). Hardly any forest remnants are left on San Cristóbal (Mauchamp and Atkinson 2010).

The remaining forest fragments are exposed to progressive degradation due to the synergistic effects of the invasion of alien species and climate change. The two strong El Niño events in 1982–83 and 1997–98, marked by anomalous warming of the sea surface temperature, air temperature and extreme precipitation, resulted in substantial impacts in the terrestrial ecosystems (Trueman et al. 2010). Scalesia forests reported high mortality, possibly due to the tree roots losing their ability to sustain the trees, because of excess water in the soil (Hamann 1979). These observations have helped us in understanding the vulnerability of species and ecosystems to potential future changes to the climate in Galapagos. *Scalesia pedunculata* may be particularly affected by ENSO, since it exhibits a natural stand-level dieback and regeneration that appears to be linked with El Niño and La Niña events (Hamann 2001).

Higher precipitation, as predicted for Galapagos, could threaten the humid zone ecosystems by changing vegetation growth rates and forest structure (Di Carlo et al. 2010). Additionally, increasing temperatures could cause species, like the *Scalesia* species, to shift their ranges to higher elevations (Larrea and Di Carlo 2011). This, combined with the short life expectancy of the *Scalesia* species, makes them more vulnerable to long-term disturbances (Hamann 2001) and to invasive species (Jäger et al. 2009)

The area of about 25,000 ha in the agricultural zone areas on the islands of Santa Cruz, San Cristóbal and Isabela, harbors a large area dominated by native vegetation (18.8%, ~ 4,600 ha) in the agroecosystems (Laso et al. 2020). This finding represents an excellent opportunity for the conservation and sustainability of ecosystem resources in these areas. As a result, some of these private farms do not only cultivate crops but also preserve fragments of native vegetation (i.e. Scalesia forest). In the humid highlands, this is crucial for capturing moisture, for fog interception, water conservation, pollinators, among other services (Chamorro et al. 2012, Pryet et al. 2012). Having these ecosystem services on their farms is an incentive for protecting the Scalesia forest, since there is an increasing awareness among the farmers about the benefits of having a Scalesia forest on the farm. A recent survey of 40 farmers on Santa Cruz showed that almost 50% (19) indicated that they wanted to either restore *Scalesia* on their land (in cases where they still had remnant patches) or wanted to plant *Scalesia* (in cases where they had *Scalesia* in the past) to increase the attractiveness of their farms to tourism, especially in the cases where the farms also host the iconic giant tortoises (Jäger, unpubl. data).

5.2.2 Objective and justification of the proposed EBA

Apart from control of invasive species, restoration actions include active restoration measures in areas where the focal threatened species is not able to regenerate without human intervention (Buddenhagen et al. 2004, Wilkinson et al. 2005). Restoration efforts should be focused on core preservation areas with high conservation values. A connection of these core areas of forest remnants of high conservation values through forest restoration efforts proposed in this EBA, will result in larger patches and an increasing community resistance to further invasion by introduced plants (Janzen 1988). These core areas will grow over time, if initial obstacles to restoration are overcome (i.e. mass production of *Scalesia* seedlings, hesitating participation of landowners, etc.). Once established, these areas will become valuable sources of seed for the restoration of this and other degraded forest fragments (Wilkinson et al. 2005). In areas where there is still a native species seed bank and conditions for a natural regeneration seem optimal (Jäger et al. 2007), active restoration might not be needed (passive restoration). In the case that an active reforestation with *Scalesia* species is necessary, seeds from as many different sites of that same area will be collected, as widely spread apart as possible, to increase the genetic diversity of offspring. Seeds will then be germinated and seedlings cultivated at the GNPD nursery greenhouses on Santa Cruz, San Cristóbal and Isabela, using proven successful methods to produce sufficient *Scalesia* seedlings to support the restoration of sites cleared of invasive plants.

This EBA addresses the preservation of intact habitat and the restoration of degraded native habitats. These approaches will improve forest fragment connectivity, ecosystem services, support biodiversity, enhance productivity and improve resilience against the effects of climate change, such as drought and aridity (see environmental benefits and adaptation scenario section).

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. Restore key remnant forest fragments in an area of 750 ha within the Galapagos National Park.

A total of 750 ha in the GNP will be restored with Scalesia and other native and endemic plant species (400 ha on Santa Cruz, 200 ha on San Cristóbal and 150 ha on Isabela). This is the same area that had been previously cleared of invasive plant species (see EBA 1, sub-activity 1.1). During the first 6 months of the project, a baseline will be established on Santa Cruz, San Cristóbal and Isabela to assess the conservation status of the 750 ha of forest fragments within the GNP. The assessment includes forest structure and composition. This baseline will allow us to prioritize fragments where to concentrate active and passive restoration actions. Further, nurseries of the GNPD on the three islands will be improved and equipped, as well as GNPD staff trained, to be able to mass-produce *Scalesia pedunculata* (on Santa Cruz and San Cristóbal) and *Scalesia cordata* (on Isabela), as well as guayabillo (*Psidium galapageium*), cafetillo (*Psychotria rufipes*) and uña de gato (*Zanthoxylum fagara*). *Scalesia* and the other species will be planted at a distance of 5 m to the next *Scalesia* or other species, this way, a total of 400 plants will be planted per hectare, totaling 300,000 *Scalesia* and other native and endemic species for the entire intervention area of 750 ha. On average, one person can plant the 400 plants per hectare in about 2 weeks. Once the 750 ha are planted, continuous follow-up control of invasive species has to be carried out (see EBA 1, sub-activity 1.1), as well as continuous re-planting of died-off seedlings. Restoration success will be evaluated with the help of permanent plots previously established and a vegetation mapping with drones and high-resolution satellite imagery (resolution of 0.5 m x 0.5 m) (see EBA 3). The prioritization and planting activity will be carried out in collaboration with NGOs with experience in restoration efforts.

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

a) Assessment of the conservation status of 750 ha of Scalesia forest fragments inside the GNP.
b) Nurseries of the GNPD on the three islands strengthened to provide native species seedlings to implement restoration activities.
c) 300.000 native plants successfully established in key restoration areas
d) 750 ha of key Scalesia forest fragments within the GNP under restoration schemes to protect threatened species and biodiversity.

Sub-activity 2.2. Conserve and restore key remnant forest fragments on farms in an area of 750 ha in the agricultural area.

The sub-activity will seek to integrate active restoration of the remaining fragments of native ecosystems that still exist on farms, as well as agroforestry practices to rehabilitate degraded agricultural areas. These practices will be implemented as a climate change adaptation strategy for increasing forest cover, number of endemic plant species, improving and maintaining the ecosystem services (like pollination, measured by the survey of the invertebrate community) and connectivity between forest remnant patches. The Ministry of Agriculture and Livestock (MAG), NGOs with ample experience in improving agriculture in Galapagos and the farmer’s associations will be involved throughout the entire implementation phase of this project.

Furthermore, over the last five years, having small patches of Scalesia forest on the farm has become an important tourist attraction (Jäger, unpubl. data). In addition, more and more farmers have turned to producing “Galapagos” shade growing coffee offering them a lucrative income. In this agroforestry system they use *Scalesia* and other native species as shade trees (Ortiz and Henderson 2011). In addition, agroforestry systems play an important role in improving water recharge and sustaining productivity, especially during the dry season (Warrier et al. 2012). Therefore, *Scalesia* trees and other native species on coffee farms will encourage the incorporation of agroforestry systems such as bio-diversification and silvopastoral systems in forestry incentive payment schemes. Furthermore, native trees could also serve as live fences within the diverse matrix of agricultural areas.

The objective of this sub-activity is to restore and rehabilitate at least ten abandoned or inactive farms within agricultural landscapes into productive areas supporting native ecosystems, with potential biological ecosystem conservation (5 on Santa Cruz, 3 on San Cristóbal and 2 on Isabela).

The specific sub-activities to implement the restoration practices in the selected farms are:

a) Design and implement a conservation categorization system and management protocols for farms on Santa Cruz, San Cristóbal and Isabela.
b) Protecting forest for ecosystem functioning and connectivity (protection of 750 ha). This practice consists of managing the native forest fragments on farms through active restoration actions for conservation/protection of environmental services, like increase in water availability through interception of fog (garúa), pollination, among others.
c) Preparation of projects that will be the object of forest incentives mechanisms promoted by local institutions (MAG, GNPD, among others). These financial mechanisms will provide resources for farmers to facilitate the implementation of appropriate forestry practices to conserve and restore forest cover.

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

a. 750 ha of agricultural land restored with *Scalesia* spp. and other native tree species, totaling 300.000 planted individuals (400 ha on Santa Cruz, 200 ha in San Cristóbal and 150 ha on Isabela) on at least 10 farms (5 on Santa Cruz, 3 on San Cristóbal and 2 on Isabela).

b. Increased connectivity between key forest fragments on farms through restoration carried out under b.

Sub-activity 2.3. Outreach activities and workshops with local community on importance of ecosystem services and how they benefit livelihoods

Training courses in restoration practices will be held for interested farmers to improve their management skills, who can then be involved in the project activities as qualified workers. Outreach activities will engage with local farmers from the project onset to ensure their support. This will be done through roundtable discussions on the proposed activities and the benefit to them, through workshops and training on Scalesia cultivation, as well as field trips to project sites. This strategy will ensure the agricultural community is engaged with the project and supports it, which is key for the success of conservation efforts. In addition, to support these communication efforts, leaflets will be produced (digital and in-print) to be distributed, not only to farmers, but also to students, local authorities and tour operators, outlining the benefits of the project, not only for biodiversity conservation but also for the local community.

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

a) Farmers trained in restoration practices to be involved in project activities as qualified labor force.
b) Biannual meetings held with the local authorities (e.g GNPD, MAG, the Galapagos Governing Council (CGREG) and the municipalities), to discuss project progress.
c) Publication of an annual technical report to the local authorities with recommendations based on the results of the monitoring (see EBA 3), to assure constant adjustment of project activities.
d) At least two presentations each are delivered at a national and international level about the project’s outcome and importance for the conservation of the Galapagos biodiversity.
e) At least two publications in open-access peer-reviewed scientific journal, discussing the key results and outcomes of the project.

f) Regular public posts on the project progress on social media, institutional blog posts and through press releases, to reach an even wider local, national and international audience.

5.2.4 Description of the species that make up the module.

Among the species that will be used for restoration, we will include:

Scalesia (*Scalesia* spp.): *Scalesia* is a genus of the family Asteraceae that is endemic to the Galapagos Islands. The genus consists of 15 endemic species that span from little shrubs to trees up to 15 m. Each of the species has adapted to different vegetation zones across the different islands. The unique forest comprised of different *Scalesia* species exhibits the highest number of plant and animal species in the highlands and are home to the Darwin's finches and flycatcher species, whose populations are currently in dramatic decline (Dvorak et al. 2012). *Scalesia pedunculata* is considered VU (vulnerable) and *Scalesia cordata* EN (endangered) according to the IUCN red list. However, both evaluations are outdated (from 1998) and need an urgent update (Tye and Loving 1998). Based on field observations, the actual categories should rather be EN for *Scalesia pedunculata* and CR (critically endangered) for *Scalesia cordata* (Jäger, unpubl. data). The Scalesia spp. have a very short life cycle (in the case of *Scalesia pedunculata*, up to 15 years, Hamann (2001)). Flower production of *Scalesia pedunculata* begins at 1-2 years of age and seeds germinate in forest openings. The tree can reach 4-4.5 m in height in a year and a total height of 10-15 m when mature (Itow, 1995; Hamann 2001). Cohort recruitment has been related to El Niño events, which periodically affect the archipelago. Increased rainfall appears to result in massive mortality of adult plants and massive recruitment from the seed bank (Lawesson 1988; Itow and Mueller-Dombois 1988). However, with the current invasion of the Scalesia forest by blackberry and guava, these massive recruitments events have not occurred anymore during recent years (Rentería et al. 2012, Jäger et al. 2017).

Miconia (*Miconia robinsoniana*):

Miconia robinsoniana is endemic to Galapagos and only occurs on Santa Cruz and San Cristóbal. The Miconia Zone on Santa Cruz extends from approximately

500 to 680 m above sea level and is dominated by the shrub *M. robinsoniana* (Melastomataceae), which can grow to 3m in height. On San Cristóbal, the Miconia zone is very reduced and can mainly be found around the lake 'El Junco' and in some areas of the agricultural zone. On both islands, the *Miconia* zone is heavily affected by invasive plant species, especially by blackberry and by guava. On Santa Cruz, it is also adversely affected by the invasive quinine tree (*Cinchona pubescens*). *Miconia robinsoniana* is considered EN (endangered) according to the IUCN red list. The Miconia zone provides important ecosystem services, as well as water regulating services in the highlands of Santa Cruz (Villa 2018).

5.2.5 Technologies to be promoted through the module.

a) Microclimate loggers

To obtain better information on invasive species and climate change impacts, presence and abundance of invasive plant species and microclimate parameters (air temperature, relative air humidity, precipitation, light availability) need to be simultaneously measured in the ecosystems.

b) Identifying pest species on *Scalesia* spp.

To guarantee project success, adverse impacts of invasive insects and pathogens on *Scalesia* and other resident tree and shrub species have to be addressed, since these are expected to increase in Galapagos due to climate change (Trueman et al. 2010). This also applies to the agricultural zone, where more species have been encountered that adversely affect crops (Cañarte Bermúdez et al. 2020).

5.3. EBA measure 3: Monitor success and impacts of invasive species control and restoration measures

TARGET INDICATORS	
At the end of the project, 1500 ha of restored Scalesia forest under a regular monitoring scheme, including a quantification of carbon stocks and productivity in restored Scalesia forest.	
At the end of the project, validation of innovative restoration practices with minimal impact on water and soil.	
BENEFICIARIES	
Direct	• 100% of participants in the monitoring program trained in the latest techniques. • GNPD technical staff from the ecosystem department • 100% farmers, from at least 10 farms, benefitting from low impact restoration practices, including invasive species control.
Indirect	• ABG

5.3.1. Description of the current situation and baseline

The objective of this module is to inform and improve the management of terrestrial invasive species and restoration actions in the highlands of Isabela, San Cristóbal and Santa Cruz. Predicting future ecosystem dynamics depends critically on an improved understanding of how disturbances and climate change have driven long-term ecological changes in the past (Salinas-de-León et al. 2020). Permanent plots allow for the characterization and modelling of active ecological processes. Since these processes can be spatially autocorrelated (e.g., pathogens, insects, windthrow, etc.), the plots provide the context to analyze how these climate- and human-driven processes are changing vegetation communities and ecosystem dynamics. Long term data from permanent plots can be used to determine how annual climate variation affects each agent of vegetation change, as well as to assess and understand the effect restoration actions over the system (see EBAs 1 and 2).

The Charles Darwin Foundation (FCD) has been monitoring over 180 permanent vegetation plots, ranging in size from 10 m x 10 m to 50 m x 50 m, since 1995 (Tye 2003). Using these long-term data sets allows us to document changes in the vegetation structure, like the distribution and expansion of invasive plant species, but also the efficacy of GNPD restoration efforts. However, to be able to address potential changes and to mitigate climate change impacts, it is indispensable to expand this monitoring and to include a coupled climatological monitoring for the different islands. This requires a better understanding of existing and past climate at a local scale that includes ecosystem complexity and changes along elevational gradients. Therefore, the current system of meteorological weather stations must be expanded and stations positioned in strategic places (see monitoring of marine ecosystems).

Monitoring the effects of management practices will prove to be more important the longer the series of permanent plot observations lasts. While it is important to establish new permanent vegetation plots, it is equally important to continue the monitoring of the plots already established. The plots provide crucial long-term baseline data that is essential to be able to address future changes in the vegetation due to interactive effect of climate change and human drivers of change (i.e. invasive species, e.g. Jäger et al. 2009). The data for some of these plots' dates back 20 and more years and correlated with climatological data, will allow for disentangling natural vegetation changes (with and without invasive species) from climate-related changes.

Additionally, assessment of vulnerability and prioritization of management action require an enhanced knowledge of the current spatial distributions of threatened and invasive species. It is critically important to have long-term data on plant community change in the different vegetation zones on different islands to be able to assess negative impacts of invasive species, as well as the vulnerability to climate change. This knowledge will provide science-based advice to the GNPD, MAG, the Galapagos Biosecurity Agency (ABG, acronym in Spanish) and other stakeholders on recommended efforts to mitigate invasive species and climate change impacts.

Through this EBA, restoration success will be evaluated with the help of permanent plots previously established and a vegetation mapping with drones and high-resolution satellite imagery (resolution of 0.5 m x 0.5 m, see section 5.3.5), in close cooperation with the GNPD and other relevant stakeholders.

Applied control techniques will be constantly monitored and evaluated to ensure high efficacy, while at the same time minimizing negative impacts on non-target species. The information produced through the monitoring program will inform the GNPD via co-implementing monitoring and restoration actions (EBA1 and 2), training, and outreach. In addition, the project will consolidate a data management and information system were all the information will be uploaded. It is envisaged the information system will inform restoration actions based on a adaptive management scheme.

Complementarily, to document restoration success and changes in the plant and animal communities of the forest fragments, a baseline will be established for different species on Santa Cruz, San Cristóbal and Isabela. Prior to the onset of restoration actions, 10 plots on each island will be established to document restoration success and changes in the plant and animal communities, as well as in the composition of agricultural crops.

Sub-activity 3.1. Assess current efforts and restoration needs, including evaluating current control techniques for invasive plant species.

This sub-activity includes two major tasks: (1) Evaluate current control techniques for invasive plant species, and (2) assess restoration efforts and necessities. For the first task, results from the monitoring of the plant communities in the permanent plots that had previously been controlled or are permanently being controlled, will be used to evaluate the efficacy and impacts of different control techniques for invasive plant species. This includes taking soil and water samples to determine contamination with herbicides. Research has shown that chemical control of invasive plant species can result in an accumulation of herbicide residuals in the soil (Gerzabek et al. 2019). Therefore, soil samples will be taken in at least 10 selected spots in the highlands of Santa Cruz, Isabela, Floreana and San Cristóbal from the top 15 cm and 10 water samples will be collected from natural water drains and grietas. Samples will be transported to the University of the Americas (UDLA) in Quito, Ecuador. Results will help to inform and adjust activities carried out under EBA 1. If residuals of the herbicides Combo are found to be accumulating in the soil, control actions will be stopped immediately.

However, based on previous studies, this is not very likely (Zehetner, unpubl. data).

With data obtained from new and already established permanent plots, restoration efforts carried out by the GNPD (e.g. reforestation of key species, and control of invasive species in Santa Cruz) will be evaluated using multivariate statistics such as multiple regression analysis. Evaluating the results from the monitoring work together with the modeling scenarios (see section 4), we will be able to: (a) identify the areas that are in need for active restoration with *Scalesia* species and other native species, and (b) select areas where a passive restoration is still possible. This distinction is important to be able to allocate scarce restoration funding accordingly.

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

a) Assessment of control techniques for invasive plant species in the Galapagos highlands, including the identification of the most cost-effective techniques with the lowest environmental risk and major impacts on invasive species.
b) Identification of priority areas to implement active and passive restoration actions, including the definition of locations to set up new permanent vegetation plots.

Sub-activity 3.2. Establish baselines for plant and animal species in areas under restoration, with a focus on rare species.

Ten new plots each (10 m × 10 m) will be established in selected representative areas in the protected and agricultural areas in the highlands of Santa Cruz, Isabela and San Cristóbal to establish a baseline for the plant communities, while at the same time visually recording key endemic animal species (e.g. giant tortoises, Galapagos rail, etc.) inside the plots and in a buffer zone of 10 m around the plots. The vegetation will be assessed using the line-intercept method (Kaiser 1983).

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

a) Consolidation of a data management and information system, where all the information will be uploaded. It is envisaged that the information system will inform restoration actions based on an adaptive management scheme. Adaptive management is the process of incorporating new scientific and programmatic information into the implementation of a project or plan to ensure that the goals of the activity are being reached efficiently. It promotes flexible decision-making to modify existing activities or create new activities, if new circumstances arise (e.g., new scientific information) or if projects are not meeting their goals. Thus, the data management system will be dimensioned to inform appropriate indicators in a faster and more accessible format for reporting, processing and analysis, that will translate into more effective mechanisms to disseminate results and enable near real-time adaptive responses.

b) An open access, user-friendly, digital platform to readily access information about key species (e.g., invasive species) under a "Social-Ecological System Knowledge Node" format to inform decision-making and strengthen Galapagos local and regional governance.

c) Assessment of plant and animal diversity in the GNP and on 40 farms to determine the status of biodiversity and to identify priority sites for future conservation activities.

Sub-activity 3.3. Monitor changes in plant communities in areas under restoration.

Monitoring of the plant communities will be continued in at least 150 of the currently 180 permanent plots established by CDF, using the line-intercept method (Kaiser 1983). The diameter at breast height (DBH) will be measured from key endemic species (like *Scalesia* spp) or invasive species (like *Psidium guajava* or *Cinchona pubescens*). For example, we will monitor plant communities in the 44 permanent 20 x 20 m plots (established in 1998), representing untouched (e.g. Los Picachos) to manually and chemically controlled plots (e.g. Media Luna, Puntudo and Cerro Crocker) to be able to disentangle climate impacts associated with El Niño from the impacts of invasive species and management control actions. It is widely acknowledged that long term monitoring is the best way to detect population and community responses to climate change, and our long-term plots represent a “gold mine” of information in this regard. Our work will focus on the key species quinine (*Cinchona pubescens*), blackberry (*Rubus niveus*), bracken (*Pteridium arachnoideum*) and Miconia (*Miconia robinsoniana*). Since blackberry has been detected in the plots during the last couple of monitoring, there is a high probability that it will increase and become dominant with increased El Niño rainfalls in the future (see section 4). Therefore, long-term data will be analyzed and related to available weather data. Further, during the monitoring of new and established permanent plots, we will determine the dominant (often introduced) insect species, since these are expected to increase in Galapagos due to climate change (Trueman et al. 2010). This also applies to the agricultural zone, where more species have been encountered that adversely affect crops (Cañarte Bermúdez et al. 2020).

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

a) Improved understanding of the conservation status of terrestrial biodiversity and their interactions with natural (GNP) the socio-ecological (agricultural zone) systems.
b) Updated assessment of terrestrial biodiversity and ecosystem services focused on ecological information from the highlands to support the implementation of the new zoning format (from 2016) in the GNP.
c) Innovative management of terrestrial invasive species in the protected and agricultural areas to protect biodiversity and promote sustainable agriculture in a scientifically validated way.

Sub-activity 3.4 Evaluate the impact of restoration by estimating the stored carbon and CO_2 sequestration rates of the ecosystems under restoration.

The activities below will be carried out at the beginning of the project and then again just before it ends, to be able to determine changes in the ecosystem.

- <u>*Measure aboveground plant biomass and nutrient contents*</u>

Climate change and high rates of global carbon emissions have focused attention on the need for high-quality monitoring systems to assess how much carbon is present in terrestrial systems and how these change over time. As a consequence, for the implementation of REDD+, it is crucial to determine the spatio-temporal variation of carbon stocks (Petrokofsky et al. 2012). Obtaining field measurements and developing estimation models to do so is an expensive and time-consuming task. A key challenge for successfully implementing REDD+ and similar mechanisms is the reliable estimation of biomass carbon stocks in above ground biomass. Biomass consists of approximately 50% carbon (Martin et al. 2018) and uncertain estimates of biomass carbon stocks resulting from difficult access, limited inventory and extent of vegetated ecosystems, makes the accurate assessment of carbon emissions difficult. The carbon stocks of interest are both above-ground and below-ground. Although above-ground biomass has generally attracted the most research over the years, pools of deadwood and litter could be as large as above-ground biomass. It is therefore essential that a variety of methods to measure deadwood and litter are being taken into account.

Aboveground biomass will be mainly measured using remote sensing, by the classification of vegetation cover and the generation of a vegetation type map, that would be calibrated, using regional-scale inputs of basal area and wood density of species in permanent plots (Asner and Mascaro 2014). This will partition the spatial variability of vegetation into relatively uniform zones or vegetation classes, which will be used to extrapolate biomass estimates. In addition, indirect estimation of biomass will be used, like quantitative relationship (e.g. regression equations) between band ratio indices (NDVI, GVI, etc.) and direct radiance values per pixel, with direct measures of biomass and parameters related directly to biomass, e.g. leaf area index, which would need to be assessed by this project. Results obtained will be validated by biomass measurements in the field of the live plant mass aboveground and belowground (using standard estimation methods - allometric and linear regression equations method), as well as the herbaceous layer on the forest floor, including the inert fraction in debris and litter (using standard methods, which include gravimetric and chemical analysis). Plant samples will be transported to the UDLA University in Quito, Ecuador, where analysis of the macro- and the main micronutrients will be conducted.

- *Measure soil and plant carbon and soil nutrients*

The biomass weight of standing trees is determined by total weight of trunk (trunk biomass) and crown dry weight (crown biomass) per hectare (see below for determining total weight of trunk and crown dry weight). The 50% amount of the dry weight of biomass is considered equivalent to the carbon stored in order to estimate the carbon stored in stands (Snowdon et al. 2002, Martin et al 2018). In the case of *Scalesia*, we expect to already have a crown when the plant is about one year old.

Carbon storage in soils is the balance between the input of dead plant material (leaf, root litter, and decaying wood) and losses from decomposition and mineralization of organic matter ('heterotrophic respiration'). Under aerobic conditions, most of the carbon entering the soil returns to the atmosphere by autotrophic root respiration and heterotrophic respiration (together called 'soil respiration' or 'soil CO2 efflux'). The mineralization rate is a function of temperature and moisture levels and chemical environment with factors such as pH, nitrogen level and the cation exchange capacity of the minerals in the soil affecting the mineralization rate of soil organic carbon (SOC). SOC stocks will be determined by a regression approach in which SOC densities (mass SOC/area) will be related to a number of auxiliary variables like temperature, precipitation, age class and land-use history. These measurements will be accompanied by a geographic information system (GIS) to calculate SOC densities for each vegetation type from available soil characteristic data and satellite-derived land cover information (Campbell et al. 2008). To validate results obtained, representative soil samples will be collected and transported to the UDLA University in Quito, Ecuador, where analysis of the macro- and the main micro nutrients will be conducted.

- *Calculate CO_2 sequestration of the ecosystems*

Carbon-sequestration capacity can refer to both the maximum rate of carbon storage and the maximum amount of carbon that can be stored. The reporting of annual rates of carbon storage and changes in carbon stocks is difficult because of the amount of annual variance in climate and in vegetation productivity. All ecosystems have a finite storage capacity for a given climate that is limited by ecophysiological constraints on primary productivity, respiration, and decomposition, resulting in a net carbon balance (Chapin et al. 2006).

We will estimate the amount of carbon sequestration based on wood density and allometric equations of tree crowns based on DBH were estimated. Crown dry weight will be multiplied by the number of trees of each species in different diameter classes. The trunk weight of trees in different diameter classes is calculated using the wood density and stand volume. The biomass weight of standing trees is calculated by total weight of trunk (trunk biomass) and crown dry weight (crown biomass). The weight of carbon dioxide in the trees will be determined by the ratio of CO_2 to C and the weight of carbon dioxide sequestered in the tree by multiplying the weight of carbon in the tree by 3.671 (IPCC 2005).

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

a) Better general information on the environmental quality of the ecosystem under restoration, like information on nutrient cycling, water erosion, enhanced water quality, herbicide movement, etc.
b) Enhanced information on the amount of CO_2 captured by the ecosystem under restoration.
c) Quantification of carbon stocks and productivity in restored Scalesia forest in the Galapagos Islands.
d) Assessment of carbon stocks and CO_2 removed annually at the landscape scale.
e) Determination of the links between soil organic carbon and water holding capacity established in restored Scalesia forests.
f) Promotion of ecosystem resilience to climate change by increased biodiversity in restored Scalesia forests.
g) Identification of areas of high conservation value for mitigating greenhouse gas emissions and preserving biodiversity in the face of changing climate.

5.3.4 Description of the species that make up the module.

Same species as described in EBA 1 and 2

5.3.5 Technologies to be promoted through the module.

a) Microclimate measurements

To measure air temperature, precipitation, relative humidity and soil moisture in the permanent plots, we will use Onset HOBO data loggers.

b) Measure plant biomass and carbon in plant and soil, as well as for CO_2 sequestration.

We will use a wedge prism to measure the basal area in diameter at breast height, for the measurement of diameters of the upper stem at a certain height of the tree, as well as the distance between trees. The wedge prism is used on one vertical plain and enables the calculation of the volume of the tree without its destruction. The non-destructive method is especially important when working in the protected ecosystems in Galapagos, like the Scalesia forest. A hypsometer will be used to estimate the height of trees. In addition, we will use tape measures, flagging tape and aluminium tree tags for the plot monitoring. Apart from this, we will use shovels, axes, pH meter, drying oven and a mobile soil analysis lab. All data and information will be processed using two Mac computers.

c) Vegetation mapping

For the remote sensing work, we will use the high-resolution satellite imagery provided by DigitalGlobe (DigitalGlobe 2021), which have a spatial resolution of 0.5 m panchromatic and 2 m multispectral. In addition, we will fly semiprofessional drones (DJI Inspire1, DJI MavicPro and DJI Spark), equipped with optical cameras at an altitude of 120 m above ground level. We will capture sequences of overlapping images, with which we will generate digital elevation models and orthophotos with a 5 cm x 5 cm spatial resolution. This allows us to determine and document the location and abundance of plant species that are notoriously difficult to map with a high accuracy, like blackberry.

d) Meteorological stations

Relate the data obtained in the monitoring under EBA 3 with climate data obtained from the meteorological stations in section “Monitoring of marine ecosystems”.

5.4. Impact on the resilience of the Galapagos system

Wholesome and functioning ecosystems enhance the natural resilience to the negative effects of climate change and reduce the vulnerability of endangered species, as well as improving livelihoods. This module proposes to use biodiversity and ecosystem services as part of an overall adaptation strategy to help species and people to adapt to the adverse impacts of climate change.

Impact on the resilience of ecosystems:

The Galapagos National Park Directorate (GNPD) has emphasized the importance of invasive species research and control in their Galapagos Invasive Species Management Plan (FIAS 2018). The need to understand the vulnerability of endemic and native biodiversity to climate change and possible invasive species impacts to Galapagos ecosystems is underscored in their Management Plan (GNPD 2014). Ecological restoration of degraded communities is not to achieve one target but to reestablish the temporal and spatial diversity inherent in natural ecosystems.

The percentage of the humid zone in the entire landmass of the Galapagos Archipelago is relatively small (~13%, INGALA et al. (1989)) and it provides important ecosystem services, like soil, water and biodiversity conservation, as well as carbon sequestration and the provision of local livelihoods. Yet the humid zone also houses most of the introduced plant species (89%, CDF, unpubl. data) and is the most degraded of all vegetation zones zone (degradation of 38% on Floreana, 88% on Santa Cruz and 94% on San Cristóbal, Watson et al. 2009), mainly due to the conversion to agricultural land in the past. The greatest obstacle to restoration success may not be lack of knowledge or funds, but lack of a cohesive framework to facilitate decision making. A state-transition model can be used to enact proactive management by maximizing restoration opportunities and minimizing obstacles (Bestelmeyer et al. 2010).

The restauration of this ecosystem with activities proposed in this module will increase its resilience, especially towards invasive species that affect the unique ecosystems and agricultural crops alike. The restoration of native and agricultural ecosystems will also gradually decrease the need for use of herbicides, which pose a further threat to human and environmental health. For example, in the experimental plots in the Scalesia forest on Santa Cruz, in the beginning, several herbicide applications were applied for the control of blackberry. But over time, only manual methods (hand-pulling) are applied now, since native vegetation is displacing blackberry and blackberry is resprouting less (Jäger et al. 2017, Walentowitz et al., submitted). Since the method of controlling invasive species, especially blackberry, has proven to be very successful over the last seven years Jäger et al. 2017; Jäger, unpubl. data), it can serve as a model for the control proposed for the protected and agricultural areas in this project.

Regarding mitigation, by protecting native forest remnants and increasing agricultural productivity through restoration and rehabilitation strategies, carbon sequestration and create/maintain microclimatic conditions will be incremented that will favor the sustainability of a cropping system. By providing shaded areas and shelter, the overall climate variability impacts will be reduced, and therefore soil moisture retention, reduce water loss from soil evapotranspiration and crop transpiration, and increase soil fertility will be increased. Their inclusion in such programs will help to maintain and restore native ecosystem integrity, safeguards livelihood benefits and thereby increase resilience to climate change.

Impact on the resilience of livelihoods:

To determine the links between viable livelihoods and restoration, it is important to develop an understanding of the economic, policy and social pressures that lead to current land use changes, like the abandonment of land and subsequent invasion by introduced species, and to identify strategies to incorporate biodiversity restoration in this land use. The conservation and restauration of native ecosystems promotes the protection of the plant and animal species unique to Galapagos. The protection of these ecosystems with their species has social benefits at a local and global level. Locally, translating to protecting these ecosystems also maintains the livelihoods of a nature-based tourism economy. By maintaining biodiversity, these areas may become an attractor for tourists which would increase the economic benefits of local inhabitants. Globally, translating to preserving a UNESCO World Heritage Site with its unique species. In addition, conserving and protecting these native ecosystems will enhance the water capture through tree leaves intercepting the heavy fog during the cool season (garúa) that will eventually charge the aquifers on the islands (Auken et al. 2009).

Invasive species, such as guava and blackberry, have adverse effects on farmland crops and farmers spend large amounts of money to combat these. Where farmers do not have the funds to control the invader, these species simply take over and turn formerly productive fields into wastelands, which then become unusable for agricultural production or native reforestation. However, many of these farmers are willing to plant *Scalesia* on their land if they had financial help for this. Having *Scalesia* on the farm would increase its biodiversity and could also be used it as a shade tree for the famous Galapagos coffee that is now increasingly grown on the islands. Controlling an even larger spread of these invasive species under a climate change scenario will help to ameliorate the effort required for their removal in croplands. This not only reduces costs for food production but also reduces the exposure of herbicides to farmers, consumers and the ecosystems, promoting better health conditions. Reforestation by endemic plant species, such as *Scalesia*, helps maintaining this land free of invasive species and promotes sustainable agroforestry practices.

This intervention will build capacity amongst local and national stakeholders and increase awareness of the local community to protect the terrestrial ecosystems from the invasion by alien species that can lower the resilience and affect livelihoods.

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