Title: Water-saving techniques for restoring desertified lands: some lessons from the field

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Running title: Nature-Based Solutions for planting in (semi-)arid lands

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Abstract

In the light of the current climate crisis, one of the most serious ecological threats is the increase of desertification. In this context, restoration projects are necessary for reverting land degradation, and nature-based solutions could help them. The Cocoon™ has been designed as a new ecotechnology for improving seedling establishment. The Cocoon consists of a donut-shaped container made out of recycled cardboard that provides water and shelter to the seedling, at least during its first year, which is the most critical for plant establishment. The Cocoon was tested on a variety of soils, Mediterranean mesoclimates, vegetation and land uses that allowed testing the effectiveness of this ecotechnology under different conditions. Six planting trials, five of them in Spain (Canary Islands, Almería, Catalonia and two in Valencia), and one in Ptolemais (Greece), were performed. With the objective of studying its functionality, the survival of the seedlings, their vigor and growth were monitored along two years. In general, the Cocoon has proven its effectiveness by increasing seedling survival compared to the conventional planting system, especially under dry growing conditions (low rainfall, soils with low water holding capacity). The Cocoon also allowed for higher growth of some species (olive trees, olm oaks and Aleppo pines). Moreover, a positive correlation between the rainfall on the site and the degradation degree of the Cocoon device was observed. Overall, the Cocoon becomes more efficient the more arid the climate or the more difficult the growing conditions are.

Keywords:

Desertification, Restoration, Plantation, Climate change adaptation, Cocoon

1. Introduction

One of the most current ecological concerns is the increased risk of desertification as a consequence of the climate crisis. According to the United Nations Convention to Combat Desertification, the areas with the highest susceptibility to desertification are dry, arid, semi-arid and sub-humid areas (MAP, 2019), like large parts of the Mediterranean region. These "drylands" occupy 41% of the planet's land surface and are inhabited by 2 billion people (MEA, 2005). A common trait of these areas is that the aridity index ranges between 0.05 and 0.65 (MAP, 2019).

Desertification, and its consequent reduction of ecosystem services, can threaten future improvements in human well-being and reverse achievements in dryland areas related to climatic impacts such as control of dust storms or floods. Desertification reduces primary production and microbial activity, modifies the nutrient cycles, and increases the degradation of soil, entailing a loss of the ability to capture carbon and a loss of biodiversity of the involved ecosystems (MEA, 2005). The consequences of desertification are either its causes, thus becoming a system that feeds back. Therefore, combating desertification becomes one of the great global environmental challenges and its effects must also be considered globally.

However, at the local level, desertification may depend on the combination of multiple factors and site-specific processes that may aggravate the problem. These include indirect factors such as population size pressure, political and socioeconomic scenarios, but also direct factors such as land use and land use management apart from climate-related processes. The main aggravating factors at the local level are: seasonal droughts with extreme rainfall variability and/or heavy rains, poor soils prone to erosion, steeped slopes that increase the energy of runoff, recurrent forest fires causing loss of vegetation cover and changes in the physical, chemical and biological soil properties (Campo et al., 2006, 2008), crisis of traditional agriculture (which causes land abandonment), unsustainable exploitation and salinization of aquifers, bad agricultural and livestock practices and overpopulation in some areas (MAP, 2019).

All these factors cause a direct impact and stress on the vegetation and its growth. Most of these conditions occur or have historically occurred throughout the Mediterranean basin. Specifically, more than two thirds of the Spanish territory are classified as arid, semi-arid and dry sub-humid areas, and more than two thirds of these territories present a risk of desertification to a greater or lesser degree (MAP, 2019; WWF, 2016). The capacity of ecosystems to regenerate is limited in those areas, and therefore restoring degraded land is becoming essential to restore the integrity of impacted forests, rangelands, mine−affected areas, and numerous habitats that host valuable biodiversity (Muñoz-Rojas, et al., 2020).

Despite the efforts made, reforestation in the Mediterranean region cannot be considered satisfactory in many cases at present due to the slow growth of planted seedlings and the extremely high mortality rates (Valdecantos et al. 2014). Plantations suffer water stress, with droughts that last between 3 and 5 months, and even nutrient limitations when the seedlings are transferred to the soil, which is typically poor in the Mediterranean region (Díaz-Hernandez et al. 2003). Even if reforestation is carried out with regular irrigation, the survival rate is at most 50% for many species, but in many cases even less, since root systems with inadequate irrigation do not penetrate deep into the soil and remain in the surface layers (Salem, 1989).

In this context, nature-based solutions could help solving environmental problems, improving reforestation projects by increasing seedling establishment. Nature-based solutions are defined as the actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Nature-based solutions is best considered an umbrella concept that covers a range of different approaches (Cohen-Shacham et al., 2006). Therefore, ecotechnologies designed for supporting restoration projects and plantings could be also included in this group of solutions.

The objective of this work is to analyze the results of the large-scale implementation of a Nature-Based Solution using a new water-saving ecotechnology, named the Cocoon™, by means of the data collected in different field trials carried out in restoration projects. The main parameters evaluated have been seedling survival, vigor, and growth to verify the effectiveness of this technology in the wide range of land uses and environmental conditions present in six study areas located in the Mediterranean region and Canary Islands.

2. Material and methods

2.1 The Cocoon device

The Cocoon™ consists of a donut-shaped container (like a torus geometrical figure) made of recycled cardboard. This device has a capacity of 25 liters of water and a central space to install the seedling. Its design aims to provide water and shelter to the seedling, at least during its first year, being the most critical one for its survival. For Cocoon installation, the soil must be prepared beforehand digging a hole where this device will be introduced (Figure 1). Over time it will degrade and be integrated into the ground.

2.2 Study Areas

The Cocoon system was used in 6 restoration areas located in Spain and Greece. In Spain five large demonstration areas were located in El Bruc (Catalonia), Jijona and Tous (Valencia), Sierra de María (Almería) and Tifaracás (Canary Islands); and in Greece one area in Ptolemais (Western Macedonia). These areas cover a variety of soils, Mediterranean mesoclimates, vegetation and land use that allow testing the effectiveness of the Cocoon device in different conditions on several desertification scenarios, and in combination with different nature-based solutions for forest-fire vulnerability reduction, endangered/endemic species protection, open-pit mines restoration or recuperation of agricultural land (CREAF, 2017). We find from burned forest soils with relatively high organic matter content in El Bruc and Tous, to poor soils with low organic matter content in Jijona (abandoned cropland) and Tifaracás (volcanic parent material). In Ptolemais the soil derives from mining debris of a former coal mine that was situated where the plantation is located, therefore it presents very high contents of carbonates and coal particles. Table 1 shows the main characteristics of the studied areas, and Table 2 that of the respective soils.

2.3 Planting

The planting scheme was based on the combination of seedlings planted directly in the soil (controls), representing the traditional way, and seedlings planted with Cocoon. Each control was surrounded by several associated Cocoons, depending on the planting possibilities of the site. As a rule, a 1:3 control:Cocoon ratio was used. Therefore, each control provides paired measures with its associated Cocoon, so an encoding system was set that allowed data coupling.

In total, 22.301 seedlings of 31 different species or varieties have been planted on a whole surface of 73 ha (see supplementary materials, Table S1). The plantation was carried out in two phases, a first one in autumn 2016, and a second one in spring-summer 2017. Cocoon installation was carried out mechanically when topographic and soil conditions made it possible. In addition to the natural rain, the Cocoons were filled with 25 L of spring water and the controls were watered once planted with a similar amount of water but no refilling/irrigation was performed thereafter.

2.4 Monitoring parameters

Monitoring parameters have been divided in two groups: One evaluating the Cocoon effects on plant vigor and growth, vegetation exclusion, and Cocoon degradation. Another one evaluating the recovery by passive restoration of the plantation areas.

Plant vigor was evaluated by the following semi-quantitative scores during their normal growing period:

3: Healthy seedling, with more than 75% of green, not wilted leaves, with active growing points (apices) visible

2: Affected seedling, with 25-75% of the leaves being wilted, yellow or brown

1: Severely affected seedling with less than 25% of the leaves being green (i.e. the majority wilted, yellow or brown)

0: Presumably dead seedling with no or only wilted leaves. Seedlings, however, may still recover by resprouting after a rain event

R: Resprouted seedling

Plant growth was assessed measuring maximum plant height, from root crown to the shoot apex, and stem diameter at the tree base (at the level of the Cocoon's lid, at 10 cm of the soil), using a caliper. Vegetation exclusion was evaluated in 1 m diameter circle around the seedling, measuring vegetation cover in two perpendicular transects. Additionally, biomass was evaluated harvesting and weighting all the vegetation inside the circle (wet weight: weight at field; dry weight: weight after drying at 60°C for 4 days). Cocoon degradation was evaluated ranging each Cocoon from 1 to 4, being 1 the intact device and 2, 3 and 4 increased degradation till complete incorporation into the soil. The state 2 corresponded to a Cocoon without lid or a partially collapsed one.

Passive restoration was measured through vegetation structure measures and floristic inventories. Structure was evaluated quantifying cover types and height in 25 m transects, with a minimum of 3 transects per ha, parallel and perpendicular to the slopes. Floristic inventories were made identifying all plant species in each area. Additionally an abundance estimation per species was done using these patterns ranks:

1: 0-5% soil cover

2: low frequency (<25% soil cover)

3: high frequency (25%-75% soil cover)

4: dominant (>75% soil cover)

A protocol for measuring all these parameters was specifically defined (CREAF, 2019). The data were obtained in two field campaigns, one before summer 2017 and another one after two years, in late spring 2019.

2.5 Statistical analysis

Plant's height, stem diameter and root development were analyzed using STATGRAPHICS Centurion XVIII, StatView and R Studio. Since the data do not follow a normal distribution, analyses of the differences between treatments were performed using the Kruskal-Wallis test. For the determination of significant differences, a value of $\alpha = 0.05$ has been used.

3. Results

3.1 Seedling survival and physiological state

Analyzing the survival values together for all the study areas and plant species, contrasted differences could be observed. Seedlings that had been planted with the Cocoon methodology showed greater survival, close to 60%, while the control ones showed lower rates with up to 40%. Regarding the vigor of the survivors, the seedlings with good health predominated in both cases (control and Cocoon treatments), although with a higher percentage in the Cocoon treatment that had only few plants severely affected or resprouted. However, some particular tendencies can be observed when data is analyzed for each planting area (Figure 2).

In El Bruc, Jijona and Tous plantations, differences between controls and Cocoons were observed regarding mortality and the number of healthy plants. In contrast, in Sierra María there were no differences in seedling mortality between control and Cocoon treatment, being 37% in both cases. In addition, control seedlings showed greater vigor, with a greater number of healthy seedlings (36%) compared to those with Cocoon (26%). Survival in Ptolemais' plantations was high on all treatments. The percentage of affected seedlings was very low, and only appeared in the Cocoon treatment. In contrast, survival in Tifaracás was low in all treatments, despite seedlings planted with Cocoon presented a higher percentage of healthy seedlings (21%), compared to controls (12%).

However, vigor results are not only dependent on location but also on plant species. For example, *Rosmarinus officinalis* and *Prunus dulcis* in Sierra María showed high survival ratios in Cocoons like respective controls, while *Tamarix gallica* presented high mortality ratios in both treatments, with mortality being much higher in the controls, which reached a 100% mortality ratio (see supplementary materials, Figure S1). In Ptolemais, highest mortality basically affected *Cupressus sempervirens* specimens (see supplementary materials, Figure S2).

The overall results in Tifaracás were heavily determined by local harsh conditions, especially drought in summer 2017, just after plantation. Despite this, better survival rates were observed in seedlings with Cocoon compared to controls. *Pistacia atlantica* had high mortality rates in both treatments, but survival was higher in Cocoons although with a high percentage of severely affected seedlings. Mortality was also high in *Juniperus turbinata*, being 100% in controls and close to 80% in Cocoons. The best survival results were obtained with *Olea europaea*, with a mortality that did not reach 25% of the specimens and a relatively high percentage of healthy seedlings, close to 50%. In respective controls, mortality was higher (32%) together with the number of affected plants.

All the species planted in El Bruc and Jijona showed a similar trend, with a better physiological state in Cocoon treatment. However, for some of them such as *Ceratonia siliqua*, *Olea europaea* var. vera, *Prunus avium* and *Prunus spinosa*, the mortality of controls exceeded 80%. In El Bruc the best results were obtained for the two subspecies of *Quercus ilex* (spp ilex and spp ballota), *Quercus faginea*, *Olea europaea* var. cornicabra and *Juglans regia*, where Cocoons had survival rates well above their respective controls (see supplementary materials, Figure S3). In Jijona, also *Quercus ilex* and *Olea europaea* obtained good results with Cocoon, with survival ratios close to 100% in some cases (see supplementary materials, Figure S4), but *Tetraclinis articulata* also obtained good results for/with both treatments, reaching 86% survival ratio of controls.

3.2 Seedling growth

Seedling growth depended on local environmental conditions but also on species, and a similar trend towards survival was observed. A clear tendency to a better growth of seedlings planted with Cocoon was noted, both in diameter and height, when survival is higher, like in *Quercus ilex* and *Olea europaea* (Figure 3). However, for some species, like *Rosmarinus officinalis*, there were no significant differences between treatments, and for others controls presented higher growth than Cocoons, like almond trees in Sierra María (Figure 3). Regarding root development, differences were only observed in *Olea europaea var. cornicabra* (Figure S12, Annex 3).

3.3 Cocoon degradation

The degradation of Cocoon is an important aspect to evaluate since its design, forseeing the use of biodegradable material, aims at incorporation into the soil, once its watering function is finished. At a general level (Figure 4), the vast majority of Cocoons presented the bowl in functional condition but with the lid of the device sunk, damaged or not present (State 1). In a quarter of the installed devices Cocoon began to show signs of degradation such as cracks or holes in its bowl (State 2). There was a lower percentage of completely degraded Cocoons (State 4). Some of the Cocoons in stage 1 could retain runoff and rainwater, increasing the water availability for the respective seedlings, as had been observed. In fact, this capacity to retain water two years after implantation, longer than the expected useful life, had been utilized in new Tifaracás plantations for refilling the bowls during summer to have more water available and improve the survival ratios.

These results differed by study area (Figure 4). Although state 2 occurred most frequently (except in Calabria), differences could be observed locally. The presence of Cocoon residues incorporated into the soil was very scarce or not reported for most areas, except in El Bruc, Calabria and Jijona. These three zones, together with Sierra María (a large proportion of Cocoons in state 3) were the ones with the greatest global Cocoon degradation. The area with the least degradation was Tifaracás, with state 1 and 2 occupying 96% of the Cocoons studied, and followed by Tous and Ptolemais (Figure 4).

3.4 Vegetation structure and diversity

The structure and floristic biodiversity data are presented as Supplementary Information in Tables S2 and S3 of Annex 4, respectively. All uncropped areas in Iberian Peninsula showed a positive evolution regarding herbaceous and/or woody vegetation cover and/or floristic composition. However, in Ptolemais and Tifaracás we could not identify differences in the structure or composition of the vegetation regarding the 2017 sampling.

The characterization of the natural vegetation in Sierra María was carried out in the temporary dry riverbank (*rambla*), since the almond plantations are subjected to tillage. Table S2 shows a reduction in the cover and height of woody plants, accompanied by an increase in the cover of herbaceous plants. Regarding plant diversity, there was a net change in 12 species (14 new species appears and

26 not found), among which it is worth mentioning the disappearance of abundant species in 2017 such as *Hordeum murinum* or *Tamarix gallica*, and the appearance with a high frequency of *Avena fatua* and *Euphorbia sp.* In 2019, the vegetation cover of the dry temporary riverbank upper zone suffered the effects of sporadic torrential rains, common in this area, generating a flood that washed away the vegetation.

In the El Bruc area, there was an increase (2019 vs. 2017 sampling) in both herbaceous and woody cover for the three sub-zones of sampling, accompanied by an increase in the average height of both types of vegetation (Table S2). This increase in plant cover was also accompanied by an increase in species diversity. With respect to the inventories of 2017, in stony and shallow soils some *Asteraceae* appeared abundant (*Centaurea scabiosa subsp. scabiosa*, *Helichrysum stoechas* and *Scorzonera angustifolia*) and grasses as *Brachypodium phoenicoides*, increased their abundance which became dominant species. In general, *Rosaceae* plants (*Amelanchier ovalis*, *Rosa canina*, *etc.*) and *Fabaceae* also increased. In agricultural soils, that are deeper and finer textured, the trend was very similar but with some differences. In these soils, *Asteraceae* showed a reduced abundance becoming testimonial species, while the *Rubiaceae* like *Galium lucidum* and *Rubia peregrina* appeared. As in the previous area, the *Fabaceae*, in particular *Dorycnium penthaphyllum*, presented a great abundance, and several species of grasses appeared although with low abundance. In addition, *Helianthemum syriacum and Rosmarinus officinalis*, abundant plants in neighboring areas that were absent in 2017, appeared in 2019 with high frequency.

In Jijona and Tous areas there was also a tendency to increase the vegetation cover of both woody and herbaceous species. Moreover in Jijona, for woody species the trend of cover increment was accompanied by an increase in the average height of the plants, but for the herbaceous species the average height was reduced or scarcely increased when compared to 2017. In Tous, there is an increase in both the cover of woody and herbaceous species. However, this gain was not accompanied by an increase in average height, which remained stable. Regarding floristic diversity, both areas remained quite stable between 2017 and 2019.

3.4 Plant competition evaluation

With respect to the data collected from the vegetation surrounding the seedlings in the different study sites (Table 3), we could observe two different tendencies. El Bruc and Jijona showed a pattern of higher biomass weight with greater cover in controls. However, in driest areas like Tifaracás, we could see a greater development of vegetation around Cocoons.

4. Discussion

Overall, significant differences were found between seedlings planted with Cocoon and controls. Seedling mortality in Cocoon was close to 40%, while in the control group it reached 60%. Besides this moderate improvement in survival, surviving plants had a better physiological state when Cocoon was used. These differences could be explained because nutrient uptake is subordinated to water availability in arid and semi-arid environments (Maestre et al. 2005; Powers and Reynolds 1999). By providing water to the plantations with the Cocoon device, the plants would be overcoming or reducing this limitation and making better use of available nutrients, causing this increase in survival and growth. In fact, Cocoon not only provides water to the plant during the first months, but it also creates a micro catchment that allows a greater infiltration of rainwater and accumulation of runoff around the plant. On the other hand, it not only increases the water supply, but also reduces losses. The plant protector reduces evapotranspiration, and the lid and the bowl itself reduce competition with herbs, especially during the first year. In addition, the seedlings planted with the Cocoon had a tendency towards a more developed root system than controls that resulted in a greater development of the aerial biomass for some species.

Within the wide range of climates tested, the driest one (Tifaracás) was also the most challenging for the Cocoon (unless re-watered), with a survival rate below 30%. However, these results cannot be considered very negative, since in previous restoration projects carried out in nearby areas with conventional planting systems, the mortality rates were close to 100% (CREAF, 2017). It is especially interesting, in this case, to analyze the balance between the increase in survival due to re-watering and the consequent increase in maintenance expenditure. Cocoon technology could be considered a viable option to reduce seedlings' mortality without increasing the maintenance expenses, although it is true also that Cocoon installation is more expensive than the traditional methods. In a new plantation carried out in 2018, Cocoons were re-filled twice during summer and the survival rate was significantly improved (see annex 5). Given these results, the option of refilling the Cocoon bowl, although it implies higher cost, could be an optimal solution for plantations in the drylands of Canary Islands.

In sub-humid regions, like Ptolemais, seedlings planted with Cocoon present similar survival to those planted with common techniques. Regarding *Cupressus sempervirens*, differences in mortality ratios were observed between seedlings with different heights planted with Cocoon: 46% in 50 cm specimens vs. 24% in those of 30 cm. This fact supported the recommendation that the seedlings planted with the Cocoon should preferably be one-year old as reported previously (Land Life

Company, 2016). *Cupressus* seedlings are sensitive to extreme weather conditions, adapting better when they are of small size (low height) because they are in better conditions to develop stronger root systems quickly. In this site, spring plantations recorded higher survival rates than autumn plantations, because of better weather conditions for *Cupressus* implantation.

In contrast, in areas with drier rainfall regimes like Jijona or El Bruc, differences between control and Cocoon are significant, demonstrating the efficacy of this device in adverse conditions (prolonged drought and high temperatures) like in the 2017 summer. This is especially true in the case of El Bruc, where a 30% reduction of annual rainfall occurred (449 mm throughout 2017), especially in summer (70% reduction, 58 mm for the whole season).

Regarding soil conditions, Cocoons could not be properly installed in shallow and stony soils, like in some parts of Tous site. Additionally, strong wind events in this site blew out shelters from the Cocoon, particularly those that were not properly installed, exposing prematurely such seedlings to high irradiation and desiccating winds. Therefore, the use of the Cocoon is neither recommended in Leptosols or those having a petrocalcic horizon near the surface (IUSS Working Group WRB, 2015), like those existing in Sierra María almond fields. Planting under these conditions means that Cocoons could not perform to their full potential, which makes this technology less competitive compared to usual methods.

Regarding the different plant species, the high mortality in *Olea europaea var*. *arbequina* plantations in El Bruc (both in control and Cocoons) should be attributed to the bad quality of the seedlings, with rotting roots, stem scars, leaf loss and chlorosis (CREAF, 2017). In contrast, arbequina olive trees planted in Jijona had a very high survival rate (almost 90%), with approximately 75% of seedlings planted with Cocoon healthy and growing, probably aided by runoff collection in Cocoons. In general, plantations in Jijona, a site with an arid climate and a very poor soil, gave very good results for Cocoon.

The response of holm oak (*Quercus ilex)* subspecies is especially remarkable. *Ballota* subspecies performed very well in El Bruc, with a survival rate greater than 60% and a statistically significant higher growth with Cocoon. This holm oak subspecies plantation could be considered as an example of assisted migration strategy for adaptation to climate change (IPCC, 2007; Pramova et al., 2019). It is an indigenous subspecies of southern Spain and northwestern Africa that was planted at higher latitude simulating the displacement of the distribution area that this tree could suffer with climate change, through the named assisted migration mechanism (Sansilvestri et al., 2016; Schwartz et al., 2012). Another plant species that responds well to assisted migration is *Tetraclinis articulata*. This small tree, despite being an Ibero-African endemism that is mostly located in northwestern Africa, and that in Europe only has two small natural populations, one in Malta and another in Sierra de Cartagena (SE Spain) (TGD, 2020), was planted in Jijona (outside its distribution area) with very good results.

These assisted migration tests were also performed with typical agricultural tree species. The Cornicabra olive tree variety was planted in El Bruc and in Jijona. This variety is typical of central and southern Spain, with vigorous trees, erect bearing and thick canopy density. It is apparently more adapted to continental climates than the Arbequin olive trees or the Vera variety, the latter one being the variety historically used in the area of El Bruc, which we could also find in different places in the province of Barcelona and Valencia (Gómez-Escalonilla and Vidal, 1984). Both in El Bruc and in Jijona, the Cornicabra variety responded better than the Arbequin variety. Cornicabra variety also adapted better than Vera in El Bruc, with Cornicabra seedlings showing higher survival rates and vigor. Since water deficit (moisture stress) is the most persistent environmental stress on fruit crops (Petros et al., 2020), Cocoon could help installing crops in arid and semi-arid lands.

As for the growth of the seedlings with Cocoon, there is yet insufficient evidence to state that this device improved it in relation to the control seedlings according to the data available. Regarding the growth in length and weight of the roots, significant differences were found only for *Olea europaea var. cornicabra* in El Bruc, being higher in the plants with Cocoon. However, as the available data only reflects plant growth in two years (2017-2019), considering the slow evolution of the vegetation in these arid and semi-arid environments (Yu & Wang, 2018), it is possible to state that the positive trends observed in many cases suggest that if the growth monitoring would be repeated after some years, these differences could increase (Shackelford et al., 2018). The greater the water and thermal stress, the more evident the microclimatic and edaphic improvement provided by Cocoon to the species planted and to the accompanying vegetation will be.

The structure and biodiversity of the accompanying vegetation showed different trends for the studied areas, related to climatic and biotic factors, including anthropogenic ones. In general, in the non-extreme Mediterranean climate sites tested an increase in vegetation growth and/or plant diversity had been observed. According to the intermediate disturbance hypothesis (Connel, 1978), the increase in biodiversity of these communities is an indicator that they are rising in complexity and maturity, as they have not reached the intermediate degree of disturbance (or recovery), where maximum floristic richness would be produced. However, the elapsed time can be considered rather short for proper assessment of improvements in biodiversity. Anyway, it must be considered that these are relatively anthropized systems, especially in the case of Sierra María, El Bruc or Jijona, where the owners try to obtain benefits planting agricultural or forest species with relatively high added value (olive, almond, truffle holm oaks), taken into account the potentiality of those soils.

As for the more arid sites, Tifaracás and Sierra María remained stable, without appreciable changes in plant biodiversity. This slow evolution could be due to the hard environmental conditions of these areas. The restoration of degraded arid lands has several limitations: (1) resource (water, nutrients, soil organic matter, propagules) levels are uniformly low; (2) harsh microenvironmental conditions limit seedling recruitment; and (3) animals have a greater potential to disrupt restoration efforts in arid systems (Roundy et al., 1993). The effect of animals in slowing down restoration dynamics could be clearly observed in Tifaracás, with an important activity of wild goats. Moreover, extreme events are also a limitation in arid land restoration (Olsson et al., 2019). The slight changes observed in Sierra María, with a reduction of woody plants, are probably due to a flood that affected the restored area in 2018.

Cocoon degradation is also related to the rainfall regime, increasing in areas with higher rainfall values. As the lid was the most exposed part of this device, it suffered the ravages before. Since Cocoon degradation is slower in dry conditions, trees growing under such conditions can also longer benefit from extended, and still needed, Cocoon support: more water available through Cocoon refilling after rain events, reduced evaporation losses, and out-performing of competing adjacent weeds. As mentioned above, this fact became advantageous for the plantation carried out in Tifaracás in 2018, where the Cocoons were refilled to increase their survival, being an experience with very good results. Moreover, partially degraded Cocoons may still provide rainwater and be a shield against evaporation, implying an extended water availability to support tree growth.

As a conclusion, the Cocoon technology proved to be useful for reforestation in a wide range of arid and semi-arid conditions. In general, conventional plantations showed higher mortalities and relatively lower vigor rates than plantations using this ecotechnology. The direct and indirect water supply, the mitigation of plant competition around the seedling, the reduction of evapotranspiration and the microcatchment effect, create a suitable set of conditions for the improvement of the physiological state of plants, which increases their survival. However, a case per case evaluation is needed before deciding to use this technology. Cocoons have an added advantage when site conditions impose more drought stress (lower rainfall, sandy textured soils with poor water retention), and/or when tree species used are less adapted to drought stress in early stages of development. However, Cocoons are less competitive than common techniques for plantations in soils with high water retention capacity, or in Mediterranean humid climates, or for planting drought tolerant species. Small differences in survival and growth, combined with higher costs of planting with Cocoons, make this ecotechnology less interesting in these situations.

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Tables

Table 1. Study areas identification and location, climatic parameters, geologic substrates and Nature-Based Solutions applied.

Site	**Region**	**UTM coordinates (ETRS89)**	**Mean annual precipitation (mm)**	**Highest/Lowest average monthly max./min. temperature (°C)**	**Potential Evapotransp. (mm/y)**	**Geological substrate**	**Nature-Based Solution scenario**
Tifaracás	Canary Islands	427779, 3095798	177	14,3-28,6	1000-1200	Volcanic	Endangered/ Endemic species restoration
Sierra María	Almería	571368, 4164540	350	0,8-30,3	600	Alluvial	Cropland restoration + rambla restoration
Jijona	Alicante	721173, 4267646	445	8,9-24,7	1388	Early Cretaceous marls	Cropland restoration
Tous	Valencia	700667, 4343691	424	10,6-25,5	1143	Cretaceous dolomites	Passive restoration acceleration
El Bruc	Barcelona	394519, 4609198	666	6,7-22,1	982	Conglomerates	Forest fire vulnerability reduction
Ptolemais	Western Macedonia	565459, 4482995	570	1,8-22,5	737	Marls- lignite	Mine restoration

Table 2. Main soil characteristics of the study areas. Values represent mean ± standard error. SOM, soil organic matter; CEC, cation exchange capacity; SOC, soil organic carbon.

Site	**Texture**	**$CaCO_3$ (%)**	**CEC (cmol kg^{-1})**	**pH water (1:2,5 w/v)**	**EC (dS/m)**	**SOM (%)**	**SOC stock (T/ha)**
Sierra de María	Clay loam	44,3 ± 29,3	18,8 ± 12,5	8,62 ± 0,24	0,60 ± 0,06	2,13 ± 1,34	37,57 ± 18,71
El Bruc	Sandy clay	28,7 ± 11,3	14,1 ± 3,3	8,45 ± 0,38	0,88 ± 0,17	3,28 ± 1,65	58,03 ± 26,18
Tous	Clay	9,4 ± 13,9	28,1 ± 5,4	8,18 ± 0,14	0,42 ± 0,01	3,39 ± 1,30	26,69 ± 9,59
Jijona	Loam	77,9 ± 6,8	11,5 ± 4,9	8,93 ± 0,17	0,80 ± 0,19	1,79 ± 1,18	27,67 ± 6,21
Tifaracás	Clay	7,1 ± 3,6	41,7 ± 1,0	8,52 ± 0,19	0,66 ± 0,09	1,49 ± 0,37	13,22 ± 4,83
Ptolemais	Sandy	67,2 ± 14,6	24,4 ± 13,6	8,26 ± 0,32	1,74 ± 0,60	7,47 ± 14,39	29,19 ± 14,02

Table 3. Herbaceous cover and plant biomass in 1 m diameter circles around control (C) and Cocoon (CO) seedlings, after 2-2.5 years of planting in four areas. Values represent mean ± standard error.

Site	**Sub-site**	**Treatment**	**Herbaceous cover (%)**	**Plant biomass (g m^{-2}, wet weight)**	**Plant biomass (g m^{-2}, dry weight)**
El Bruc	EB1	C	47 ± 3	178 ± 85	76 ± 36
El Bruc	EB1	CO	33 ± 18	271 ± 111	132 ± 51
El Bruc	EB2	C	93 ± 5	850 ± 217	227 ± 104
El Bruc	EB2	CO	60 ± 8	612 ± 195	204 ± 25
El Bruc	EB3	C	53 ± 22	273 ± 207	149 ± 93
El Bruc	EB3	CO	31 ± 7	258 ± 118	133 ± 62
Jijona	JI1	C	19 ± 3	258 ± 38	128 ± 20
Jijona	JI1	CO	12 ± 2	333 ± 141	134 ± 49
Jijona	JI2	C	52 ± 11	596 ± 217	342 ± 55
Jijona	JI2	CO	22 ± 9	337 ± 31	183 ± 23
Tous	TO1	C	0 ± 0	0 ± 0	0 ± 0
Tous	TO1	CO	8 ± 2	98 ± 24	48 ± 12
Tous	TO2	C	3 ± 1	57 ± 14	23 ± 12
Tous	TO2	CO	9 ± 1	189 ± 26	98 ± 12
Tifaracás	TI1	C	70 ± 35	77 ± 41	71 ± 36
Tifaracás	TI1	CO	95 ± 5	95 ± 15	89 ± 14
Ptolemais	PT2	C	52 ± 7	984 ± 12	887 ± 8
Ptolemais	PT2	CO	52 ± 7	942 ± 10	859 ± 6
Ptolemais	PT3	C	47 ± 7	773 ± 8	702 ± 5

Ptolemais	PT3	CO	49 ± 10	912 ± 10	833 ± 6