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Assessing Water-Saving Technologies and the Impact of Giant Tortoise Herbivory on the Restoration of *Opuntia megasperma* var. *orientalis* on Española Island—Galapagos

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Abstract: The prickly pear (*Opuntia megasperma* var. *orientalis*), a pivotal species for the ecological balance of Española Island in Galapagos, has witnessed a severe decline in its population due to the enduring presence of introduced feral goats over several decades. Additionally, the inherent slow recovery of this species, requiring several years of development, has contributed to its population decline. Several attempts were carried out to restore this species, but they were not successful due to the island's extreme arid conditions. Subsequently, innovative water-saving technologies were introduced to ensure the survival and growth of the Opuntia species. Two water-saving technologies, Groasis Waterboxx® and Hydrogel, were applied in two distinct treatments, the first involving Waterboxx solely, and the second combining Waterboxx with Hydrogel, alongside a control group. Planting involved two types of cacti: cladodes and seedlings. To safeguard against potential damage from giant tortoises and local birds, protective mesh fencing was installed around the plants. Each monitoring session recorded plant survival and growth, evaluating the impact of water-saving technologies on cactus survival, maximum plant height reached, age at the time of plant death, and growth achieved since planting. Additionally, the study assessed the influence of climate on plant survival and growth. Unfortunately, the employment of protective mesh fences and Waterboxx containers resulted in the unintended loss of specific bird species. Consequently, a decision was taken to remove these protective measures, resulting in a substantial rise in herbivorous activity, and the subsequent mortality of nearly all plants. Our findings underscore the efficacy of water-saving technologies in Opuntia restoration. However, successful application necessitates a better understanding of these technologies within the unique conditions of the island. Future endeavors should focus on refining these techniques to minimize avian mortality while fostering biodiversity and restoring ecological equilibrium.

Keywords: biodiversity; cladodes; climate variability; ecological restoration; herbivores; invasive species; pads; prickly pear cacti; protective fences; seedlings; slow recovery; survival

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1. Introduction

The Galapagos Islands are known for their fragile ecosystems and unique biodiversity [1]. Certain keystone species are essential for maintaining the dynamics of these ecosystems, including members of the Cactaceae family [1–4]. In the genus *Opuntia*, six endemic species and 14 endemic subspecies are present [1–4]. These are critical sources of sustenance and shelter for various other species, such as endemic birds, tortoises, lizards, and invertebrates [5].

Among these is *Opuntia megasperma* [2]. which includes three subspecies: *megasperma*, naturally occurring on Floreana Island; *mesophytica* on San Cristobal; and *orientalis*, which is found on the easternmost islands of the Archipelago, namely Española Island and its nearby islets [2,6,7]. *O. megasperma* var. *orientalis* is considered endangered [8].

The population of Opuntia cacti on Española Island has been significantly reduced owing to multiple factors, including the introduction of feral goats (*Capra hircus*) during the late 19th century [9,10]. These mammals voraciously consumed Opuntias in direct competition with the native giant tortoise of Española (*Chenoloidis hoodensis*), thus reducing their natural habitat [11,12]. This ecological disruption led to a significant decline in *Opuntia* numbers.

The decline in the giant tortoise population further contributed to the reduction of the Opuntia population. These tortoises serve as long-distance seed dispersers, with their digestive tracts playing a crucial role in seed scarification and, consequently, seed germination [12–14]. The tortoise population was almost exterminated by unregulated hunting in the early 20th century, with only 14 individuals remaining in the 1960s [15]. These tortoises were relocated to a breeding center on Santa Cruz Island, and in recent years around 2000 individuals were repatriated to Española through joint efforts between the Charles Darwin Foundation and the Galapagos National Park [16–18]. Despite the growth in the tortoise population, their absence for several decades considerably constrained the Opuntia population, as they were limited in spreading across the island [19].

Further ecological interactions on the island, particularly giant tortoises' habit of seeking refuge beneath mature *Opuntia* cacti against high temperatures and solar radiation, constrain both asexual and sexual reproduction in cacti by promoting the consumption of fallen cladodes and impeding new plant propagation from these cladodes [12,20]. Birds, including cactus finches (*Geospiza conirostris*), mockingbirds (*Mimus macdonaldi*), and Galapagos doves (*Zenaida galapagoensis*), have depressed the sexual reproduction of the *Opuntia* population by eating its seeds from both fruits and tortoise droppings [12,21].

Thus, despite the eradication of goats in 1978 and the reintroduction of tortoises onto Española Island after 30 years of absence, the prickly pear population did not recover [19]. Part of the reason was their slow growth rate, which ranged from 0.4 to 7.6 cm per year [11,22]. The slow recovery allowed faster-growing species like *Prosopis juliflora* and *Cordia lutea* to expand, creating interspecific competition that hindered the recovery of the depleted *Opuntia* population [23].

On islands like Española, drought poses a significant challenge to the survival of seedlings and propagules. Given the impracticality of irrigation, water-saving technologies, such as the 15-L cylindrical polypropylene Waterboxx, which serves as a rainwater collector and distribution system through a wick, offer a viable alternative for supplying water to planted vegetation. Incorporating such technologies may significantly enhance the success of ecological restoration efforts by providing shade and protective cover to optimize plant growth, reduce evapotranspiration rates, and extend water access periods [5,24–27]. In addition, Hydrogel, a polymer matrix able to absorb several times its mass in water [27,28], can play a pivotal role in increasing plant water availability and resilience, as shown by previous research in the Galapagos Islands [25,29,30].

The present study was designed to evaluate the impact of water-saving technologies, specifically Waterboxx, both in isolation and in combination with Hydrogel, on various quantitative parameters, including survival rates, plant height, age, and overall growth. These evaluations were conducted across several prickly pear cactus batches, using both cladodes and seedlings planted at different dates. The study also investigated population changes resulting from these interventions.

2. Materials and Methods

2.1. Study Area

The study was conducted on Española Island, located in the southeast of the Galapagos Archipelago. The island has a total area of 60.48 km^2. The study site, known as "Las Tunas" (1°21′48″ S; 89°41′53″ W), is situated approximately 2 km inland from the seashore. It encompasses an elevation range of 19 to 92 m above sea level (Figure 1).

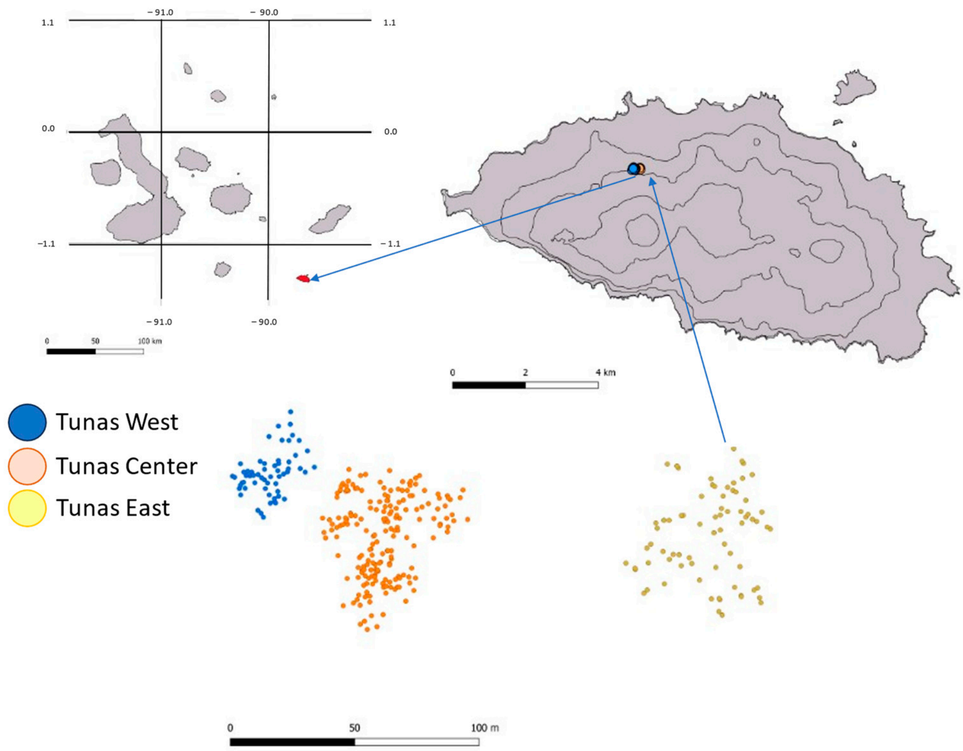

Figure 1. The study site where the specimens were planted is shown by the colored dots. The prickly pear plants were distributed in three main groups: Tunas West (blue), Tunas Center (orange), and Tunas East (yellow). The sites' positions on Española Island are shown at top right, and the location of Española within the Galapagos archipelago is shown at top left.

The study site, characterized by semi-arid conditions with an annual precipitation of 10–600 mm and an average temperature of 23.8 °C, has soils resulting from a geological uplift process, comprising mainly igneous rock and clay [23,31,32].

2.2. Implementation of the Study

In 2014, an initiative to restore the population of *O. megasperma* on Española Island was launched by the Galapagos Verde 2050 (GV2050) program, implemented by the Charles Darwin Foundation in collaboration with the Galapagos National Park directorate and other institutions [33].

From 2014 to 2017, on several field trips, we collected about 5000 prickly pear seeds from semi ripened fruits. Although this can present challenges for germination due to seed dormancy, we maximized success through careful seed treatment. The seeds were germinated in a sterile substrate mix of peat and sand at a room temperature of 22 °C.

Unfortunately, the initial attempts resulted in a limited number of seedlings [33]. Consequently, in June 2017, we shifted to asexual propagation, gathering 48 cladodes from a pool of 17 mature plants for this purpose. The strategic planting of these 48 pads aimed to assess the impact of water-saving technologies, particularly the Groasis Waterboxx® and Hydrogel, on the overall condition of the plants. This comprehensive assessment included factors such as the likelihood of survival, growth, and long-term endurance (longevity) under the influence of these technologies.

The experiment involved Waterboxx alone, providing shelter, shade, and a continuous water supply to the plants. We also tested a combination of Waterboxx with Hydrogel, aiming to demonstrate that this combination is more effective than using only Waterboxx. Hydrogel, a polymer that retains a significant amount of water, was used in this treatment. The control consisted of untreated plants for comparison.

In the "Waterboxx alone" treatment, the Waterboxx containers were installed by excavating holes wide enough to accommodate the Waterboxx boxes, which had a circular dimension of 26 cm radius and a height of 38.5 cm. In the planting process, each hole was initially hydrated by pouring 5 L of water into the soil. Following this, the cacti were planted directly into the moistened hole. Subsequently, a Waterboxx container was strategically placed around each cactus, and an additional 15 L of water was poured into the container. To further optimize water conservation, the lid of the box was securely closed, serving to inhibit evaporation. Moreover, the design of the Waterboxx allows it to channel rainwater into the container, ensuring a gradual and sustained water supply to the planted cactus through a wick system. This comprehensive approach not only facilitates immediate hydration during planting, but also establishes an efficient mechanism for ongoing water provision, contributing to the plant's sustained growth and resilience.

For the "Waterboxx plus Hydrogel" treatment, the brand of Hydrogel used was Cosecha de Lluvia [34–36]. Prior to planting each specimen, holes were excavated with dimensions suitable for accommodating individual plants.

The Hydrogel solution was meticulously prepared by adding 1.75 g of Hydrogel powder per liter of water, using a methodology consistent with previous studies conducted in the Galapagos Islands [24,29,30,35]. To initiate the planting procedure, a hole was excavated and five liters of Hydrogel solution was subsequently applied to enhance soil hydration. In the control group, only five liters of water was employed. After the complete absorption of the Hydrogel solution or water into the soil, the specimen was carefully planted. The planting process concluded with the installation of the Waterboxx container, which held 15 L of water. For the control group and the treatment without hydrogel, the container was not installed; an additional 15 L of water was added.

Before planting, the cladodes went through a special preparation process. This entailed the cutting and healing of the tissue at the base over a 36-h period. Following this, the plants were immersed in a solution composed of water and a root growth stimulant, Raiz Plant® 500 [36], enriched with mineral fertilizers, humic acids, and phytohormones. The purpose of this comprehensive preparation was to promote robust root development.

For seedlings, the process was more direct, as they were extracted from their pots and planted into the prepared hole following the same irrigation process as the cladodes, depending on the treatment. This supplementary watering ensured sustained hydration for the newly planted cacti, fostering optimal conditions for their growth and establishment.

We divided the experiment into six batches. Each batch, planted on distinct dates, comprised two subgroups: one with treated plants (either subjected to Waterboxx alone or in combination with Hydrogel) and another subgroup with untreated plants that served as the control within the same batch.

The initial batch, planted in June 2017, consisted of 40 cladodes treated with a combination of Waterboxx and Hydrogel (W + H), using one pot per plant for each treatment. This combined approach aimed to enhance the effectiveness of the Groasis Waterboxx® in the extreme arid conditions of Española Island. Additionally, eight cladodes were left untreated. Throughout the planting procedure, due consideration was given to the prospective threat of herbivory posed by Española tortoises. To protect the planted individuals, we fixed a physical barrier of wire mesh pieces measuring 1.75 × 0.75 m (Figure S1). Each fence was circular with a diameter of 92 cm, enclosing an area of approximately 0.2 square meters. To enhance this protection, we placed rocks to reinforce the fences (Figure S1).

In November 2017, an additional set of 66 cladodes was planted. At that time, a new question emerged regarding whether to exclusively use Waterboxx solely to provide water and shelter and observe its effects on the pads. We clarified our intention to evaluate the impact of Waterboxx plus hydrogel and compared it with the effects of using Waterboxx alone on the cacti.

Following the initial propagation efforts carried out previously since 2014, a subsequent batch of seeds was germinated in 2017, resulting in healthy seedlings. By the end of 2018, 18-month-old seedlings were ready to be reintroduced to Española, and 82 individuals were planted using Waterboxx + Hydrogel vs. controls as treatment.

The population was increased in 2019 by planting 144 additional cladodes (14 in February, 20 in April, and 110 in August). At the end of planting, we had planted a total of 340 individuals, as depicted in Table 1.

Table 1. Number of planted cladodes and seedlings at six planting dates, treatments (C = control − without any treatment, W = Waterboxx, W + H = Waterboxx and Hydrogel combined), average monthly temperature, and total monthly precipitation during the planting month.

Planting Date	Treatment	Cladodes	Seedlings	Total by Batch	Temperature (°C)	Precipitation (mm)
26 June 2017	C	8	0	48	24.7	1.71
	W + H	40	0			
22 November 2017	C	7	0	66	26	3.4
	W	59	0			
20 November 2018	C	0	9	82	26.9	4.2
	W + H	0	73			
6 February 2019	C	4	0	14	27.6	136.8
	W + H	10	0			
26 April 2019	C	3	0	20	26.6	195.5
	W + H	17	0			
31 August 2019	C	25	0	110	21.5	20.8
	W + H	85	0			
Total cladodes or seedlings		258	82			
Total W + H		225				
Total Waterboxx		59				
Total Control		56				
Total plants		340				

Eleven monitoring sessions were conducted from June 2017 to November 2021, to calculate survival rates and measure the height of both cladodes and seedlings. The first six monitoring sessions, until August 2019, were combined with planting activities. During this time, we collected data on survival rates. Subsequently, during the following five sessions until November 2021, we simply monitored growth and survival, with no additional planting. We categorized the causes of plant death as either "herbivory" or "other".

2.3. Statistical Analysis

We conducted four analyses: (1) a batch-specific survival analysis over time; (2) an assessment of treatment effects on plant height, age, and growth; and (3) a comparison of yields between seedlings and cladodes.

In conducting the temporal survival analysis by batch, we employed survival tables to document the count of surviving plants in each batch at every monitoring instance. This facilitated the comparative assessment of survival rates across batches.

Regarding the assessment of the effect of the water-saving technologies on plant traits, we conducted a linear regression analysis, incorporating the t-test to evaluate the significance of individual coefficients. We acknowledge the imbalanced treatment/control relationship, as mentioned earlier. Despite the imbalanced sample sizes, we believe that this analysis best aligns with the reality of the study's data. Alternative statistical methods were explored, and it was found that methods such as GLM are less suitable for this specific assessment due to the distributional characteristics of the continuous outcome variable. In this analysis, the independent variables were the treatments, while "plant height" (defined as the maximum height reached by the plant), "plant age" (described as the age until the plant was seen alive), and "plant growth" of cladodes and seedlings (represented as the difference between the final and initial plant height) served as dependent variables. To determine significant differences among the treatments, a post hoc Tukey Honestly Significant Difference (HSD) test was performed following the regression analysis. The *p*-values obtained were adjusted using the Holm–Bonferroni method to account for multiple comparisons and control for false-positive results [37].

Additionally, we examined the impact of treatment, planting date, and their interactions on height, age, and growth traits using regression models to investigate potential variations in treatment effects across different planting dates. The significance of the observed impacts was determined based on *p*-values.

We conducted a comprehensive comparative analysis of performance metrics encompassing height, age, and growth between cladodes and seedlings. Specific linear regression models were employed for each group (cladodes and seedlings), followed by the computation of statistical differences within each group.

All statistical analyses were carried out using R version 4.2.2 [38].

3. Results

3.1. Survival Analysis

The survival rates of five different batches of locally planted cladodes gradually declined over 11 monitoring dates until August 2019 (Figure 2). A faster decrease in survival was observed among seedlings (planted as Batch 3: Figure 2). Removal of the protective fencing in June 2020 led to a significant increase in the mortality rate at the next monitoring conducted in November 2020. This rise in mortality was primarily attributed to tortoises consuming the young plants.

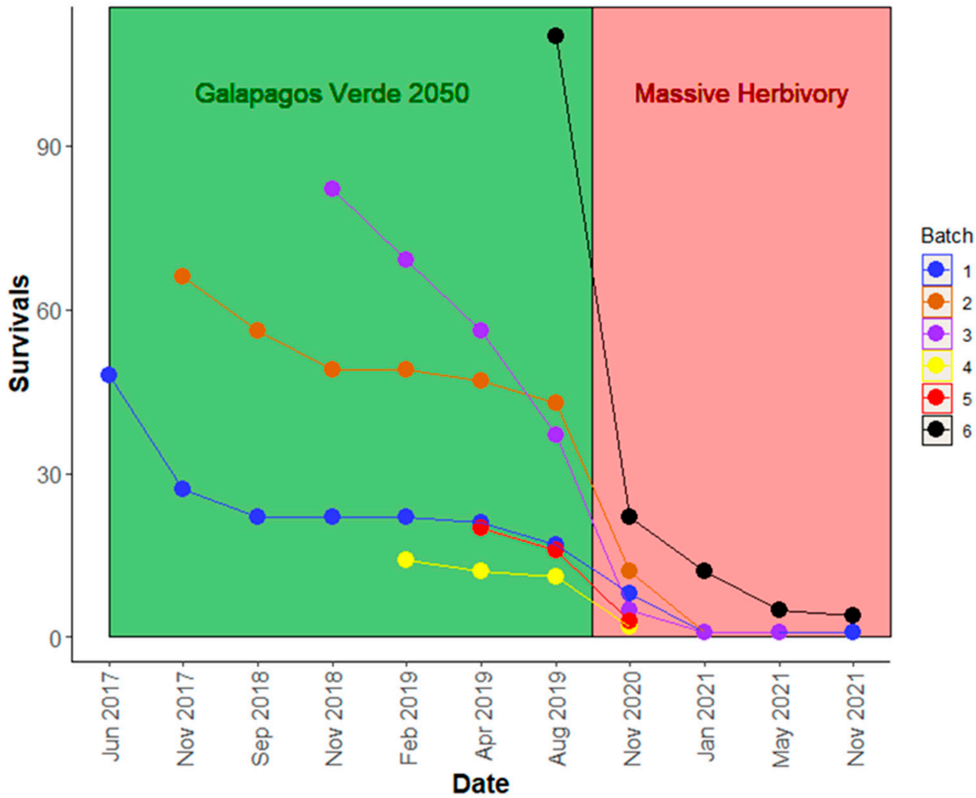

Figure 2. Survival of *O. megasperma* individuals (2017–2021), with colored lines indicating different planting dates. Batches 1, 2, 4, 5, and 6 were planted cladodes, and batch 3 comprised 18-month-old seedlings. The green background signifies the period until fence removal, while pink indicates the herbivory phase after fence removal.

The plants subjected to the water-saving treatments exhibited significantly enhanced survival and resilience compared to the control plants. This disparity was most pronounced in Batch 2 (cladodes with Waterboxx alone) and Batch 3 (seedlings), as observed in Figure S2.

3.2. Effect of Water-Saving Technologies on Height, Age, and Growth of Plants

The results highlight significant differences in plant height, particularly within batches 4 and 6, as displayed in Table 2. While there may be the appearance of similar plant height values across batches (Table S1), a closer statistical analysis unveiled notable disparities.

Table 2. Comparative statistical analysis of treatments (Hydrogel and Waterboxx, Waterboxx alone, control) within batches for the analyzed traits (plant height, age, and growth). The use of Waterboxx + Hydrogel was consistent across all batches, except Batch 2. F values (variance ratios) with $p < 0.05$ indicate significant differences in bold.

		Batch 1	**Batch 2**	**Batch 3**	**Batch 4**	**Batch 5**	**Batch 6**
Trait	N	48	66	82	14	20	110
Plant height	F	1.613	0.041	0.012	6.439	0.305	8.169
	p	0.211	0.840	0.972	**0.026**	0.587	**0.005**
Plant age	F	0.129	10.233	0.026	0.064	18.773	17.864
	p	0.720	**0.002**	0.872	0.803	**<0.001**	**<0.001**
Plant growth	F	0.127	0.827	0.001	1.573	1.468	21.055
	p	0.723	0.366	0.920	0.233	0.241	**<0.001**

Analysis of plant age values revealed statistically significant differences in three out of the six batches (Batches 2, 5, and 6), as illustrated in Table 2. Specifically, Batch 2 exhibited greater plant age values, while Batches 5 and 6 remained within a comparable range, as indicated in Table S1.

Analyzing plant growth makes it evident that the treatment significantly influences Batch 6 (Table 2), with plant growth notably lower than in the remaining batches, as indicated in Table S1. This discrepancy underscores the treatment's distinct impact on growth patterns across different batches.

Furthermore, we assessed the effects of treatment, planting date, and their interactions on our three studied traits: height, age, and growth (Table S2). For plant height, treatment and planting date both have significant effects, as indicated by very low p-values (<0.001). However, the interaction effect is not significant ($p = 0.542$). Plant age follows a similar pattern, with treatment and planting date significantly affecting it, while the interaction effect is not statistically significant ($p < 0.001$ for treatment; $p = 0.006$ for planting date; $p = 0.131$ for interaction). In terms of plant growth, treatment and planting date also exert significant effects, ($p = 0.003$) and ($p < 0.001$), respectively. The interaction effect, however, is not significant ($p = 0.353$).

3.3. Cladodes vs. Seedlings

We assessed the effects of treatments on the studied traits in cladodes and seedlings. Generally, cladodes had better response in height, age, and growth to water-saving technologies compared to seedlings. Cladodes demonstrated accelerated growth with Waterboxx alone, contrasting with the slower growth pattern observed with Waterboxx + Hydrogel and the control. Cladode responses differed statistically between treatments, whereas nonsignificant differences were found for seedlings (Figure 3).

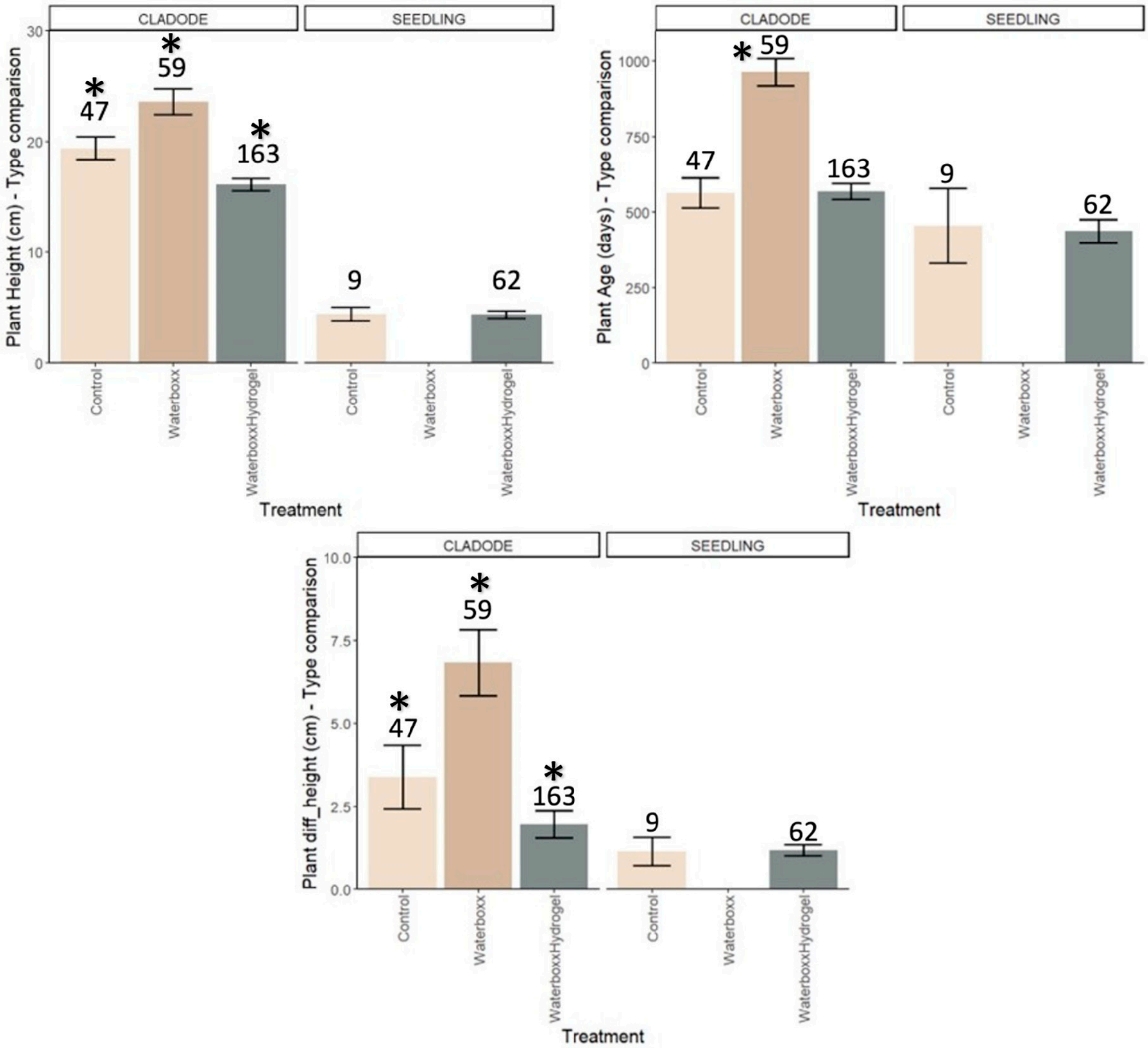

Figure 3. The barplots depict the effects of treatments on cladodes and seedlings. Cladodes are on the left and seedlings on the right. Top left: plant height; top right: plant age; bottom: plant growth (height difference). Seedlings received Waterboxx + Hydrogel; one cladode batch had Waterboxx alone to assess its effectiveness. The asterisk (*) indicates the statistical differences between treatments.

4. Discussion

Our findings describe the performance of the evaluated cacti, highlighting their adaptability in two distinct stages: before and after the removal of protective barriers and Waterboxx containers. Clearly, cactus survival declined gradually before the fences were removed (Figure S3). On the other hand, when the fences were removed in June 2020, mortality increased considerably. Subsequently, in November 2020, the Waterboxx containers were also removed, exposing the plants further and subjecting them to additional stress due to water scarcity. By the end of the experiment, only three plants remained, emphasizing the critical role that the fences and Waterboxx containers played in the survival of the plants. The consecutive La Niña events that occurred from 2020 to 2022 resulted in colder-than-average sea surface temperatures [39], may also have influenced the growth and survival of the cacti.

Due to the severe drought on Española during this period, its terrestrial birds observed the Waterboxx containers as a potential source of freshwater, especially during the dry season. Galapagos finches, mockingbirds, and doves became skilled at opening the Waterboxx lids to access water. Unfortunately, a few individuals became trapped in the fences when attempting to exit, which was why the fences were removed. The consequences of this decision need to be considered relative to the costs of and benefits to the whole ecosystem, including the *Opuntia* cacti and the birds. While the *Opuntia* cactus is a widespread species, it is also a keystone species, providing a vital water source, shelter, and food for various animals. The long-term establishment and conservation of the Opuntia cactus could prove beneficial to both the cactus and the diverse fauna that depend on it. In these experiments, we applied the precautionary principle and removed both fences and containers to prevent further incidents, but this may be reconsidered if further attempts are made to promote *Opuntia* regeneration on Española. Our results demonstrate the interplay of beneficial outcomes in one aspect and negative consequences in another. In the specific context of Española, methods should be designed to alleviate adverse impacts stemming from technologies to enhance the survival and ecological rehabilitation of pivotal species like Opuntia. The focus should be on shielding the *Opuntia* from destructive herbivory while ensuring the preservation of native species.

A previous study of *Opuntia megasperma* var. *orientalis* on Española at Punta Cevallos evaluated the survival of cacti with and without fence protection. Mortality in plants without fences reached 60%, confirming our results on the crucial role of protective mesh in the early-stage survival of *Opuntia* (Figure S3). Another long-term trial to evaluate exclusions using pads and seedlings was carried out [40] at four sites in Española, but the results were not published.

Analyzing plant survival based on treatments, all the water-saving technologies outperformed their respective control groups, as seen in Figure S2. These results reinforce previous studies [5], which showed that water-saving technologies were effective at increasing survival and growth rates for a different species of *Opuntia* on South Plaza, another island in Galapagos.

When we assessed the impact of water-saving technologies on plant traits like height, growth, and plant age, we noted that the achieved plant ages exhibited the most significant differences. This underscores the effectiveness of water-saving technologies in influencing this particular trait. The benefits of Hydrogel were demonstrated in other studies [24,29,30], but, contrastingly, when hydrogel was combined with the Waterboxx treatment, our results showed lower performance than the Waterboxx treated plants and the untreated plants.

When we analyzed the effect of treatments, planting dates, and their interactions on the studied plant traits—height, age, and growth—this effect was significant when these factors were evaluated separately; however, when we evaluated the effect of their interactions, we could not see statistical differences. This demonstrates that the individual impact of treatments, planting dates, and other factors on the plant traits is discernible, but when considering their combined influence, there is no conclusive evidence of a significant interaction effect among these variables. In another study developed in a similar species, it was possible to observe statistical differences between different planting dates [41], influenced by specific characteristics in the environment on the dates when the cacti were planted. Additionally, fertilization was found to affect the accumulation of macronutrients in plants, indicating a divergence in traits. However, the interaction between treatments and planting dates on traits was not evaluated in this study, emphasizing the need for more studies to assess this interaction within the Cactaceae family and thus draw more accurate conclusions.

The displacement of protective fences and Waterboxx containers led to a higher mortality rate in the seedling-based batch, indicating that cladodes have better survival than seedlings. Despite having protective spines, seedlings were vulnerable to mechanical damage, such as trampling by giant tortoises and physical harm incurred from bites by local birds actively seeking a water source within the seedlings. In contrast, the cladodes demonstrated greater resilience to these environmental challenges. Furthermore, the advanced growth stage of cladodes allows faster fruiting and improved overall survival than seedlings, although this comes at the cost of more limited genetic diversity, as they are clones of the original plant [42]. This can be partially addressed by harvesting cladodes from as many mature individuals as possible [15].

The older cladodes, which had been planted for about two years before fence removal, and the seedlings, around three years old, had not grown enough to protect themselves from herbivory, especially from the Española giant tortoise.

Cladodes exhibited more pronounced differences between treatments than seedlings, suggesting that seedlings may be less susceptible to drought stress. This could be attributed to the fact that seedlings already possess developed roots, while cladodes take time to establish their root systems. Cladodes possess a significant water content, rendering them more susceptible to desiccation. Water-saving technologies, such as Waterboxx and Hydrogel, engender sustained cladode hydration, enhancing growth and survival.

On the other hand, the cladodes were more vulnerable to herbivory due to their elevated water content. Cladodes tend to possess weaker spines than seedlings, which develop stronger spines as they reach the subadult stage, and in Española, this characteristic is even more pronounced. Unlike seedlings, mature cladodes lack robust spine defense, making them susceptible to herbivorous activities.

5. Conclusions

This study investigates a crucial step in the ecological restoration of Española Island's fragile ecosystem, focusing on *Opuntia megasperma* var. *orientalis* as a key species for maintaining the ecosystem, as it supports numerous other species on the island. To inform larger-scale restoration projects, we have attempted to identify effective tools for enhancing Opuntia survival and growth.

The use of water-saving technologies significantly enhanced the longevity of young *Opuntia megasperma* var. *orientalis*. However, unintended consequences emerged, as these advancements inadvertently led to bird mortality.

Based on our results, cladodes exhibit a promising performance compared to seedlings, suggesting they could be a preferable option for ecological restoration. However, further studies are required for long-term validation. The survival of cladodes is contingent on avoiding trampling by tortoises. In habitats with tortoises, protective fencing is essential to mitigate herbivore damage. The challenge in such scenarios is to devise a system that prevents birds from becoming trapped in the fences.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16030369/s1, Table S1. Summary statistics for plant height, age, and growth traits across different batches. Batch averages, maximum values, minimum values, sample sizes (n), and standard errors (SE) are presented for the variables: plant height (cm), age (days), and growth (cm). Table S2. Comparative analysis of cladodes and seedlings, utilizing linear regression with respect to treatment and planting date interactions. Figure S1. Fences placed around the Opuntias. Additional protection with rock was supplied to avoid fence damage by tortoises. Figure S2. Number of surviving plants based on batch and treatment. Red lines represent Control, blue is Waterboxx + Hydrogel (W + H), and purple is Waterboxx only. Figure S3. Population balance between survivals and planted individuals on each monitoring date. The green background represents the time period when the plants were protected by the fences, and the red background represents the time when the fences were removed and no more plantings were conducted.

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