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RESEARCH ARTICLE

Biodiversity, Planning and Development – Towards Best Practice

Plant science meets the decision-making process of restoration in quarries and waste dumps of a remote archipelago

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Abstract

1. Special Services Sites (SSS) in the Galapagos refer to anthropogenically degraded areas such as quarries and waste dumps. These areas pose significant challenges for restoration due to adverse physical and weather conditions that hinder plant survival. Since 2013, the Galapagos Verde 2050 (GV2050) program has been working on the restoration of these SSS, serving as a scientific advisor to the Galapagos National Park Directorate (GNPD). GV2050 employs various restoration tools to enhance plant survival, conducts long-term monitoring and follows an adaptive management approach where previous results guide future restoration activities. The aim of this study was to assess the survival of plant species used in four different SSS and to evaluate how these results inform decision-making among Galapagos stakeholders.
2. Monitoring of plant species was conducted from 2013 to 2022, and their mortality was analysed using Cox models. To understand the decision-making workflow in SSS restoration and stakeholder interactions, information was gathered from meetings with GNPD staff.
3. The results demonstrated that several restoration tools positively impacted plant species survival, although the effects varied by tool and species across different SSS.
4. The analysis of the decision-making process revealed that multiple actors, including the GNPD, local agencies, government bodies, NGOs, the community and others, are involved in the initial planning stages of restoration. However, in later phases, most restoration results are primarily prepared by the GV2050 and reported to local authorities.
5. *Practical implications*: Despite the unique nature and importance of the Galapagos, better practices could be implemented if the monitoring of SSS

restoration and adaptive management is conducted collaboratively by GV2050 and GNP

KEYWORDS
arid vegetation, Galapagos, garbage dumps, mine, quarry

1 | INTRODUCTION

Traditionally, ecological restoration follows after man-made disturbances, aiming to restore degraded areas by improving biota structure and ecosystem functions (Callicott, 2002). Some anthropogenically degraded areas, such as garbage dumps and quarries, present extreme challenges for restoration due to contamination, absence of soil and the presence of foreign elements (Carlson et al., 2015; Freitas et al., 2004; Nagendran et al., 2006; Navarro & Carbonell, 2008). These often require active interventions like phytoremediation and planting.

The situation becomes even more challenging in islands or remote archipelagos, where development pressures are high and restoration faces additional constraints. In Easter Island, for example, the increasing volume of waste has significantly accelerated ecosystem degradation (Durán & Rodriguez, 2011), while in Cuba, similar issues have been reported (Rodríguez & Reyes, 2000). Additionally, quarries on islands can rapidly expand, sometimes even limiting the space available for urban growth (Mouflis et al., 2008).

The Galapagos Archipelago is renowned for its magnificent biota and landscapes and is recognized worldwide as a model of inspiration in ecology and evolution (Harpp et al., 2014). However, it is not exempt from degradation, as there is a continually growing population of locals and tourists (Gardener & Grenier, 2011), which requires the management of waste and extraction of materials for construction (Ragazzi et al., 2014). This population has grown from approximately 2300 inhabitants in 1962 to over 25,000 inhabitants in 2022 (INEC, 2022). In Galapagos, areas dedicated to these activities are referred to by the local authority, the Galapagos National Park Directorate (GNPD), as 'Special Services Sites' (hereafter: SSS). These are defined as areas 'within the Galapagos National Park where there is a permanent or nearly permanent human presence … These are spaces that, due to the activities they support, maintain highly degraded ecosystems both in their structure and function' (GNPD, 2014). The GNPD has established in its management plan that following use, SSS must be reforested or restored with surrounding native and endemic plant species (GNPD, 2014).

Restoring such areas remains highly challenging, with few global guidelines and examples available for quarries and garbage dumps (Vaverková et al., 2019; Wenjun et al., 2008), until recently (Young et al., 2022). This is true even in the current context of the United Nations Decade on Ecosystem Restoration (2021–2030), which emphasizes the urgency of large-scale restoration efforts worldwide. Unlike degraded natural areas where regeneration or passive restoration through succession can be applied, these areas depend on active restoration measures, such as planting and soil management (Kumar et al., 2019). Usually, these areas can suffer from poor water retention and lack of organic matter (Soria et al., 2021). For example, natural succession in quarries has been proposed to be limited by a lack of substantial soil following degradation (Yuan et al., 2006).

The Galapagos Verde 2050 Program (GV2050) is a science-based ecological restoration program of the Charles Darwin Foundation (CDF), which has been involved since 2013 in several projects of restoration and conservation of the archipelago's flora (Calle-Loor & Jaramillo, 2024; Jaramillo et al., 2023; Tapia et al., 2019; Velasco et al., 2024). One project in particular involves the recovery of SSS in three different islands: Floreana, Baltra and San Cristobal. The aim of this project is to provide science-based recommendations to the GNPD for recovering these areas to their preliminary levels of vegetation structure and functionality after they have been closed. To achieve this, the GV2050 employs a three-phase staged-scale adaptive management approach (Bakker et al., 2018; Jaramillo et al., 2020), starting with a pilot project in 2013; then, followed by the official first phase between 2014 and 2017 focusing on restoration and sustainable agriculture; and then the current second phase (2018–2027) focused on restoration and conservation. In this procedure, several restoration tools are tested in field conditions and with different species combinations over the first years to evaluate their effectiveness in improving the growth and survival of planted seedlings. Restoration efforts are then continued with the combinations that had better results (i.e. survival and growth) (Negoita et al., 2022; Plunkett et al., 2023; Velasco & Jaramillo, 2024). During the restoration process, the CDF acts as the scientific advisor of the GNPD and regularly communicates restoration results to the GNPD. As a final step, after over a decade, the restoration results are compared with natural sites and adjacent naturally recovered areas to evaluate the general effect of the restoration effort.

For the aims of this study, we focus on the two initial steps: testing the mortality chance of target species by different restoration tools, and reporting the procedure of feedback and monitoring by the interaction of the GV2050 and the GNPD.

2 | MATERIALS AND METHODS

2.1 | Stage I—Mortality and growth

2.1.1 | Sites description

Since 2013, several restoration actions have been performed in Galapagos SSS, as represented in Figure 1. For this purpose, the

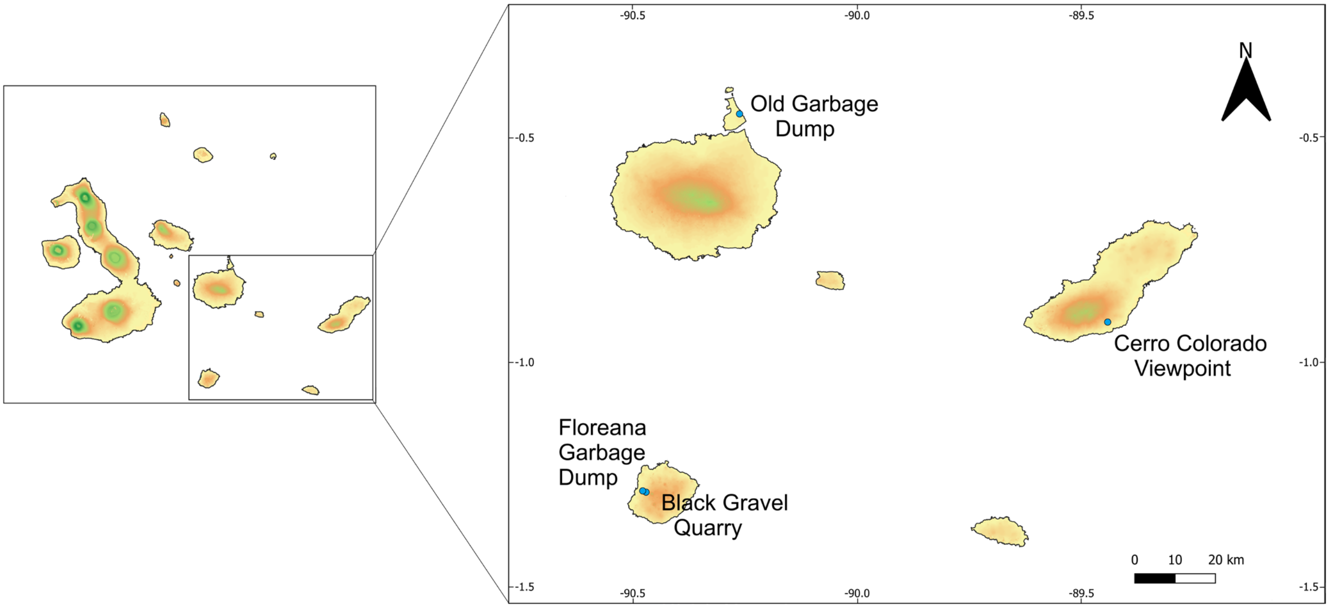

FIGURE 1 Location of Special Services Sites of Galapagos included in the study. Quarries: Cerro Colorado Viewpoint (San Cristobal Island), Black Gravel Quarry (Floreana Island); Garbage Dumps: Old one (Baltra Island) and the one in Floreana. Maps colours represent altitude/vegetation gradient. Yellow: Arid lowlands; orange: Intermediate transition zone; green: Humid highlands.

GNPD grants GV2050 a research permit, which is renewed annually (permit PC-41-23). Specificities for each site are included in the following sections.

Black Gravel Quarry

Floreana Island has two gravel quarries within the national park area, one of red gravel and another of black gravel (GNPD, 2005; Jaramillo et al., 2020). The Black Gravel Quarry is located next to the main road from Puerto Velasco Ibarra to the highlands of Floreana, approximately 2 km from the urban area (−1.2811, −90.4679). This quarry has been operational since at least 1996, as it was included in the list of sites where extractive activities are permitted (Amador et al., 1996). It is surrounded by native dry forests that are home to several endemic trees and shrubs, such as *Lippia salicifolia*, *Lecocarpus pinnatifidus*, *Darwiniothamnus tenuifolius*, *Psidium galapageium* and *Pisonia floribunda* (CDF, 2023). The quarry remains active, except for a 0.09 ha area next to the main road where the GV2050 initiative began restoration efforts in 2014.

Mirador Cerro Colorado Gravel Quarry

The Cerro Colorado Viewpoint is an old quarry located in the south-eastern part of San Cristobal (−0.9151, −89.4345). This site was also listed in 1996 as a location where extractive activities are allowed (Amador et al., 1996). Previously known as 'Cerro Verde', the site gets its current name from the nearby Cerro Colorado Viewpoint and its distinctive red clay soil (Jaramillo, 1999). Of the four mines in San Cristobal, it is the only one within the national park area (Quimbiulco, 2008). It is an important habitat for several plants endemic to San Cristobal, such as *Lecocarpus darwinii*, *Calandrinia galapagosa* and *Psidium galapageium* (Jaramillo et al., 2011; Tye & Jaramillo, 2022). In 1993, a fence was built to protect the *C. galapagosa* population from goats, and it was replaced in 1999 to protect both *C. galapagosa* and *L. lecocarpoides* (Jaramillo et al., 2011). This fence was replaced in 1999 to protect both *C. galapagosa* and *L. lecocarpoides* (Jaramillo, 1999). The quarry is currently closed (Quimbiulco, 2008). Since 2019, GV2050 has been working on the ecological restoration of a 0.10 ha area at this site.

Baltra's Garbage Dump

The Baltra Old Garbage Dump was an area of around 1.75 ha where waste material was deposited during the occupation of the WWII 'Beta' military base on the island (Woram, 1991), similar to other parts of the world (Denton et al., 2016). The site is located less than 1 km from Baltra's airport terminal building but is out of sight of tourists (−0.4478, −90.2629). The SSS was created before the GNPD jurisdiction and lacked any formal management measures for waste deposition. Some WWII garbage (e.g. fences, tin, bullets) can still be found around. Additionally, waste material from later constructions has also been deposited there. The GV2050 began restoration efforts in the area in 2013 (Jaramillo et al., 2017, 2024). In 2013, 2016 and 2018, the GV2050, in collaboration with the Ecuadorian Air Force, the GNPD, the Biosecurity Agency of Galapagos, the Ecuadorian Marine Force and volunteers, made considerable efforts onsite by collecting waste material before conducting plantings. Finally, the main vegetation of Baltra consists of native dry trees and shrubs, such as *Bursera malacophylla*, *Parkinsonia aculeata* and *Castela galapageia* (CDF, 2023).

Floreana's Garbage Dump

Floreana's Garbage Dump is located next to the main road from Puerto Velasco Ibarra to the highlands of Floreana, about 1.4 km from the urban area (−1.2780, −90.4741). The site was first mentioned as an SSS in the 2005 GNPD Management Plan (GNPD, 2005). The GV2050 began restoration efforts here in 2014, focusing on a 0.11 ha area (Jaramillo et al., 2017, 2020). The surrounding vegetation is similar to that of the Black Gravel quarry, with native dry endemic trees such as *Cordia lutea* and abundant shrubs such as *Gossypium darwinii* and *Waltheria ovata* (CDF, 2023).

2.1.2 | Planting, species selection and restoration tools

Planting in these areas was performed from June 2013 until August 2023. Species selection was done considering keystone, common pioneer and mid-successional species most representative of the vegetation zone and altitude of the area (Table 1). It is important to consider that the Galapagos archipelago, due to its isolation, lacks late-successional species as contrary to the mainland vegetation (Itow, 1995). Species were produced in the GV2050 greenhouse in Floreana Island, in the PNG greenhouse in San Cristobal Island and in Santa Cruz Island (Figure 1) for species from Baltra Island and later repatriated. All seedlings were produced from locally collected seeds. The seedlings were sowed around 3–6 months after germinating for most species, with the exception of *Opuntia* species, for which seedlings were around 3–4 years old. The seedlings were planted under field conditions using one or a combination of the next restoration tools: Groasis Waterboxx, Hydrogel, Biochar. These have shown promising results in improving the growth and survival of several plant species in Galapagos (Negoita et al., 2022; Plunkett et al., 2023; Velasco & Jaramillo, 2024) and worldwide (Jaramillo et al., 2020). Details of each of the restoration tools can be found in Table S1. Overall, as the project is managed according to the availability of plants and restoration tools over the years, the quantity of plants and treatments varied accordingly (Table 1; Table S2).

2.1.3 | Monitoring

Monitoring of the plantings was performed every 3 months. Growth and overall condition were assessed per plant, and their survival was scored as alive or dead. The data were recorded through a mobile app developed for the project, which automatically uploaded it to a platform (https://www.galapagosverde2050.com/) to visualize it through a shiny app that summarizes the restoration process (https://gv2050.shinyapps.io/GV2050-restoR/). After plants reached a considerable size (i.e. usually above 1 m for shrubs or trees and more than 10 cm of thickness in *Opuntia* cacti), Groasis Waterboxx were removed.

TABLE 1 Species and number of plantings used per Special Service Sites.

Species	Family	Habit	Old Garbage Dump	Floreana Garbage Dump	Black Gravel Mine	Cerro Colorado Viewpoint
Acacia macracantha Humb. & Bonpl. ex Willd.	Fabaceae	Tree	391	28	21	
Alternanthera filifolia ssp. filifolia (Hook. f.) Howell	Amaranthaceae	Shrub		17		
Bursera graveolens (Kunth) Triana & Planch.	Burseraceae	Tree		12	16	
Bursera malacophylla B.L. Rob.	Burseraceae	Tree	19			
Calandrinia galapagosa H. St. John	Montiaceae	Tree				42
Castela galapageia Hook. f.	Simaroubaceae	Shrub	290			
Cordia lutea Lam.	Boraginaceae	Tree		12		58
Croton scouleri var. *scouleri* Hook. f.	Euphorbiaceae	Shrub		18	35	
Gossypium darwinii G. Watt	Malvaceae	Shrub		30	50	
Lecocarpus darwinii Adsersen	Asteraceae	Shrub				79
Lecocarpus pinnatifidus Decne	Asteraceae	Shrub		24		
Lycium minimum C.L. Hitchc.	Solanaceae	Shrub	102			
Opuntia echios var. *echios* Howell	Cactaceae	Cacti	178			
Parkinsonia aculeata L.	Fabaceae	Tree	104	17	51	
Piscidia carthagenensis Jacq.	Fabaceae	Tree				88
Psidium galapageium Hook. f.	Myrtaceae	Tree				27
Scalesia crockeri Howell	Asteraceae	Shrub	28			
Senna pistaciifolia var. *picta* (G.Don) Irwin & Barneby	Fabaceae	Shrub	131			
Vallesia glabra var. *glabra* (Cav.) Link	Apocynaceae	Shrub	141			14
Waltheria ovata Cav.	Malvaceae	Shrub		37	15	
			1384	195	188	308

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2.1.4 | Analyses

Mortality of species data was analysed through Cox Proportional Hazards Models, using time-to-event data. These models were selected because they have been shown to be more robust than Kaplan–Meier methods in accounting for confounder effects (i.e. repeated measures) (Handorf et al., 2022). The Cox models were fitted using *start* and *stop* times as the interval between monitoring, and the deaths scored as 1 (i.e. time-to-event). The model used *treatment* (i.e. restoration tool) in interaction with *species* and with data clustered through *plant_ID* to account for repeated measures. Because our goal was to evaluate treatment effects within each site rather than compare across sites, we fitted separate Cox models for each site. This approach accounts for the unique species composition, environmental conditions and sampling design at each location, which could otherwise violate model assumptions if pooled. As the restoration process started in 2013 with subsequent plantings and inclusion of study sites and restoration tools, the data is considerably unbalanced (Table S2). To balance sufficiently the analysis, three levels of filtering were included: including treatment combinations with sample sizes of 15 or higher ($n \geq 15$), requiring treatment combinations to have a corresponding control with a sufficient sample size, and limiting the analysis to plantings before 2023. The purpose of the last filter is to reduce potential effects of low differences between treatment and controls from considering too many young plants. The number of replicates for controls and treatments can be found in Table S2. Final effects of independent variables were assessed through chi-square statistic, and overall performance of the model with concordance between predicted and observed data, a Wald-chi test and Likelihood Ratio test. Final representation of the Cox model was made through forest plots, using controls as baseline in x-axis = 1 (i.e. logscale).

All analyses were performed in R version 4.4.1 (R Core Team, 2024) with packages *survival* (Therneau & Lumley, 2015), *survminer* (Kassambara et al., 2021) and *forestplot* (Gordon & Lumley, 2023).

2.2 | Stage II—Coupled-monitoring and feedback with the GNPD

To report the management of SSS and the decision-making involved in the restoration process, we had a meeting with the GNPD staff from: the Directorate of Terrestrial Ecosystems, the Process of Conservation and Restoration of Insular Ecosystems and the Responsible for the Environmental Quality Process. The discussion was about our and their monitoring, how these articulate, and how the progress to achieve the restoration goals is assessed. Data were collected through the next open-ended questions:

a. How did the process of restoring the SSS begin?
b. Which type of stakeholders can use natural areas for development of SSS?
c. How long does the licence agreement for SSS last?
d. What are the decisions take to restore or rehabilitate the SSS?
e. How does the GNPD monitor the restoration activities?
f. Which are the indicators of success?

The information retrieved from the meeting was schematized and summarized in blocks. Before handing in the manuscript, the information retrieved from the GNPD was reviewed and approved by their staff, the researchers' team of the GV2050 and the Science Directorate of the CDF.

3 | RESULTS

3.1 | Stage I—Mortality and growth

All mortality Cox models were robust according to the Wald-chi test and LR test (Table 2), and all exhibited high concordance between predicted and observed data. Treatment was strongly significant on its own only at the Old Garbage Dump and marginally significant at the Cerro Colorado Viewpoint. In contrast, species identity was a strong predictor of mortality in most SSS sites. More importantly, the interaction shows to violate the Cox model assumption (Global, $p < 0.01$), indicating that the interaction effect is not kept across time. However, the increasing density of Schoenfeld residuals over time reflects the cumulative nature of mortality events and the monitoring structure of the study, rather than strong changes in effect magnitude (Figure S1). Most combinations per species were context dependent on the SSS (Figures 2–5), with most positive effects in both garbage dumps (Figures 4 and 5). All in all, across sites, Waterboxx was the treatment with the most frequent positive effects, followed by Cocoon or Waterboxx in combination with Hydrogel. The two biodegradable treatments, Growboxx or Cocoon by themselves had mostly neutral effects, while few negative effects were found for some species in Cerro Colorado Viewpoint and Baltra Old Garbage Dump (Figures 3 and 5).

3.2 | Stage II—Coupled-monitoring and feedback with the GNPD

3.2.1 | GNPD and stakeholders involvement

The decision-making process of restoration and management follows several steps (Figure 6). In a first step, the GV2050 acted establishing the restoration design in a pilot project, together with the collaboration of several actors. The actors are divided in four bigger and four smaller ones, depending on their importance in the decision-making. The major ones include: the Galapagos National Park Directorate (GNPD); the Agency of Biosecurity of Galapagos (ABG), which acts supervising the translocation of plants between nurseries and SSS, and assessing the lack of pests; Groasis company, which donated the first restoration tools to be used; and the local

TABLE 2 Summary of mortality Cox model for Special Services Sites.

	Garbage dump			Black Gravel Quarry			Old Garbage Dump			Cerro Colorado Viewpoint		
Mortality	Chisq	df	p	Chisq	df	p	Chisq	df	p	Chisq	df	p
Treatment	2.1	3	0.55	1.9	2	0.37	36.9	3	<0.01	10.8	6	0.09
Species	33.9	8	<0.01	53.2	5	<0.01	19.9	8	0.01	4.5	5	0.48
Treatment:species	28.0	9	<0.01	60.9	8	<0.01	62.4	18	<0.01	32.9	18	0.02
Global	45.7	20	<0.01	66.6	21	<0.01	101.0	29	<0.01	66.5	29	<0.01
Concordance	0.77±0.03			0.70±0.03			0.70±0.01			0.77±0.03		
	Statistic	df	p	Statistic	df	p	Statistic	df	p	Statistic	df	p
Wald-chi test	166.8	20	<0.01	26.7	21	0.03	631.8	29	<0.01	92.71	29	<0.01
LR test	137.5	20	<0.01	61.3	21	<0.01	562.5	29	<0.01	115.8	29	<0.01

Note: Value significant $p \leq 0.05$.

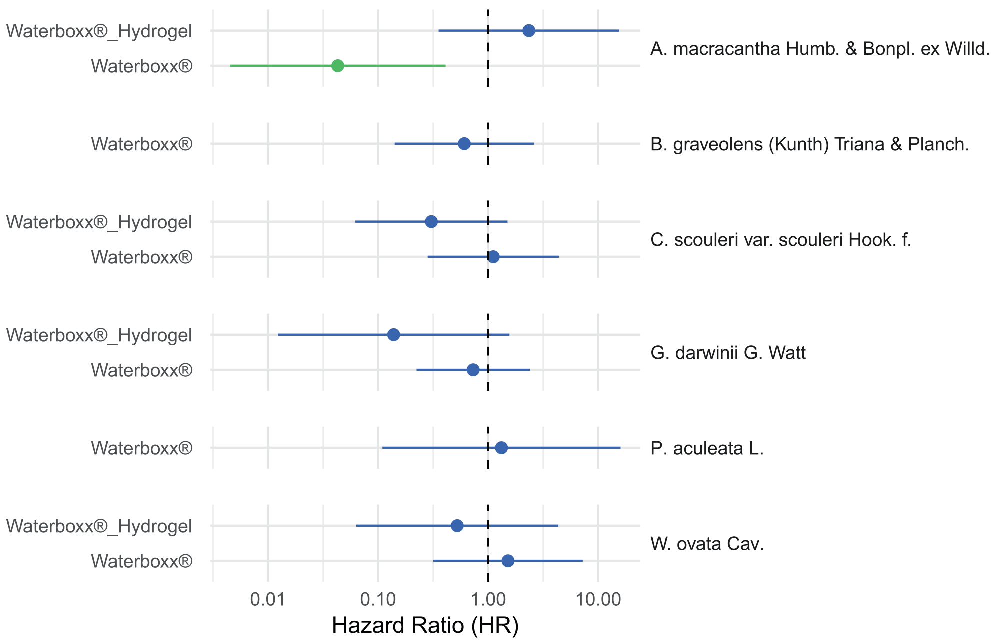

FIGURE 2 Hazard ratios of the mortality model for Floreana Black Gravel Quarry. HR in logscale representing their mean and 95% CI and separated by species (right) and treatment (left). Green labels indicate HR lower than expected by chance (i.e. low mortality), and in blue, no significantly different than the control (vertical dashed line).

government aid in field operations. The smaller actors include: local community and schools close to SSS, which are communicated about the restoration activities; park rangers, which aid with the know-how and field suggestions for the restoration process; and local NGOs, which can collaborate with the same restoration activities or conduct other complementary.

The GNPD publishes every 10 years on average a *Management Plan* where it indicates the monitoring of several kinds of areas, including SSS (Amador et al., 1996; GNPD, 2005, 2014; Ministerio de Agricultura y Ganadería, 1974). Explicitly, this has been made since the management plans were published in 1996 (Amador et al., 1996). Specifically, for SSS, the document requests that both quarries and garbage dumps, after the end of the usufruct of the area, must have restoration activities done to recover them. However, how the restoration and evaluation must be done (e.g. functions or structure) is not included in the document. Despite the fact that until some years ago SSS were possible to be requested by private entities, these are now only allowed to be executed/managed by governmental institutions (i.e. municipalities and local government). The stakeholders have to sign a *license agreement* with the GNPD, which gives them access to loan the area for 50 years with an option for renewal. Depending on the type of SSS, two different workflows for monitoring and restoration can be applied (Figure 6).

3.2.2 | Quarries

Each year, the GNPD establishes an *Annual Operational Plan* to manage Galapagos areas. This is a forward-looking document that details the activities, projects and resources needed for the management

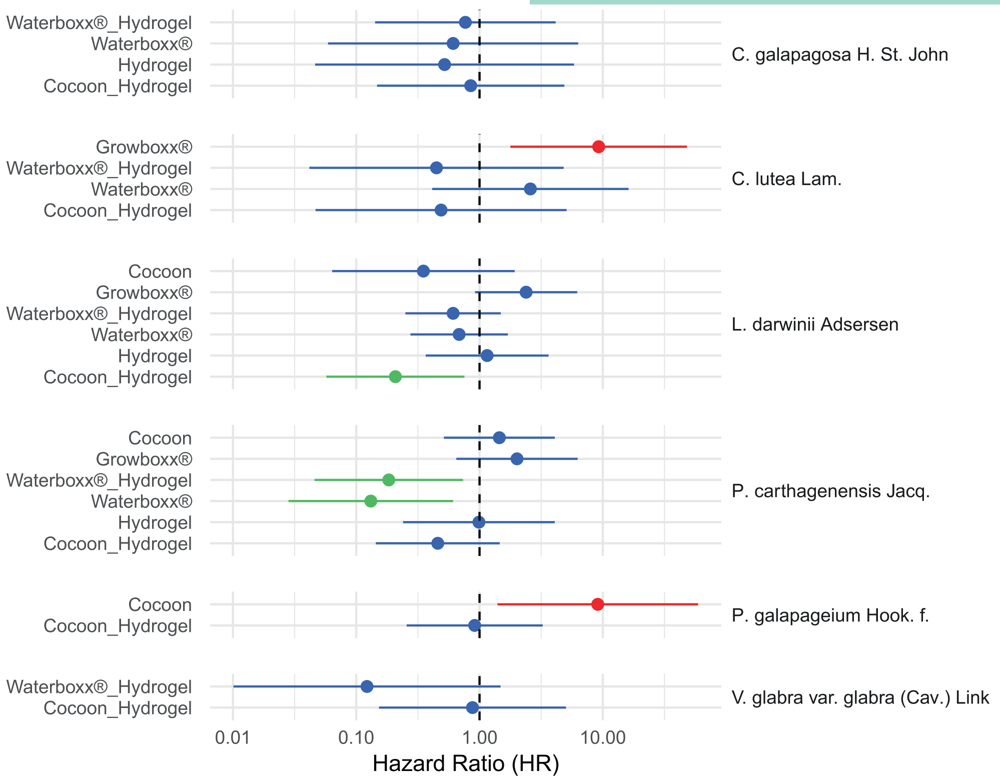

FIGURE 3 Hazard ratios of the mortality model for Cerro Colorado Viewpoint. HR in logscale representing their mean and 95% CI and separated by species (right) and treatment (left). Red labels indicate HR higher than expected by chance (i.e. high mortality), green lower than expected by chance (i.e. low mortality), and in blue, no significantly different than the control (vertical dashed line).

and conservation of the Galapagos National Park for a specific year (GNPD, 2014). This plan includes strategies for biodiversity protection, visitor management, environmental education, scientific research, cooperation with other entities and monitoring planning for SSS. Monitoring patrols are performed by park rangers, randomly during the year in the SSS, to evaluate that activities are performed according to the guidelines established.

3.2.3 | Garbage dumps

Garbage dumps receive the same actions as quarries, but also consider two additional steps. If park rangers confirm during the management phase that activities are outside the boundaries authorized by the licence agreement, stakeholders must act for rectification. Additionally, stakeholders agree to perform restoration activities through their private management plan.

3.2.4 | CDF–GV2050 in the monitoring and reporting

The CDF relates to the GNPD as its main scientific advisor and, through the GV2050 restoration program, conducts research activities. Four different documents are presented periodically by the institution to the GNPD: (a) a research proposal to get a research permit, which is renewed annually. This document includes the research objectives, methods and is annually updated according to adaptive management strategies, which can include, for example, inclusion or deletion of treatments depending on the plants' growth and mortality results and expansion of study sites, (b) field reports for each planting or monitoring—made around every 3 months—indicating the experimental design, treatments or additional findings of the activity, such as reports of pests or weeds, their management or recommendations to manage them by park rangers. It is also important to mention that before field excursions, the GV2050 provides workshops and training for park rangers, (c) annual report, which summarizes all activities made during the year and is mandatory to renew the research permit. Finally, (d) technical reports that compile important long-term results in a more scientific fashion. The last are socialized with the community and can even sometimes lead to scientific publications.

4 | DISCUSSION

This study focused on the plants' mortality results from an adaptive management restoration program currently active in quarries and garbage dumps in the Galapagos archipelago, and how these results interconnect with the protocols requested by the

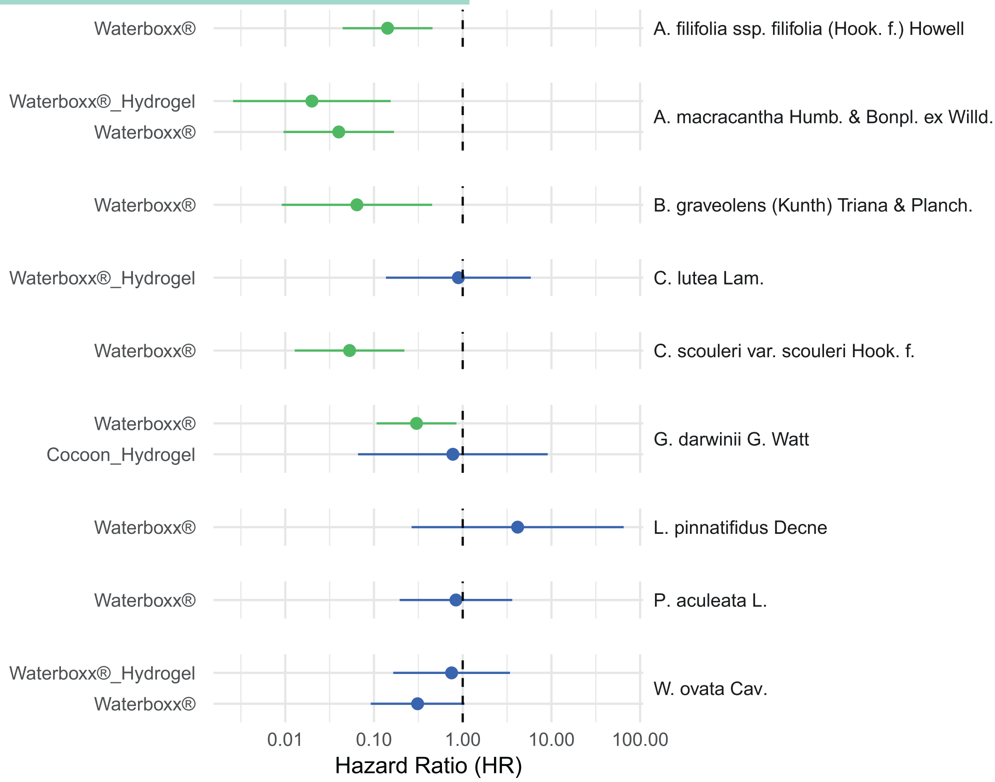

FIGURE 4 Hazard ratios of the mortality model for Floreana Garbage Dump. HR in logscale representing their mean and 95% CI and separated by species (right) and treatment (left). Green labels indicate HR lower than expected by chance (i.e. low mortality), and in blue, no significantly different than the control (vertical dashed line).

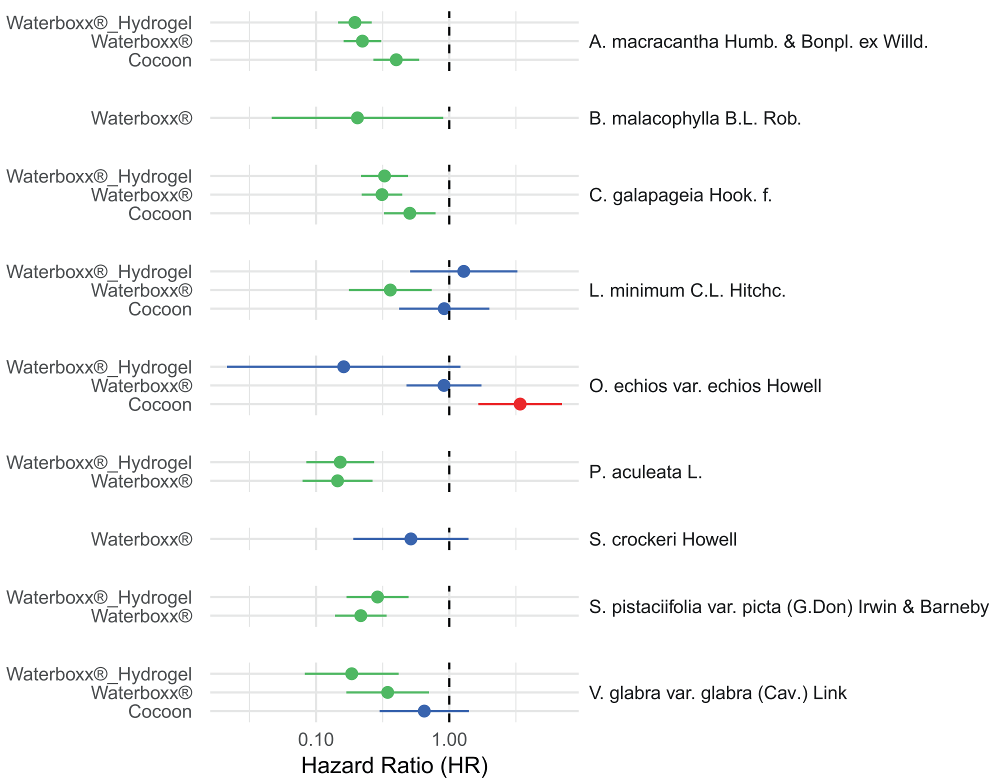

FIGURE 5 Hazard ratios of the mortality model for Baltra Old Garbage Dump. HR in logscale representing their mean and 95% CI and separated by species (right) and treatment (left). Red labels indicate HR higher than expected by chance (i.e. high mortality), green lower than expected by chance (i.e. low mortality), and in blue, no significantly different than the control (vertical dashed line).

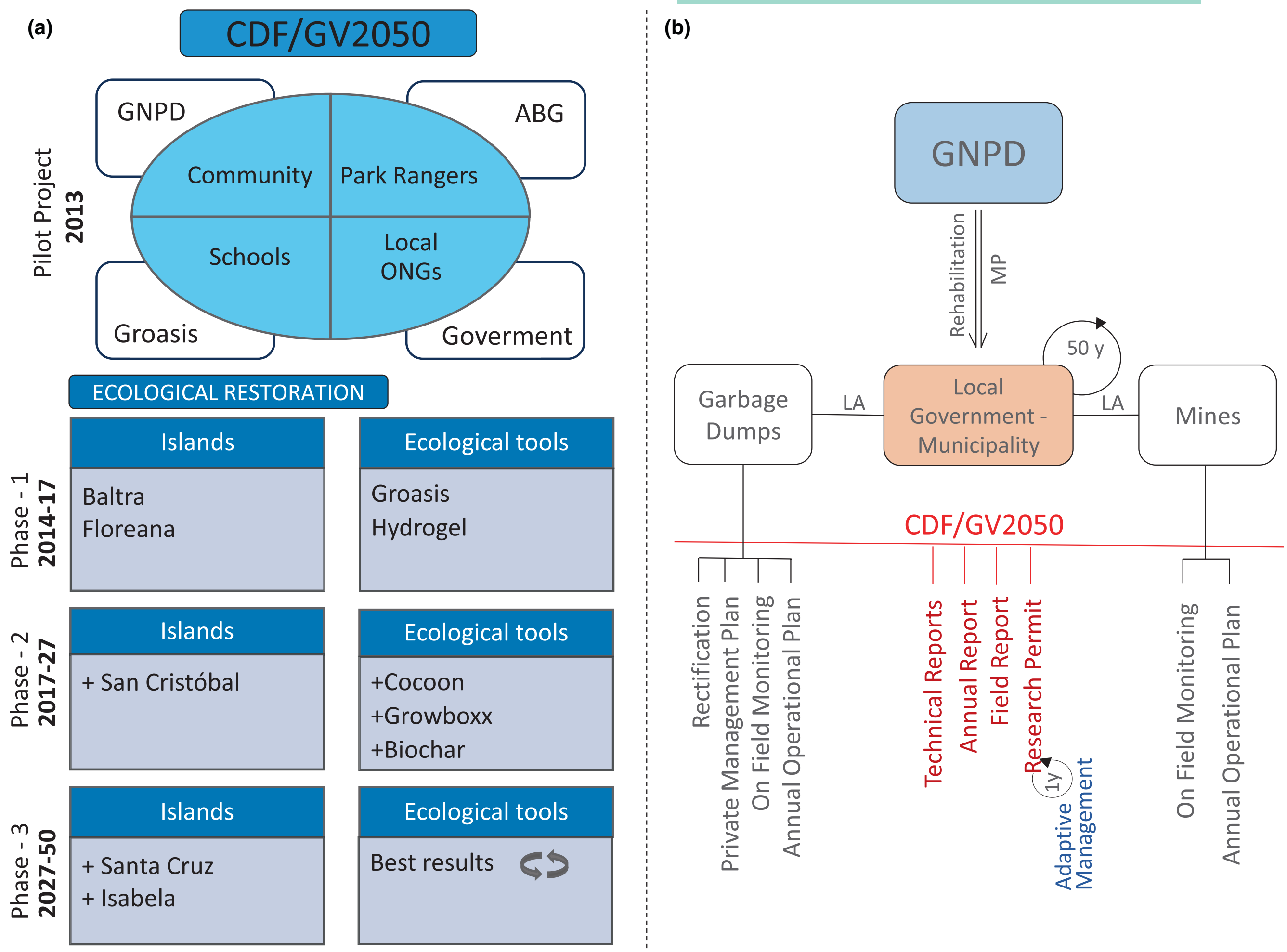

FIGURE 6 Schematic representation of the restoration workflow. (a) The gestation of the pilot project and the three phases of the GV2050 restoration procedure, with increasing study sites (islands) and treatments, until adaptive management restoration (best results). Colours are just decorative. (b) The management and restoration process of SSS, involving GNPD, stakeholders and the GV2050. The horizontal line in the right panel indicates that the GV2050 process is acting there through different reports/documents. LA, licence agreement; MP, management plan; y, years.

regulatory authorities and the pre- and post-plans to manage these areas. Overall, our results indicated that several restoration tools reduce the mortality of plants over long-run monitoring and that this effect is dependent on species and study sites. These results are periodically informed to the main stakeholders of Galapagos through several documents by the scientific institution (i.e. CDF) and through many protocols and monitorings which are also made by the GNPD.

Despite the results, our study presents limitations that should be considered when interpreting the findings. First, the experimental design included an imbalance in the number of replicates among treatments, largely due to the natural setting of a restoration program, with logistical constraints and differential treatments and seedling availability across sites. This may have influenced the statistical power to detect treatment effects. Second, while the study provides valuable insights into restoration in SSS in Galapagos, caution should be taken when extrapolating the outcomes to other archipelagos or island regions, given the unique biophysical and ecological context of the Galapagos Islands. Future efforts should aim to replicate similar restoration experiments across more sites and under more homogeneous experimental conditions to validate and refine the recommendations presented here.

4.1 | Restoration treatment and species mortality

Other studies have shown that technologies such as Hydrogel (Chirino et al., 2011; Thomas, 2008), Cocoon (Carabassa et al., 2019) and Waterboxx (Lund et al., 2024) have positive effects on increasing the survival of plants used in restoration programs in other arid or subtropical areas, which align with the conditions of the SSS presented in this study. The findings of our research and all these studies indicate that mortality effects are dependent on species, but our study also highlights that there exists variation between sites, even if these have similar climatic conditions. This could suggest that post-mined and landfill edaphic conditions can produce high variation in the final outcomes, as another research has shown (Cross et al., 2021; Risueño et al., 2020). Waterboxx has also shown positive effects on specific *Opuntia* or *Scalesia* species in the Galapagos archipelago (Plunkett et al., 2023; Tapia et al., 2019). Our results show that, also in SSS, Waterboxx is the restoration tool that most frequently reduced the mortality chance (Figures 2–5), probably due to its capacity to be refilled with rainwater (Negoita et al., 2022).

Because the GV2050 operates as an adaptive management program, other restoration tools have been included over the years. For example, since the research permit issued in 2024, a new treatment, biochar, has been included. This tool has shown promising results in restoration contexts worldwide (Garau et al., 2023; Thomas & Gale, 2015), but experiments in Galapagos will be analysed just in the coming years. In this study, we also incorporated results for Growboxx in Cerro Colorado Viewpoint, which was included as treatment since 2022. This restoration tool has been used in agriculture in Galapagos (Jaramillo et al., 2023) with some positive effects, but this is the first time in restoration contexts. Despite the lower combination of this treatment with different species, this was the only tool exhibiting neutral or negative effects (Figure 3). Then, these preliminary results suggest fewer opportunities to include it further in the adaptive management. Through this exemplification, GV2050 aims not only to reduce the consumption of restoration resources in the remote archipelago (Negoita et al., 2022) but also to implement a staged and scalable procedure that is more scientifically rigorous and ecologically meaningful, ultimately achieving a greater restoration impact (Bakker et al., 2018; Velasco et al., 2024).

The insights from this study are relevant to other remote archipelagos seeking to restore vegetation in degraded sites such as closed mines or landfills. While tree planting is often advertised as a simple solution, effective restoration requires strategies that are tailored to each site's specific conditions and grounded in long-term planning, implementation and monitoring (Brancalion & Holl, 2020). Recent publications on post-mining ecosystem reconstruction highlight the value of science-based approaches. For example, a study has demonstrated that selecting species suited to poor soils and incorporating hyperspectral remote sensing inform adaptive management strategies and improve restoration outcomes (Tibbett, 2024). This study provides a methodology that can be replicated in other archipelagos experiencing similar environmental degradation to guide restoration efforts.

4.2 | Connecting research-based restoration with Galapagos stakeholders

As restoration is a process, this research adheres to the idea that restoration should follow an adaptive management workflow (DeLuca et al., 2010), where continued monitoring should suggest improvement of the design and treatments, as well as stakeholder participation. The mortality monitoring of the CDF/GV2050 is periodically informed to the GNPD, and this institution proceeds with monitoring of other aspects of the SSS as well.

Other studies have shown that for contaminated areas, the decision-making process of restoration must involve stakeholders to define correctly the aims and future vision of the restored area (Farag et al., 2017; Hooper et al., 2016). For example, both main institutions GNPD and CDF hand-in annual reports; however, the main regulatory body, the *Management Plan*, changes every several years. As other research suggests, this communication is also important to address legislative changes from bigger governmental institutions, which can affect the management of restored sites (LoSchiavo et al., 2013). In the Galapagos context, this has meant that additional processes and documents have been added through the decades (Amador et al., 1996; GNPD, 2005, 2014; Ministerio de Agricultura y Ganadería, 1974) or that additional protocols have been released to updated several managements plans (Castaño et al., 2023; Conservation International et al., 2011; Fundación Charles Darwin y Dirección del Parque Nacional Galápagos, 2009; GNPD, 2017, 2021).

Albeit the GV2050 restoration process is communicated periodically, better interconnection with GNPD monitoring is needed as well as feedback on the expected results according to their management plan. After the exercise of conducting this research and the meeting with the staff of the GNPD, new indicators of success (e.g. percentage of covered area) were suggested to be incorporated in the GNPD Annual Operation Plan. Through this, park rangers monitoring SSS can directly score information on the restoration process for their internal evaluation. Finally, even in a place as Galapagos, renowned for its unique biodiversity, several actions are still needed to properly link stakeholders with the restoration agenda. Other institutions are also performing wide-scale restoration in the archipelago; thus, better communication and monitoring reporting must be exchanged between all actors.

AUTHOR CONTRIBUTIONS

Patricia Jaramillo Díaz conceived the research, its design and supervised and administrated the funding for the project; Danyer Zambrano, Patricia Jaramillo Díaz, Anna Calle-Loor and Paúl Mayorga curated the data; Nicolás Velasco made the formal analyses, graphs and wrote the first draft. All authors performed the planting and monitoring and have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.v6wwpzh8q (Jaramillo, 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Overview of the restoration tools.

Table S2. Summary of replicates per treatment and control per species and Special Service Site.

Figure S1. Schoenfeld residuals for the interaction between treatment and species across the four study sites.

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