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RESEARCH ARTICLE

Cost-effectiveness of water-saving technologies for restoration of tropical dry forest: a case study from the Galapagos Islands, Ecuador

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Tropical dry forests are among the most threatened of ecosystems globally, especially on islands, where two key challenges face efforts to restore them: (1) dealing with water scarcity and (2) reliably predicting costs and benefits of alternative approaches given limited resources available for restoration. In this study, we evaluated the cost-effectiveness of using water-saving technologies (WSTs) that increase available water during tropical dry forest restoration efforts. Between 2014 and 2018, 4,983 seedlings of 29 woody species were planted across 16 sites in the Galapagos Islands, Ecuador. Seedlings were randomly assigned to a combination of four WST treatments as well as a "no technology" control treatment; seedling survival and all planting costs were subsequently monitored. When analyzing all species together we found that Groasis, Groasis + Hydrogel, and Cocoon WST treatments generally had a significant and cost-effective positive effect on 2-year plant survival (95% credible highest density interval > 0). However, the extent of these effects on plant survival and cost-effectiveness varied by species and site due to differences in plant survival. For example, Groasis or Groasis + Hydrogel were the most cost-effective restoration methods for eight of the nine species analyzed independently, while the control treatment was most cost-effective for *Opuntia echios* var. *echios* on Baltra Island. Overall, we found that despite their initial costs, WSTs can reduce costs by at least 34% when restoring tropical dry forests in remote sites such as the Galapagos Islands and likely elsewhere in the arid tropics where water availability limits plant growth.

Key words: cost analysis, ecosystem restoration, Galapagos Verde 2050, Groasis waterboxx, island conservation, plant restoration

Implications for Practice

- Water-saving technologies (WSTs), such as the Groasis Waterboxx can provide cost-effective improvements in survival when planting tropical dry forest plant species, especially in remote sites.
- These results can be scaled to entire islands and ecosystems for providing cost-effective solutions to entire restoration outcomes.
- The cost-effectiveness of using WSTs is often species- and site-specific so an adaptive management approach using preliminary trials is necessary for ensuring the most effective application of these technologies.

Introduction

Tropical dry forests are among the most threatened terrestrial ecosystems worldwide (Myers et al. 2000). Dry forest plant species are particularly vulnerable on oceanic islands where up to 10% of all endemic plant species are threatened with extinction (Caujapé-Castells et al. 2010). Restoration of these species faces two key challenges: (1) the scarcity of water limits plant survival in tropical dry forest ecosystems (Khurana & Singh 2001; Cabin et al. 2002) and (2) resources for restoration that are limited and must be used efficiently for successful large-scale restoration planning (Bruner et al. 2004; McCarthy et al. 2012; Buddenhagen & Tye 2015).

The primary challenge for restoring tropical dry forests is the scarcity and unpredictability of water availability because it is necessary for ensuring the survival of planted seedlings (Snell & Rea 1999; Khurana & Singh 2001; Tapia et al. 2019). As a result, novel technologies that increase the efficiency of water application in dry climates have been developed and are now available (Liu et al. 2013; Hoff 2014). Referred to as water-saving technologies (WSTs), these technologies ensure that the water is supplied directly to the plant roots at a rate that

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the plants use the water so that it is not wasted through runoff. WSTs function by either supplying water to plant roots through a capillary wick from a collection tank, or through a polymer powder that is mixed with the soil and its hydrophilic molecular structure increases soil water availability (Kulkarni 2011; Liu et al. 2013; Hoff 2014). The efficacy of using some of these technologies in tropical dry forest restoration; however, remains understudied despite the water being a clear limiting factor.

Uncertainty around the perceived cost-effectiveness of WSTs for many arid tropical plant species hinders tropical dry forest restoration (Fajardo et al. 2013; Werden et al. 2018). In particular, estimating and optimizing the costs of scaling-up restoration efforts from local-to-island- and ecosystem-scales in remote sites remains an understudied challenge in tropical forest restoration (Holl et al. 2003; Carrion et al. 2011; Holl 2017). Combining active restoration with experimentation and monitoring of both biological and financial metrics of success can enable an adaptive management of dry forest restoration (Gibbs et al. 1999; Keith et al. 2011; Bakker et al. 2018).

To address these questions, we used data from a case study based in the Galapagos Islands, Ecuador, which represent a useful system for studying these challenges of tropical dry forest restoration (Gillespie et al. 2020). Despite harboring extensive dry forests, many have been profoundly altered by introduced pest species such as goats, and, in some cases, historic land use (Hamann 1981; Jäger et al. 2009; Restrepo et al. 2012), making them high priorities for restoration efforts. Started in 2013 in collaboration with the Galapagos National Park Directorate (GNPD), the Galapagos Verde 2050 (GV2050) project of the Charles Darwin Foundation is primarily focused on testing the effectiveness of WSTs in an adaptive management framework to advance ecosystem restoration (Jaramillo et al. 2020). The GV2050 project monitored 4,983 plantings of 29 tropical dry forest species on five islands, which enables a synthesis of the cost-effectiveness of WSTs at the individual species and ecosystem-level scales of restoration. Our objectives are to (1) test the effect of WSTs on tropical dry forest plant survival; (2) evaluate the relative cost-effectiveness of using WSTs for restoring dry forest plant species; and (3) estimate the costs of scaling-up restoration efforts to the entire islands and ecosystems.

Methods

Study Sites and Focal Species

The Galapagos Islands are located in the Pacific Ocean along the equatorial line 1,000 km west of mainland Ecuador, South America (0°44′S, 90°19′W; Fig. 1). The dry lowland zone where the present study is focused experiences a median annual rainfall of 227 mm, with 71% occurring during the wet season months of January through May, leaving 7 months of the year with less than 10 cm of total precipitation (Trueman & D'Ozouville 2010). The El Niño Southern Oscillation (ENSO) can lead to a large variation in rainfall around these median estimates, with up to 3 m of precipitation in some years (Trueman & D'Ozouville 2010). Within the archipelago, 16 sites of conservation concern across six islands were identified based on declines in keystone or endangered plant species for inclusion in restoration trials. Within these study sites, two islands, Baltra and Plaza Sur, were chosen for evaluating the costs of large-scale restoration due to the island-wide habitat degradation of these islands. The Baltra Island (0°27′S, 90°16′W) is located

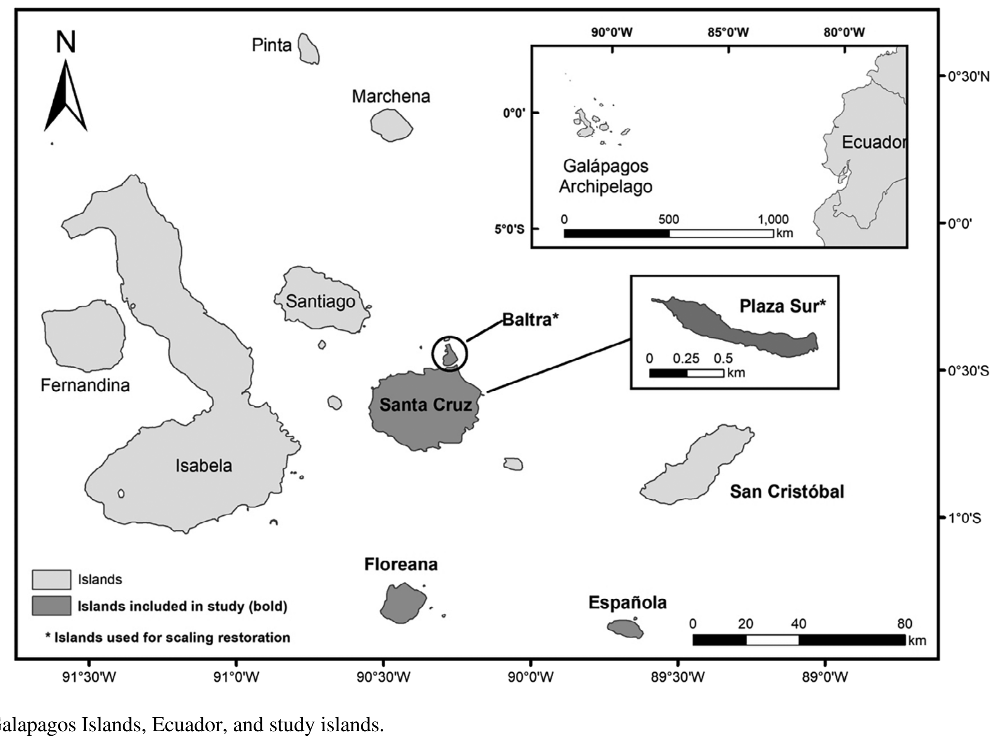

Figure 1. Map of Galapagos Islands, Ecuador, and study islands.

north of Santa Cruz Island with a maximum elevation of 30 m and area of 26 km^2. Baltra Island was used as a military base in World War II and was cleared of native vegetation (Cayot & Menoscal 1992; Snell et al. 1995). Plaza Sur Island (0°35′0″S, 90°948″W) is also an arid, but smaller, island of only 0.13 km^2 and 23 m maximum elevation on the northeast coast of Santa Cruz Island (Snell et al. 1995), and one of major tourism importance, hosting one of the most heavily visited sites in the archipelago. There, various factors have led to a dramatic decline in the population of endemic *Opuntia echios* var. *echios* cacti on the island since the 1950s (Sulloway & Noonan 2015). Prickly-pear cacti are a keystone species that the endemic land iguanas (*Conolophus subcristatus*) rely on as their primary food source on this island (Snell et al. 1994; Sulloway & Noonan 2015) as well as a major tourist attraction in the Galapagos, making both an environmental and economic case for restoring and protecting the ecosystem of this island (Epler 2007; Brewington 2013).

Experimental Treatments, Planting, and Monitoring

Three types of WSTs (two types of water-boxes and one polymer powder) and control plantings with no technology were used as experimental treatments for evaluating the effect of WST on plant survival and overall costs. Each WST was installed according to established protocols (Table 1). A total of 4,983 individual plants of 29 native or endemic tropical dry forest species were planted using these treatments between 2014 and 2018. Planting expeditions to sites were conducted opportunistically during this period, with no bias towards any particular time of year, and all seedlings were planted a minimum of two meters apart. Planting depth depended on the species and size of each seedling, but was based on ensuring roots were fully buried beneath the soil. Seeds for propagating each species were sourced from the same sites where they were later replanted. Each seed was germinated and grown at the Charles Darwin Research Station on Santa Cruz Island, Galapagos, for at least 1 year using standard propagation procedures (Jaramillo et al. 2017). Each seedling was randomly assigned a treatment based on the approximate ratio of one control for every seven technology treatments (693 controls, 367 Cocoon, 3,055 Groasis, and 868 Groasis + Hydrogel). This unbalanced design was chosen due to the presumed advantage of WSTs in reducing mortality when planting species of potential conservation concern but did not impact the analysis or interpretation of results. Wire fences were secured and maintained around each individual plant on Plaza Sur and Baltra Islands to prevent damage by native herbivores present at those sites. Each planting was visited approximately every 3 months to monitor survival from 2014 to 2020.

Analysis of Plant Survival

We used a hierarchical Bayesian framework for analysis to incorporate random effects while generating probabilistic estimates of the effect of planting treatments. Plant survival was used as the metric to evaluate the efficacy and cost-effectiveness of each treatment in this study because survival provides a simple but direct link to restoration success. To account for the effect of natural water availability we used precipitation data from Santa Cruz Island (Trueman & D'Ozouville 2010) to generate an index of water availability over the duration of this study. This Standardized Precipitation Index (SPI) was calculated using available precipitation data from 1970 to 2020 with a 7-month rolling window using the "SPEI" package in R (Lotsch et al. 2003; Vicente-Serrano et al. 2010; Haverkamp et al. 2017).

Two logistic regression models were fit to evaluate both the overall effect of treatments (all-species model) and the species-specific effects of treatments (species-specific model) on plant survival. In both cases, year survival was modeled as a function of WST treatment with mean SPI as a covariate and the expedition in which individuals were planted as a random effect. Planting expedition was added to account for any non-independence of plantings that occurred within the same planting expedition (e.g. due to changing personnel). Mean SPI was calculated as the mean SPI value across the first 2 years after planting or until death if the plant survived less than 2 years. The all-species model also included species as a random effect to account for any unique species-level differences. These models were parameterized with Markov Chain Monte Carlo (MCMC) using the "R2jags" package in R (Su & Yajima 2012). MCMC was run with three chains for 20,000 iterations after a 5,000-iteration burn-in. Convergence was ensured by checking that all R-hat values were below 1.1. Non-informative priors were used for the estimation of all parameter coefficients to ensure no bias when generating these initial results. Finally, the survival of each species by island by treatment combination was predicted using the posterior distribution coefficients of the fixed-effect model parameters (treatment and SPI).

A power analysis was conducted to ensure that only species by island by treatment combinations that met adequate sample sizes were included in the species-specific analysis (Supplement S1). Eight species met these inclusion criteria, *Acacia macracantha*, *Castela galapageia, Lycium minimum*, *Parkinsonia aculeata*, *O. echios* var. *echios*, *Senna pistaciifolia* var. *picta*, and *Vallesia glabra* var. *glabra* on Baltra Island, *O. echios* var. *echios* on Plaza Sur Island, and *Scalesia affinis* ssp. *affinis* on Santa Cruz Island (Table 2).

Cost-Effectiveness Analysis and Scaling Costs

To quantify the costs of restoration, the cost, and time of every operation in our restoration process were recorded on a per species per island per treatment basis (see Supplement S2 for a full description of all cost assumptions and parameters used in these predictions). Distributions of predicted potential costs were estimated by combining data from all planting expeditions to date (2014–2020). However, costs also depended on the length of a planting expedition and the number of staff per expedition, but those data were not always available. Thus, a bootstrapped simulation of costs was generated by varying the number of days and number of staff per expedition. This simulation generated a distribution of potential costs for each species by island by treatment combination based on the full range of expedition scenarios (Supplement S2). Finally, the 95% highest density

Table 1. Description of treatments used in this study.

Technology	*Groasis Waterboxx ("Groasis")*	*Cocoon System ("Cocoon")*	*Hydrogel Polymer ("Hydrogel")*	*No Technology ("Control")*
Description	A polypropylene donut-shaped container filled with water at the time of planting that subsequently collects water from rain and dew. Seedlings are planted in the center of the container where they receive water through a nylon wick in the bottom of the container	A biodegradable donut-shaped container that only receives water at the time of planting. Seedlings are planted in the center of the container where they receive water through two nylon wicks	Hydrogel is a biodegradable polymer powder that can increase the water-holding capacity of the soil by up to 400%, and thus increase available water to plants	Control plants were planted in the ground without the use of any technologies
Characteristics	• Increases soil-water availability • Protection from ground herbivory • Protection from overexposure to sunlight • Reusable, but must be removed from each plant after several years which generates an added cost	• Increases soil-water availability • 99% biodegradable	• Increases soil-water availability • 100% biodegradable	—
Watering protocol	Each Groasis was then filled with approximately 15 L of water at the time of planting and refilled with water during subsequent monitoring visits if the boxes were empty. Groasis also collects additional water from rainfall and dew	Each Cocoon was filled with 15 L of water once at the time of planting, but received no water thereafter	The Hydrogel powder was initially hydrated with a ratio of 12.5 g per liter of water and 1 L of this solution was mixed with the soil at the time of planting	Control plants were planted with approximately 5 L of water applied to the base of the seedling and no further water applied after planting
Notes	This treatment was used with plantings from 2014 to 2018	This treatment was used with plantings from 2016 to 2018	This treatment was used exclusively on some treatments in 2018 in combination with Groasis technologies, to form an additional treatment of Groasis + Hydrogel	Controls were used from 2014 to 2018
References	Liu et al. (2013), Hoff (2014)	Abdullah (2017)	Montesano et al. (2015), El-Asmar et al. (2017)	

interval (HDI) of these cost distributions was extracted to remove unlikely scenario cost estimates.

Cost distributions were then combined with the probabilistic survival distributions predicted from the survival analysis by dividing costs by survival probability. This yielded the expected cost per surviving individual. An additional 10% mortality rate was added to predicted survival when calculating these expected cost distributions to account for mortality that could occur after 2 years of growth. The 80% HDI and highest density value (HDV; analogous to the mode or estimate of highest probability) were extracted for the distributions of expected costs and survival rate.

The costs of scaling restoration to the entirety of Plaza Sur Island or per hectare on Baltra Island were estimated by multiplying the expected cost distribution of each species and treatment by the number of additional plants needed to reach restoration targets. The restoration target for Plaza Sur was derived from estimates of the historic population density of Opuntias on Plaza Sur Island (Sulloway & Noonan 2015). This yielded three different cost scenarios for Plaza Sur Island (one for each treatment used). For Baltra Island, a literature search was first conducted to generate estimates on the historic composition and density of species on similar but undisturbed arid habitats in the Galapagos (sources from which estimates were extracted and averaged: Racine & Downhower 1974; Reeder & Riechert 1975; Hamann 1981). Four species were selected to estimate cost scaling on Baltra: *A. macracantha*, *C. galapageia*, *O. echios* var. *echios*, and *P. aculeata* (563 controls, 334 Cocoon, 39 Cocoon + Hydrogel, 2,498 Groasis, and 617 Groasis + Hydrogel). Three species that had been planted on Baltra were not included in this scaling estimation because although those species have been recorded as native to Baltra (*L. minimum*, *S. pistaciifolia* var. *picta*, and *V. glabra* var. *glabra*), abundance estimates of those species in similar habitats were not found in the literature. This suggests that those species are relatively low in abundance and excluding them should not significantly affect our final estimate of scaling up restoration on Baltra Island. The expected cost distribution of

Table 2. Planting costs, survival, and expected costs of restoring eight tropical dry forest species. HDV (highest density value) represents the value with the highest probability. Eighty percent HDI (highest density interval) represents the interval of estimates that contain 80% of the most probable values. Distribution of total cost per planting is based on bootstrapping planting expedition scenarios and survival estimates are based on predicted survival from logistic Bayesian model coefficients. The expected cost is calculated as the total cost per planting divided by the survival rate (see Supplement S2 for a description of all cost assumptions).

Species	*Island*	*Treatment*	*Planting Time Cost*	*Planting Materials Cost*	*Fence Time Cost*	*Fence Materials Cost*	*Seedling Cost*	*Total Cost Per Planting (HDV ± 80% HDI)*	*Estimated Survival Rate (HDV ± 80% HDI)*	*Expected Cost Per Surviving Adult (HDV ± 80% HDI)*
Acacia	Baltra	Groasis + Hydrogel	$17.66	$3.16	$0	$0	$1.63	$21.44 ($17.20, $30.01)	79.0% (21.9%, 89.3%)	$31 ($19.38, $125)
macracantha		Groasis	$17.69	$2.75	$0	$0	$1.63	$21.17 ($15.69, $29.47)	76.9% (17.6%, 86.6%)	$35 ($19.64, $122)
		Cocoon + Hydrogel	$12.09	$12.51	$0	$0	$1.63	$25.81 ($23.72, $29.48)	0.1% (0.0%, 1.8%)	∞
		Cocoon	$12.13	$12.10	$0	$0	$1.63	$25.50 ($23.44, $29.34)	5.0% (0.2%, 51.5%)	$64 ($26.31, $627)
		Control	$4.11	$0.06	$0	$0	$1.63	$5.40 ($4.13, $7.81)	0.1% (0.0%, 1.2%)	$862 ($16.19, $14,983)
Castela	Baltra	Groasis + Hydrogel	$17.78	$3.16	$0	$0	$1.84	$21.91 ($17.27, $30.10)	<0.1% (<0.1%, <0.1%)	∞
galapageia		Groasis	$17.75	$2.75	$0	$0	$1.84	$21.58 ($15.91, $26.97)	5.6% (0.1%, 78.4%)	$43 ($20, $733)
		Cocoon	$11.85	$12.10	$0	$0	$1.84	$25.49 ($23.42, $29.28)	2.4% (0.0%, 55.9%)	$420 ($26, $2,848)
		Control	$4.04	$0.06	$0	$0	$1.84	$5.58 ($4.30, $7.41)	<0.1% (<0.1%, <0.1%)	∞
Lycium minimum	Baltra	Groasis + Hydrogel	$17.38	$3.16	$0	$0	$1.86	$22.02 ($19.68, $27.16)	83.2% (29.4%, 89.9%)	$29.53 ($19.15, $81)
		Groasis	$17.25	$2.75	$0	$0	$1.86	$21.57 ($19.32, $26.74)	81.1% (24.4%, 89.7%)	$30.39 ($18.62, $94)
		Cocoon	$12.09	$12.10	$0	$0	$1.86	$25.73 ($24.06, $29.58)	6.4% (0.4%, 67.4%)	$57.40 ($26.06, $396)
		Control	$3.73	$0.06	$0	$0	$1.86	$5.58 ($5.09, $6.72)	<0.1% (<0.1%, <0.1%)	∞
Opuntia echios	Baltra	Groasis	$17.57	$2.75	$6.38	$26.37	$19.30	$71.04 ($63.85, $81.67)	81.4% (40.0%, 89.7%)	$93.38 ($72.87, $191.86)
var. *echios*		Cocoon	$11.80	$12.10	$6.38	$26.37	$19.30	$75.59 ($72.39, $81.61)	6.0% (1.0%, 67.3%)	$173.10 ($80.91, $1,310.29)
		Control	$4.01	$0.06	$6.38	$26.37	$19.30	$55.55 ($52.70, $63.90)	85.0% (59.5%, 89.9%)	$67.45 ($60.51, $105.93)
O. echios var.	Plaza Sur	Groasis + Hydrogel	$60.36	$3.16	$21.46	$26.37	$38.60	$96.30 ($94.19, $169.45)	12.9% (5.4%, 34.9%)	$433.87 ($198.36, $1,227.46)
echios		Groasis	$60.36	$2.75	$21.46	$26.37	$38.60	$154.53 ($94.14, $169.04)	63.8% (51.1%, 81.6%)	$217.81 ($123.23, $293.82)
		Control	$11.98	$0.06	$21.46	$26.37	$38.60	$76.65 ($74.61, $104.91)	14.6% (6.3%, 32.7%)	$328.04 ($155.92, $768.68)
Parkinsonia	Baltra	Groasis + Hydrogel	$17.25	$3.16	$0	$0	$0.72	$20.84 ($16.56, $26.25)	<0.1% (<0.1%, <0.1%)	∞
aculeata		Groasis	$17.40	$2.75	$0	$0	$0.72	$20.45 ($16.43, $25.84)	86.1% (5.6%, 90.0%)	$215 ($15.67, $400)
		Control	$3.85	$0.06	$0	$0	$0.72	$4.50 ($3.58, $5.71)	<0.1% (<0.1%, <0.1%)	∞
Scalesia affinis	Santa Cruz	Groasis	$12.95	$2.75	$0	$0	$18.90	$34.00 ($30.02, $40.42)	1.9% (0.1%, 8.5%)	$552.72 ($95.86, $2,388.62)
ssp. *affinis*		Control	$2.66	$0.06	$0	$0	$18.90	$21.61 ($20.45, $22.57)	0.1% (0.0%, 0.9%)	$5,913.21 ($237.90, $70,348.31)
Senna pistaciifolia	Baltra	Groasis + Hydrogel	$17.11	$3.16	$0	$0	$1.76	$21.69 ($17.74, $28.31)	3.3% (0.0%, 83.3%)	$37 ($19.54, $3,184)
var. *picta*		Groasis	$17.40	$2.75	$0	$0	$1.76	$21.22 ($16.69, $27.90)	86.7% (3.6%, 90.0%)	$30 ($17.50, $578)
		Control	$3.81	$0.06	$0	$0	$1.76	$5.44 ($4.32, $6.66)	<0.1% (<0.1%, <0.1%)	∞
Vallesia glabra	Baltra	Groasis + Hydrogel	$17.11	$3.16	$0	$0	$0.84	$20.78 ($17.74, $24.97)	0.3% (0.0%, 1.5%)	$2,069 ($183.93, $10,583)
var. *glabra*		Groasis	$17.25	$2.75	$0	$0	$0.84	$20.56 ($17.38, $24.56)	16.9% (5.4%, 22.1%)	$114 ($67.41, $229)
		Cocoon	$12.04	$12.10	$0	$0	$0.84	$24.45 ($22.52, $28.76)	<0.1% (<0.1%, <0.1%)	∞
		Control	$3.77	$0.06	$0	$0	$0.84	$4.55 ($4.00, $5.74)	<0.1% (<0.1%, <0.1%)	∞

each treatment with the lowest median cost within each species was summed to produce the overall restoration cost estimate for each hectare of this island.

Results

Overall Water-Saving Technology Effects on Plant Survival

When used to model 2-year survival across all species, Groasis, Groasis + Hydrogel, and Cocoon treatments all generated positive posterior effect sizes on plant survival (Fig. 2). Plants grown with Groasis survived best with a median posterior coefficient of 3.13 (95% HDI = 2.81–3.47; 27.8% median survival ranging from 9.1 to 60.1%). The Groasis with Hydrogel treatment yielded the next greatest relative effect on plant survival with a median posterior coefficient of 2.60 (95% HDI = 2.07–3.14; 18.5% median survival ranging from 4.6 to 52%). Finally, plants grown with Cocoon had the lowest survival with a relative median posterior coefficient of 1.73 (95% HDI = 1.24–2.20; 8.7% median survival ranging from 2 to 29.8%). The Cocoon with Hydrogel treatment was only available for one species (*Acacia macracantha*) and so was not included in the aggregate analysis. Control plantings overall had a median 2-year survival of 1.7% with a 95% HDI range of 0.6–4.5%. Mean SPI during the first 2 years of growth had a significant, but negative effect on 2-year survival (95% HDI = median of −2.65, ranging from −2.94 to −2.38).

When modeling the effect of treatment on the survival of each species, six out of the nine species-by-island plantings survived best under the Groasis treatment (*Castela galapageia* on Baltra, *Opuntia echios* var. *echios* on Plaza Sur, *Parkinsonia aculeata* on Baltra, *Scalesia affinis* ssp. *affinis* on Santa Cruz, *Senna pistaciifolia* var. *picta* on Baltra, and *Vallesia glabra* var. *glabra* on Baltra) with a median predicted survival of 26, 63, 46, 4, 41, and 15%, respectively (Table 2; Fig. 3). Two out of these nine species-by-island plantings survived best under the treatment that combined Groasis with Hydrogel (*A. macracantha* on Baltra and *Lycium minimum* on Baltra) with a median predicted survival of 55.7 and 63.8%, respectively (Table 2; Fig. 3). One of the species-by-island planting combinations survived best under the control treatment (*O. echios* var. *echios* on Baltra) with a median predicted survival of 77% (Table 2; Fig. 3).

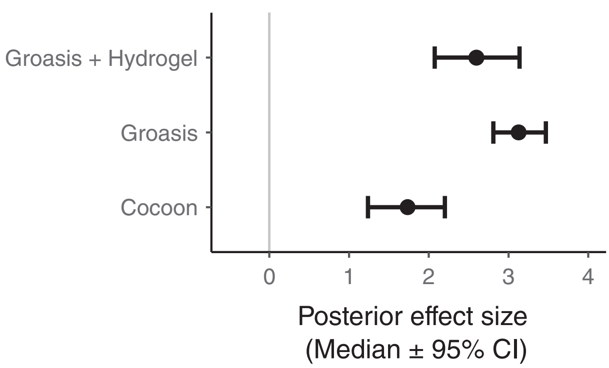

Figure 2. Posterior relative effect size of planting treatment (water-saving technology) on 2-year survival of 29 dry tropical forest species native or endemic to Galapagos, Ecuador. Sample size = control = 693, Cocoon = 367, Groasis = 3,055, Groasis + Hydrogel = 868. The reference category is based on control effects. Effect sizes derived from technology-specific coefficients from logistic hierarchical Bayesian model (see Methods section).

Cost-Effectiveness of Water-Saving Technologies by Species

In all nine species-by-island planting combinations, those treatments that yielded the highest survival rates also yielded the lowest expected cost per surviving adult (Table 2; Fig. 3). *Acacia macracantha* on Baltra Island was most cost-effective when planted with Groasis + Hydrogel, with an expected cost estimate HDV of $31 per surviving adult (80% HDI = $19.38–$125). Planting this species without technologies yielded an estimated survival rate lower than 2%, which generated an expected cost estimate HDV of $862 per surviving adult (80% HDI = $16.19–$14,983). *Castela galapageia* on Baltra Island was most cost-effective when planted with Groasis, with an expected cost estimate HDV of $43 per surviving adult (80% HDI = $20–$733). Planting this species without technologies yielded no surviving plants. *Lycium minimum* on Baltra Island was most cost-effective when planted with Groasis + Hydrogel, with an expected cost estimate HDV of $29.53 per surviving adult (80% HDI = $19.15–$81). Planting this species without technologies yielded an estimated survival rate lower than 1%, which generated an impractically large expected cost. *Opuntia echios* var. *echios* on Baltra Island was most cost-effective when planted without technologies, with an expected cost estimate HDV of $67.45 per surviving adult (80% HDI = $60.51–$105.93), while this species on Plaza Sur Island was most cost-effective when planted with Groasis with an expected cost estimate HDV of $217.81 per surviving adult (80% HDI = $123.23–$293.81). *Parkinsonia aculeata* on Baltra Island was most cost-effective when planted with Groasis, with an expected cost estimate HDV of $215 per surviving adult (80% HDI = $15.67–$400). Planting this species without technologies yielded an estimated survival rate less than 1%, which generated an impractically large expected cost. *Scalesia affinis* ssp. *affinis* on Santa Cruz Island was most cost-effective when planted with Groasis, with an expected cost estimate HDV of $552.72 per surviving adult (80% HDI = $95.86–$2,388.62). Planting this species without technologies yielded an estimated survival rate less than 1%, which generated an impractically large expected cost. *Senna pistaciifolia* on Baltra Island was most cost-effective when planted with Groasis, with an expected cost estimate HDV of $30 per surviving adult (80% HDI = $17.50–$578). Planting this species without technologies yielded no surviving plants. Finally, *V. glabra* var. *glabra* on Baltra Island was most cost-effective when planted with Groasis, with an expected cost estimate HDV of $114 per surviving adult (80% HDI = $67.41–$229). Planting this species without technologies yielded no surviving plants.

Estimation of Large-Scale Restoration Costs

The restoration target for *O. echios* var. *echios* (hereafter “Opuntia”) on Plaza Sur Island was set at 2,000 mature Opuntia trees

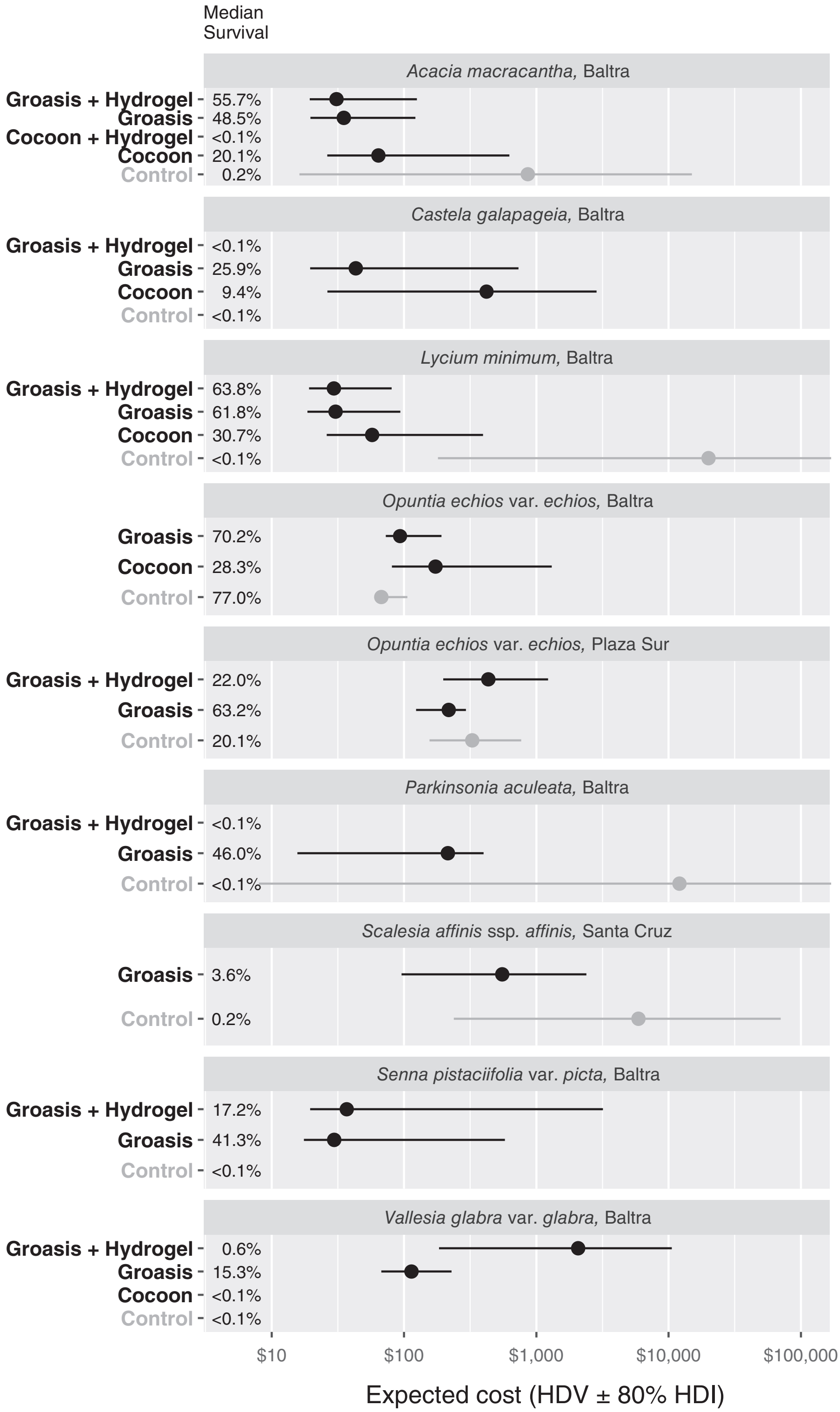

Figure 3. Expected cost of reaching adult stage for eight tropical dry forest species of the Galapagos Islands. HDV (highest-density value) represents the value with the highest probability. The 80% HDI (highest-density interval) represents the interval of estimates that contain 80% of the most probable values. The *x*-axis of expected cost is log-scaled. Some cost estimates are missing in the cases where low survival leads to impractically high-cost estimates that are impossible to approximate with any accuracy.

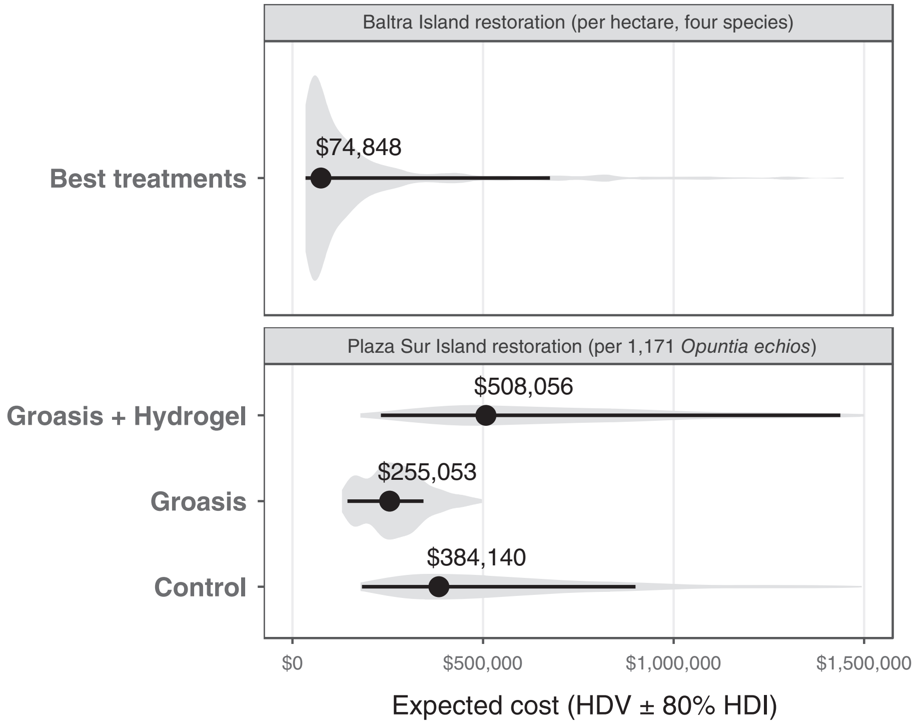

Figure 4. Estimated scaled costs for restoring Baltra and Plaza Sur Islands. Baltra is based on the cost of restoring four species per hectare using the most cost-effective treatments for each species. Plaza Sur is based on the cost of restoring 1,171 additional adult *Opuntia echios* var. *echios* trees using three potential treatments. HDV (highest density value) represents the value with the highest probability. Eighty percent HDI (highest density interval) represents the interval of estimates that contain 80% of the most probable values.

(Sulloway & Noonan 2015). A recent survey indicated 426 original remaining Opuntias (Jaramillo et al. 2017) and 448 surviving Opuntias that had been planted by GV2050 so far. If the surviving Opuntias already planted experience a 10% mortality until maturity, 1,171 Opuntias would be needed to reach a restoration target of 2,000 individuals. Groasis was the most cost-efficient technology for reaching this restoration target, estimated at costing an HDV of $255,053 ranging from $144,302 to $344,066 (80% HDI) compared to an HDV of $384,140 or $508,056 if planting without a technology or with Groasis + Hydrogel, respectively (Fig. 4).

The restoration targets for Baltra Island were set, per hectare, at 400 individuals of *C. galapageia*, 60 individuals of *A. macracantha*, 343 individuals of *O. echios* var. *echios*, and 60 individuals of *P. aculeata*. *Castela galapageia* and *P. aculeata* were most cost-effective when planted with Groasis, *A. macracantha* when planted with Groasis + Hydrogel, and *O. echios* var. *echios* when planted without any technology (Table 2). In total, the expected cost of restoration per hectare on Baltra was estimated at an HDV of $74,848 ranging from $34,344 to $675,646 (80% HDI) (Fig. 4). Extrapolating this to the entire 2,072 ha island yields an estimated HDV of $155 million. However, re-establishing patches of plant communities on only a portion of the total island area could subsequently serve as colonization nuclei to recolonize the remainder of the island over time (Corbin & Holl 2012). In the scenario that only 10% of the total area of the island is manually restored in this way, the estimated HDV would be $15.5 million.

Discussion

By increasing plant survival, WST in general provided a cost-effective improvement over not using these technologies in restoring tropical dry forest plant species in Galapagos despite the higher initial costs of using WST. These results were most evident when scaling the use of these technologies to an entire island or ecosystem level, but were often species- or site-specific due to a high level of variability in outcomes driven by variation in plant survival. This is a substantive finding given that the up-front costs of tools such as WSTs may be perceived as an impediment for restoration projects (Tye 2006; McCarthy et al. 2012; Mappin et al. 2019). Our findings are in line with other studies that evaluated WSTs for tropical dry forest restoration (Fajardo et al. 2013).

Despite the general positive effect of WSTs on plant survival, the technologies were not equally beneficial among species. The Groasis Waterboxx on its own yielded the highest rates of survival compared to other technologies, and this technology was also part of the most cost-effective solutions for eight of the nine species by island evaluations. Groasis has several potential advantages over Cocoon because it continues to accumulate water after planting and it also protects seedlings from the drying effects of direct sunlight and herbivory (Liu et al. 2013; Hoff 2014). No previous studies to our knowledge have directly compared the Groasis and Cocoon technologies, and we found that the Cocoon system is not as effective as Groasis. However, its ability to biodegrade makes it an ideal candidate for use in especially remote sites where plantings cannot be easily accessed to remove the technology as is required with Groasis. Hydrogel was not used on its own in this study but adding it to Groasis was only marginally cost-effective for two species (*Acacia macracantha* and *Lycium minimum*). This result is consistent with Fajardo et al. (2013), who found that Hydrogel alone was more cost-effective than combining it with other treatments. Further work needs to be performed to evaluate the use of Hydrogel because it may not always be beneficial (Ruthrof et al. 2010; Werden et al. 2018). The quantity and method of how Hydrogel is applied to the soil may be a critical aspect of its effectiveness (El-Asmar et al. 2017).

Species- and island-specific differences also determined the context in which WSTs were most effective. WSTs are designed to aid plant growth and survival for species that cannot access sufficient water in their environment (Liu et al. 2013; Groasis® 2019). Our findings support this because the *Opuntia* tree cactus, with clear adaptations for water stress (Racine & Downhower 1974; Hicks & Mauchamp 1996), was the only species studied that did not show a positive effect of WST on one of the islands where it grows, and showed only a minor effect on its other island. WSTs also tended to be most cost-effective in remote sites or for species where high fixed costs outweigh the additional costs of using these technologies. In other words, species and islands with high costs in seed collection, nursery care, and transportation required a lower survival advantage for technologies to be cost-effective. For example, planting Opuntias with the Groasis technology on the remote island of Plaza Sur required a minimum plant survival that is 42% greater than control plantings for these technologies to be cost-effective. This contrasts with the more accessible Baltra Island where survival using technology treatments must be at least 200–500% greater than control treatments for those technologies to be cost-effective.

Nonetheless, much variation in the estimated expected costs of restoring tropical dry forest species in the Galapagos was driven by variation in survival rates. For example, *S. pistaciifolia* when planted with Groasis had an expected cost that ranged at least 33-fold ($17.50–$578) and its predicted survival had a similar large variation ranging from 3.6 to 90%, compared to only a range of $16.69–$27.90 in the costs of planting one individual. This variation in survival may be driven by multiple environmental conditions in tropical dry forests aside from water availability, including herbivory and nutrient availability (Bhadouria et al. 2017), so it is important that restoration projects begin with pilot experiments in which WSTs are first tested with all focal species at the study sites that are monitored for a minimum of several years (Khurana & Singh 2001; Murray & Marmorek 2004). An adaptive management approach can be used to initiate restoration in cases where urgent intervention is necessary by adjusting the experimental design as results become available (Walsh et al. 2012).

Scaling Restoration Costs

Relatively few studies in tropical dry forest restoration estimate costs despite its importance for long-term planning and conservation decision-making (Cook et al. 2013; Palma & Laurance 2015; Dimson & Gillespie 2020). In this study, we estimated the costs of expanding restoration to island- and ecosystem-level scales by multiplying the expected costs of restoring an individual plant by the number of individuals required to meet restoration targets. On Baltra Island, our estimated expected cost per hectare of restoration using the most cost-effective treatment combinations is comparable to other estimates of tropical dry forest restoration (Powell et al. 2017). More importantly, our estimates suggest that WSTs can help save hundreds of thousands of dollars as is the case on Plaza Sur Island (34% reduction in costs), or make the difference between feasible and infeasible restoration by increasing survival from zero as is the case for the four species used on Baltra Island. Furthermore, as at the individual plant level, we found a large variation in expected costs when scaling up to the island- or ecosystem-level. For example, when using Groasis on Plaza Sur, the 80% HDI ranged from $144,302 to $344,066 (57 – 135% of the HDV). Similar, but to a greater extent, restoring four target species per hectare on Baltra Island using the most effective technology treatments ranged from 46 to 903% of the HDV. The variability associated with the benefits and cost-effectiveness of these technologies emphasizes the importance of using pilot studies designed to test the effectiveness of each technology on the focal species and restoration sites before implementing large-scale use. Restoration projects should also put more importance on recording and evaluating restoration costs to estimate the total costs of reaching restoration targets (Naidoo et al. 2006; Dimson & Gillespie 2020). Reporting this variation in potential costs can allow scientists and decision makers to evaluate and compare the associated risks with the potential ecologic benefits using decision analyses (Wade 2000; Falcy 2016).

Future Work

Estimating accurate costs of restoration at the island or ecosystem scale also depends on accurate restoration targets (White & Walker 1997; Bush et al. 2014). Our current restoration targets were generated by aggregating together available data from multiple historic studies across the Galapagos. Future work should directly measure the abundance of species in comparable reference ecosystems for more accurate restoration targets (DPNG 2014).

Another aspect of this study that could be improved relates to volumes of water supplied between the controls and treatments at the time of planting and during subsequent monitoring visits. Although each technology requires a slightly different volume of water based on its specific protocol and shape (Jaramillo et al. 2020), control plantings should receive an amount of water that is comparable to technology treatments to ensure WST benefits are not solely the result of differences in water application. Control treatments did not receive any water after initial planting, so this could be one reason WST treatments were associated with greater plant survival. Nonetheless, our current results provide an essential proof-of-concept on the value of evaluating novel WSTs for tropical dry forest restoration and estimating the costs and benefits of using these tools.

Finally, the current analysis and cost evaluation is only based on the first 2 years of plant survival (Powell et al. 2017). Continuing the long-term GV2050 project will provide additional data for increasing the accuracy of these evaluations. This is particularly important in the context of substantial inter-annual variation in precipitation that occurs in Galapagos that will influence outcomes of the plant species evaluated, many of which are long-lived.

Overall, our findings generally corroborate previous studies that demonstrated a positive effect of WSTs on plant survival, but our analysis also indicated that use of WST's can dramatically reduce large-scale restoration costs. WSTs therefore have important implications for improving the future of active restoration and reforestation of tropical dry forests worldwide (Griscom & Ashton 2010).

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Statement of Competing Interests

The authors were staff or consultants of the Charles Darwin Foundation (CDF) at the time of this study. The CDF's Galapagos Verde 2050 project, of which the study was a part, was developed in consultation with the COmON Foundation (https://www.comon.earth/map-of-projects/), which provided funding for the study, is a major donor to the CDF and advises its Board. The equipment evaluated in this study was manufactured by and purchased from Groasis B.V., a company independent of COmON but which supplies several COmON initiatives (https://www.groasis.com/en/projects). Groasis and COmON had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors declare no other competing interests.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Power analysis.

Supplement S2. Cost assumptions and parameters.

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