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Carpobrotus Management in a Mediterranean Sand Dune Ecosystem: Minimum Effective Glyphosate Dose and an Evaluation of Tarping

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ABSTRACT

At a global scale, biological invasions represent one of the most important threats to biodiversity conservation. The *Carpobrotus (Aizoaceae*) genus, which is native to South Africa, has been introduced into five different continents and is particularly invasive in many coastal habitats. The application of glyphosate avoids some problems associated with manually controlling *Carpobrotus* over large spatial scales. However, before this practice can be extended and its impact minimized, its effectiveness under different application conditions must be assessed first. Thus, glyphosate was sprayed at different concentrations (0.5, 0.4, 0.3, 0.2, 0.1, and 0.05 g/m^2) on experimental plots with 100% *Carpobrotus* coverage to determine the minimum effective dose. Tarping was also evaluated as an alternative method for *Carpobrotus* management over reduced areas. Thus, four different weed-control fabric types were tested: black anti-weed fabric, sewn felt, black G-300 polyethylene, and Fijavert coconut-anti-weed matting on experimental plots with 100% *Carpobrotus* coverage. The obtained results showed that the minimum effective dose of glyphosate which prevents *Carpobrotus* regrowth in dune ecosystems was 0.4 g/m^2. It was also shown that at least three months of tarping were required under winter conditions to produce complete *Carpobrotus* plant wilting and thus, prevent their regrowth. No significant effect on *Carpobrotus* growth was observed in terms of the fabric type used for the tarping tests. The presence of native species seedlings in the experimental plots after the death of the *Carpobrotus* plants following the application of herbicides or tarping was also monitored.

Keywords: invasive plant species, chemical control, dune restoration, herbicides, iceplants, weed-control fabric

INTRODUCTION

Invasive species are a major element of global change and are contributing to the worldwide loss of biodiversity, ecosystem degradation, and the impairment of ecosystem services (Pysek and Richarson, 2010). The succulent *Carpobrotus* (L.) N.E. Br. (*Aizoaceae*) genus is one of the foremost invaders of Mediterranean coastal ecosystems (Campoy et al. 2018; Giulio et al. 2020; Mifsud, 2021). In Spain, *Carpobrotus* is present in every coastal peninsular and insular province (Sanz–Elorza et al. 2004). The *Carpobrotus* genus, which is native to South Africa, was widely used as an ornamental and for soil stabilization (Sanz–Elorza et al. 2004; Campoy et al. 2018; Mifsud, 2021). However, it has now dispersed from the planting areas, becoming an extensively distributed invasive species present in five different continents, and has become widely naturalized in many coastal habitats, such as active and stabilized dunes, coastal scrub, and rocky coast (Campoy et al. 2018; Mifsud, 2021). *Carpobrotus* grows horizontally and radially in all directions and forms monospecific carpets which attain near-dominance (Campoy et al. 2018). Moreover, numerous studies have shown that *Carpobrotus* strongly affects the native plant and animal species as well as soil characteristics (for a review, see Campoy et al. 2018).

Eradication is a key conservation tool to mitigate the impact of these biological invasions and is considered the best option when preventive action fails. Different techniques such as mechanical, chemical, or biological methods can be used, according to the specific biology of the invasive species in question, and considering the cost, efficiency, and feasibility of these methods. The *Carpobrotus* management and eradication campaigns have been implemented in many places around the world, making it the invasive plant most often targeted by the eradication activities in Mediterranean habitats (Campoy et al. 2018). Furthermore, the effects of specific eradication activities on soil, community recovery, and revegetation have also been evaluated in recent years (Buisson et al. 2020; Lazzaro et al. 2020; Fos et al. 2021).

Mechanical removal is the most common method used for *Carpobrotus* eradication (DiTomaso et al. 2013; Campoy et al. 2018; Chenot et al. 2018); this approach is generally effective, but is time and labor intensive and can involve logistical problems, because it generates large amounts of plant material (DiTomaso et al. 2013; Campoy et al. 2018; Chenot et al. 2018). Additionally, physical removal can require subsequent work to monitor the cleaned areas to prevent the reappearance of new individuals (Campoy et al. 2018; Chenot et al. 2018). Indeed, recent reports have shown that follow-up monitoring was necessary for at least 7 years to prevent *Carpobrotus* return and to ensure success (Buisson et al. 2020).

Chemical methods involving herbicide spraying have also been employed for *Carpobrotus* control, with glyphosate, N-(phosphonomethyl) glycine being the most often used herbicide (Albert 1995; Campoy et al. 2018; Lazzaro et al. 2020), although others have also been evaluated (Smyth et al. 2011; Lazzaro et al. 2020). Moreover, the effectiveness of glyphosate is increased when a 1% surfactant is added to break the leaf cuticles (Albert 1995; DiTomaso et al. 2013; Campoy et al. 2018). In addition to glyphosate, at least five other herbicides or formulations have been shown to be effective in the eradication of *Carpobrotus*, (1) paraquat plus simazine and benzoylprop-ethyl (Guerreiro, 1977); (2) glyphosate plus diquat (Smyth et al. 2011), (3) aminocyclopyrachlor plus chlorsulfuron (DiTomaso et al. 2013); and (4–5) different formulations of three active principal ingredients: glyphosate and triclopyr + fluroxypyr (Lazzaro et al. 2020).

Glyphosate has been shown to be effective for *Carpobrotus* eradication when sprayed at concentrations of 3.6 and 5.4 kg/ha (Guerreiro, 1977), 2.9 to 3.1 kg/ha (Hueso et al. 2005), 4.0 kg/ha (Smyth et al. 2011), or of 3.6 kg/ha (Lazzaro et al. 2020). This compound was also highly effective when sprayed on experimental plots at 40 kg/ha–around 10 times the maximum recommended dose range (EFSA 2017)–in a study evaluating the effects of residual glyphosate on the restoration of natural vegetation by sowing (Fos et al. 2021). However, to date, no studies have examined the minimum effective dose required for the eradication of *Carpobrotus*.

Another potential strategy for invasive plant control is solarization and tarping, a technique that has been widely employed with success in agricultural contexts. While the term solarization generally refers to soil sterilization, in the tarping technique, an opaque plastic cover is placed over the soil surface to exclude the solar light and increase solar heating, which kills the plants but may not involve total sterilization of the soil (Marushia and Allen 2011; Hunter et al. 2016). Tarping has been used for the control and eradication of *Carpobrotus* in California (Albert 1995; DiTomaso et al. 2013), although few details about this technique, its contradictions, and effectiveness have been reported to date. Similarly, no information is available in the academic literature regarding the way this eradication methodology could affect the potential revegetation of the areas previously occupied by *Carpobrotus*.

Thus, in this work, the experimental plots with 100% *Carpobrotus* coverage were sprayed with different doses of glyphosate to find the minimum effective dose required for the total *Carpobrotus* eradication. The effectiveness and viability of the tarping methodology on experimental plots under winter conditions for the eradication of *Carpobrotus* in sand dune ecosystem by using four different types of weed-control fabrics were evaluated as well.

MATERIALS AND METHODS

Location of the natural area

The natural area used for controlled glyphosate applications and evaluation of the tarping technique was one coastal location on the *Aigua Blanca* beach (38° 55′10″ N, 0° 07′16″ W) in Oliva, in the province of Valencia (Spain). The coastal areas studied were selected with the supervision of environmental officers from the Valencian Regional Government and Spanish Ministry of Environment. This area is included in the 'Dunes of *La Safor'* listing in the Sites of Community Importance on the Valencian Community (July 19, 2006, European Commission). The natural habitats at this site include (1) embryonic shifting dunes 2110; (2) shifting dunes along the shoreline with *Ammophila arenaria* 2120; (3) *Crucianellion maritimae* fixed beach dunes 2210; (4) *Malcolmietalia* dune grasslands 2230; and (5) *Cisto-Lavenduletalia* dune sclerophyllous scrubs 2260. In this coastal area, *Carpobrotus* produces thick mats that form continuous, monospecific carpets (Figure 1).

Glyphosate application assays

Under controlled conditions, glyphosate (36 g/l, as an ammonium salt; Touchdown, Syngenta Iberica, Spain) was sprayed on plant leaves in 1 m^2 experimental plots with 100% *Carpobrotus* coverage (Figure 1) at doses of 0.5, 0.4, 0.3, 0.2, 0.1, or 0.05 g/m^2. A previous trial applied the doses of 4.0, 2.0, 1.0, or 0.7 g/m^2 on one experimental plot; here, two plots per dose were tested (Figure 1), applying 200 ml glyphosate and a non-ionic surfactant (0.1% v/v; Temojan, Manvert, Spain) per plot, using a hand-held spray bottle at a height of 50–60 cm above the *Carpobrotus* plants. The applications were started on September 12, 2007 and the experimental plots were visited to evaluate the effectiveness of the treatments 7, 14, 25, 48, and 82 days afterwards.

Tarping test

Four types of weed-control fabrics were tested to evaluate the effectiveness of tarping on *Carpobrotus* eradication: black anti-weed fabric (Figure 2A), sewn felt (Figure 2B), black G-300 polyethylene (Figure 2C), and Fijavert coconut-anti-weed matting (Figure 2D). All the fabrics were used on two 8 m^2 (2 × 4 m) experimental plots (Figure 2) with 100% *Carpobrotus* coverage and were fixed to the substrate with pegs. The fabrics were put in place on November 10, 2008 and were periodically monitored (at 7, 14, 21, 37, 59, and 89 days) to determine their effect. At each visit, the lower right corner of the fabric (with respect to the coastline) was lifted to observe and photograph the *Carpobrotus* plants (Figure 4). We kept the fabrics on the *Carpobrotus* plots for 59 days at one site (January 7, 2009) and 89 days at the other (February 4, 2009).

RESULTS

The minimum effective glyphosate dose for *Carpobrotus* eradication

Seven days after spraying glyphosate on the experimental plots at different doses, the *Carpobrotus* plants showed no obvious signs of degradation. The herbicide application had no effect in most of the experimental plots at doses of 0.1 and 0.05 g/m^2 at any of the time points (Figure 3, D25). Fourteen days after glyphosate spraying at 0.5 to 0.4 g/m^2, some *Carpobrotus*

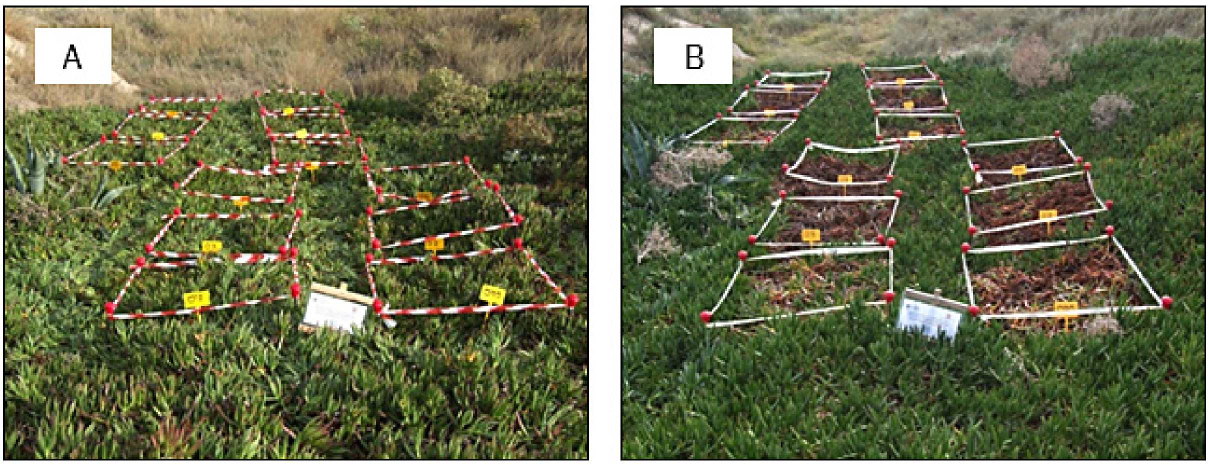

Figure 1. General aspect of the experimental plots before (A) and after (B) the application of glyphosate at different concentrations

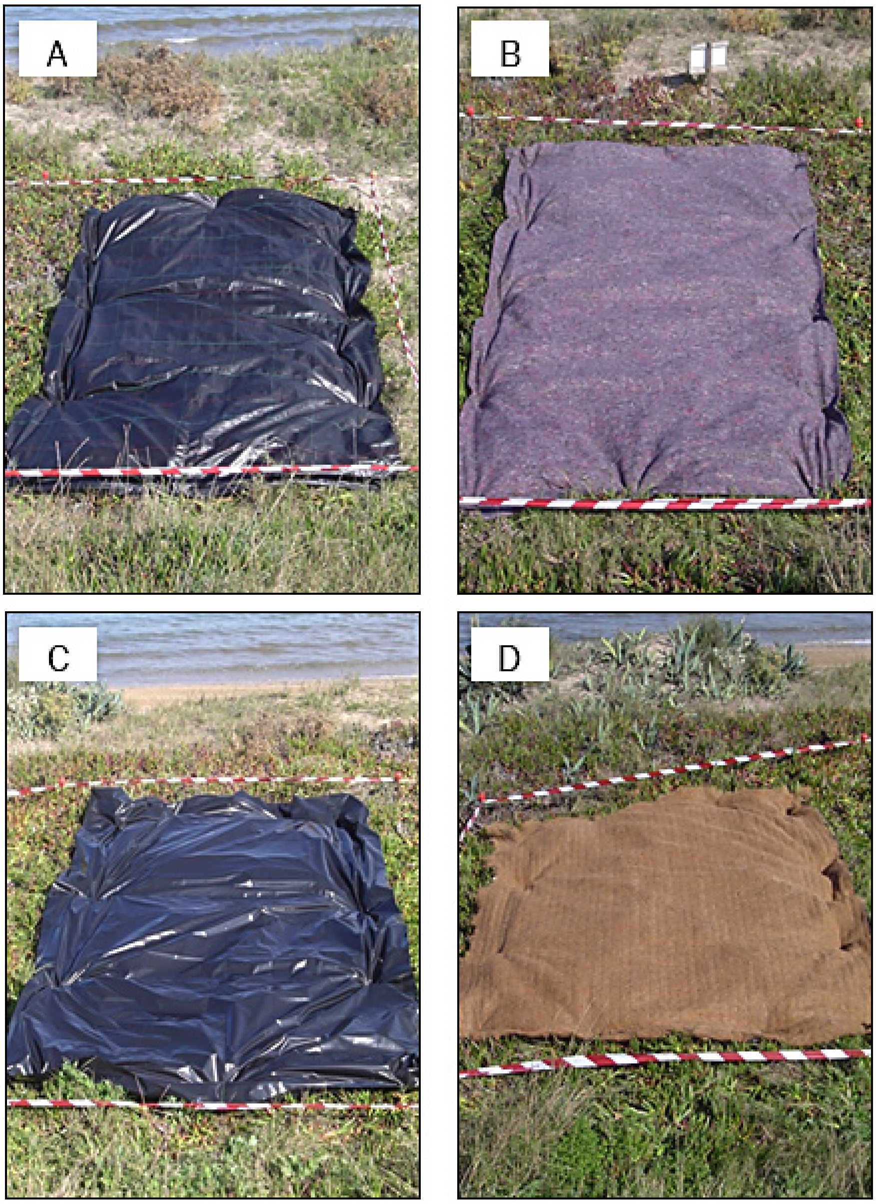

Figure 2. General aspect of the experimental plots with the four types of anti-weed fabrics used for the covering *Carpobrotus*: (A) black anti-weed fabric; (B) sewn felt; (C) black G-300 polyethylene; and (D) Fijavert coconut-anti-weed matting

plants had begun to show a yellowish coloration (Figure 3, D14), and after 25 days at the same dose, the plants had started to turn yellowish-brown, although the leaves and branches still maintained a typical succulent appearance (Figure 3, D25). Forty-eight days after spraying glyphosate at 0.5 and 0.4 g/m^2, the *Carpobrotus* in the whole experimental plots were dark brown and most of them were dry (Figure 3, D48); The *Carpobrotus* plants sprayed at 0.3 and 0.2 g/m^2 doses still had yellowish-brown leaves and branches, and most of the *Carpobrotus* sprayed at 0.1 and 0.05 g/m^2 were still a yellowish-green and had a typical succulent appearance (Figure 3, D48). Finally, 82 days after glyphosate spraying at 0.5 and 0.4 g/m^2, the *Carpobrotus* appeared dry and had fragmented leaves and branches; some plants were gray-black (Figure 3, D82); of the experimental plots sprayed at 0.3 g/m^2, some still had branches with the capacity to grow. Thus, it was estimated that the effectiveness of the glyphosate spraying ranged from 90 to 95%.

Carpobrotus eradication using tarping

Seven and 14 days after covering, the *Carpobrotus* plants showed no obvious signs of tarping with any of the anti-weed fabrics we tested.

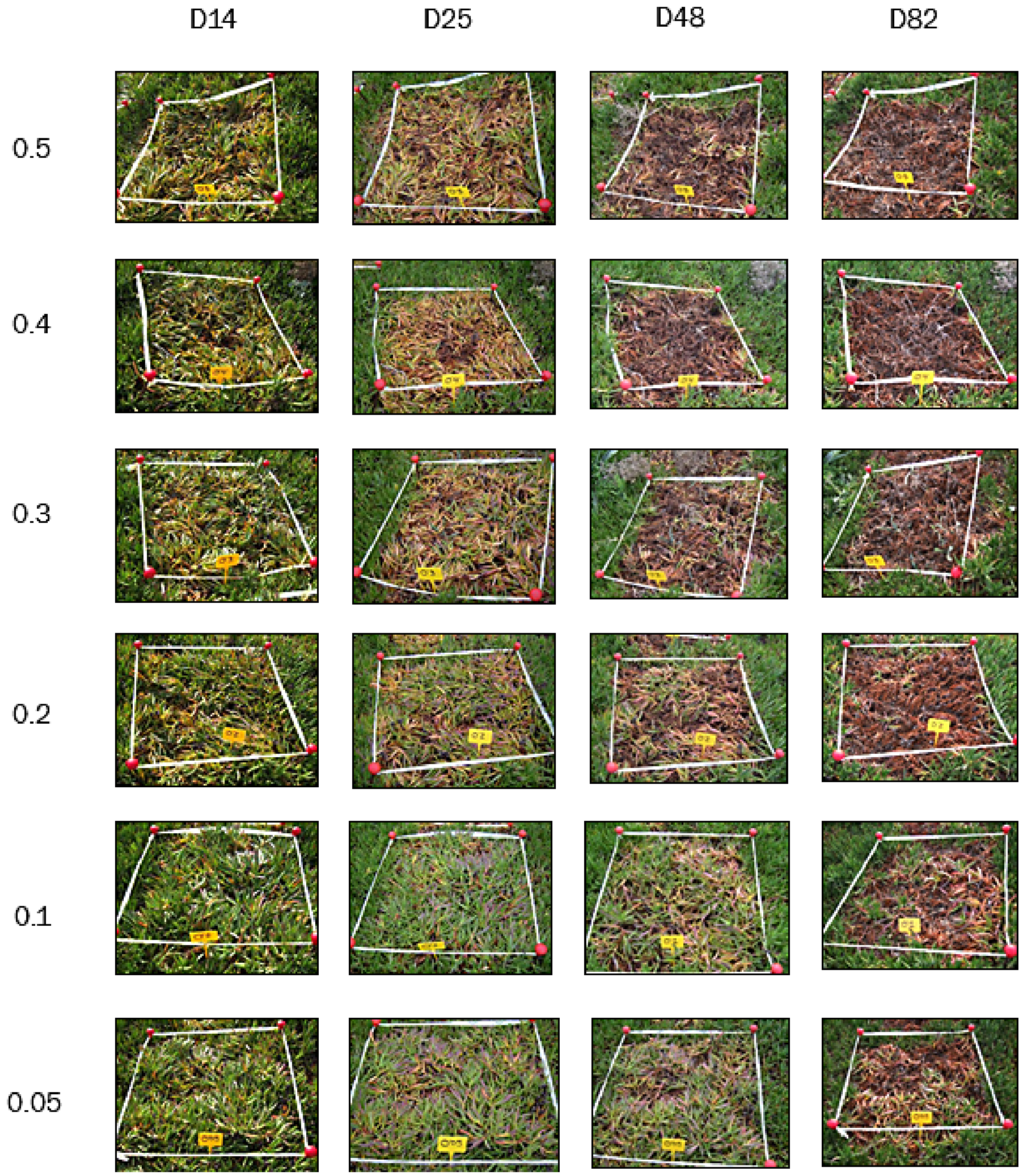

Figure 3. Effects of glyphosate application at different doses (0.5, 0.4, 0.3, 0.2, 0.1, and 0.05 g/m^2) on the *Carpobrotus* plants 14, 25, 48, and 84 days after manual spraying on experimental plots.

After 21 days, the only discernable difference with respect to uncovered plants was that they were a slightly lighter shade. The *Carpobrotus* plants retained their characteristic succulent appearance but had generally become yellow after 37 days of tarping (supplementary Figure 4, D37). Fifty-nine days after covering them with the fabrics, the plants had started to wilt and were predominantly brown (Figure 4, D59). Finally, the *Carpobrotus* in the whole experimental plot had become dark brown or gray after 89 days of tarping (Figure 5).

DISCUSSION

The obtained results show the effects and symptoms of the *Carpobrotus* plants over time after glyphosate spraying at different doses (Figure 3). They also indicate that 4.0 kg/ha was the minimum effective dose that prevents the complete regrowth of these plants. This dose is higher than the maximum recommended dose (2.88 kg/ha) for treating fields and is around the maximum cumulative application rate for any

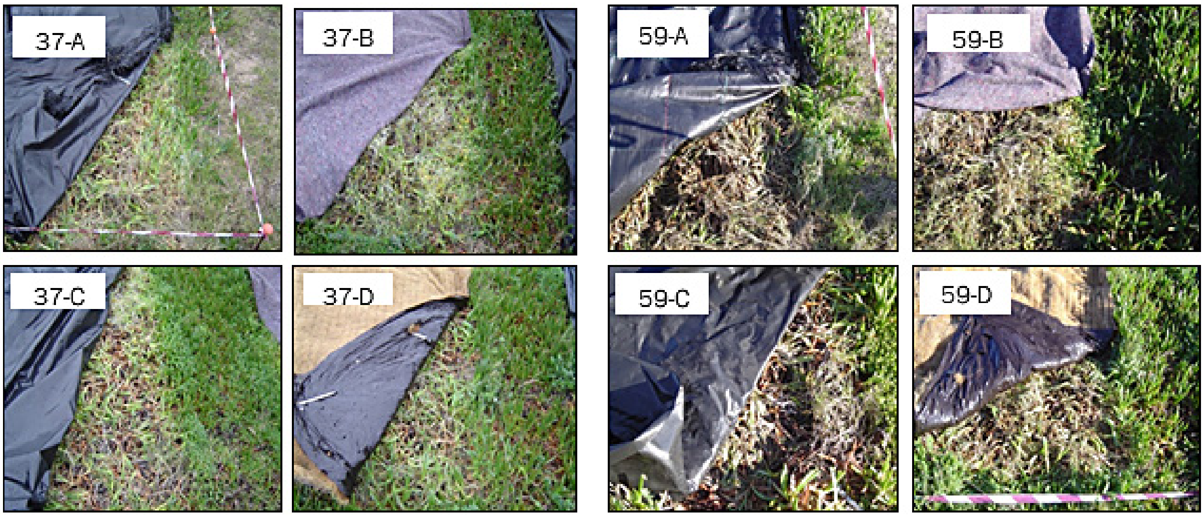

Figure 4. Effects on the *Carpobrotus* plants 37 and 59 days after tarping with different anti-weed fabric types: (A) black anti-weed fabric; (B) sewn felt; (C) black G-300 polyethylene; and (D) Fijavert coconut-anti-weed matting

12-month period (4.32 kg/ha; EFSA, 2017). The minimum effective dose was comparable to the one reported by Smyth et al. (2011) but was somewhat higher than that used by Guerreiro (1977), Hueso et al. (2005), and Lazzaro et al. (2020). In the latter case, the glyphosate was sprayed in winter and its effectiveness was 80 to 90%; to achieve complete eradication, they also carried out a second application two months later on the live plants (Lazzaro et al. 2020). In this study, it was found that only *Carpobrotus* plants directly sprayed by the glyphosate solution were affected (Figure 1). Moreover, in the summer of 2008, 11 different native plant species and 3 invasive species were observed on these experimental plots (Table 1). Thus, as previously reported (Walker et al. 2016; Fos et al. 2021), the conducted observations indicated that targeted glyphosate spraying effectively controlled invasive species without adversely affecting the surrounding vegetation.

Glyphosate is currently one of the most widely used herbicides worldwide, with applications in agriculture, forestry, industrial weed control, and lawn and garden maintenance (Henderson et al. 2010). However, its use in the control and eradication of invasive plants has been limited because of the concerns about its effects on environmental or human health (Campoy et al. 2018; Lazzaro et al. 2020). Nonetheless, it has been shown that context and scale must be considered when applying bans on the small-scale use of glyphosate, such as for the purposes of invasive plant control (Pergl et al. 2020). Indeed, given the effectiveness of this herbicide and its lower economic cost compared to mechanical plant removal methods (Fos et al. 2021); it is being increasingly used in invasive plant control and eradication campaigns. Indeed, in addition to its use for controlling *Carpobrotus* (Lazzaro et al. 2020; Fos et al. 2021), the application of glyphosate has also been shown to be effective for the management of *Imperata cylindrica* (L.) Beauv. (Aulakh et al. 2014; Enloe et al. 2018), *Opuntia dillenii* Haw. and *Agave americana* L. (Arevalo et al. 2015), *Pennisetum purpureum* Schumach. (Grey et al. 2015), *Sarracenia purpurea* L. (Walker et al. 2016), *Centranthus ruber* (L.) DC (Geerts et al. 2017), *Andropogon gayanus* Kunth. (Luck et al. 2019), *Brachypodium pinnatum* (L.) P.Beauv. (Redhead et al. 2019), *Poa annua* (L.) (William et al. 2019), *Oxalis pes-caprae* L. (Lazzaro et al. 2019), and *Gypsophila paniculata* L. (Rice et al. 2020). The effective doses required to eradicate these invasive species varied between the minimum doses of 0.28 kg/ha (Enloe et al. 2018) to 0.71 kg/ha (William et al. 2019) to the maximum doses of 4.48 kg/ha (Aulakh et al. 2014) to 5.3 kg/ha (Luck et al. 2019).

It should also be noted that the emergence of native species was observed after glyphosate spraying, with at least 11 species being identified in the set of experimental plots (Table 1). Similarly, the appearance of native plant seedlings after glyphosate spraying has also been reported for other areas invaded by *Carpobrotus* in Spain (8 species, Hueso et al. 2005), Ireland (7 species, Smyth et al. 2011), and Italy (17 species, Lazzaro et al. 2020). In fact, a recent report showed

Figure 5. Effects on the *Carpobrotus* plants 89 days after tarping with different anti-weed fabrics: (A) black anti-weed fabric; (B) sewn felt; (C) black G-300 polyethylene; and (D) Fijavert coconut-anti-weed matting

that, under laboratory conditions, seedling emergence of three native species was unaffected in the sand collected after spraying glyphosate at 10 times the maximum recommended dose on the plots with 100% *Carpobrotus* coverage (Fos et al. 2021). These current results also confirmed that germination of the native species seeds present in the sand from the areas where glyphosate was applied to *Carpobrotus* was not inhibited. In contrast, germination inhibition did occur when this herbicide was applied directly to the sand (Fos et al. 2021). However, given that the growth habit of *Carpobrotus* (as dense monospecific carpets with radial, clonal growth and a nodal structure; Campoy et al. 2018), glyphosate contact with the sand would be largely avoided when used to spray these plants.

The obtained results also indicate, for first time, the effects and symptoms exhibited over time by the *Carpobrotus* plants after tarping with

Table 1. Species sampled in the monitoring of experimental plots after the control of *Carpobrotus* (by using glyphosate in 2008 and by tarping in 2009)

Species	Life form	Glyphosate plots	Tarping plots
Carpobrotus spp. *	C	present	present
Agave americana L.*	P	present	present
Ammophila arenaria (L.) Link.	H	present	present
Centaurea seridis L.	H	present	
Echinophora spinosa L.	H	present	
Euphorbia paralias L.	C	present	
Lotus creticus L.	C	present	present
Malcolmia littorea (L.) W.T.Aiton	C	present	present
Medicago marina L.	C	present	present
Oxalis pes-caprae L.*	G	present	present
Pancratium maritimum L.	G		present
Scabiosa atropurpurea L.	H	present	
Senecio vulgaris L.	T	present	
Sonchus tenerrimus L.	T	present	
Sporobolus pungens (Schreber) Kunth	G	present	present

* Invasive plant species. C = Chamaephyte, G = Geophyte, H = Hemicryptophyte, P = Phanerophyte, T = Therophyte

four different types of fabric (Figure 4 and 5). They also showed that at least three months of tarping are required under winter conditions to produce complete wilting of these plants and to prevent their regrowth (Figure 5, D89). The *Carpobrotus* leaves are succulent and have a triangular cross-section with a chlorenchyma that surrounds large, colorless storage tissue (Earnshaw et al. 1987). The high water content of this tissue, coupled with the dense growth of these plants means that the wilting and drying caused by tarping takes a long time for *Carpobrotus*.

The previous results have indicated both the effectiveness (DiTomasso et al. 2013) and ineffectiveness (Albert 1995) of the use of solarization and tarping methods for the management of the *Carpobrotus* plants. In agreement with the former study, the data presented here confirmed that tarping was an efficient method for *Carpobrotus* eradication. Tarping has also been successfully employed in agricultural contexts and for the management and control of other invasive plant species. For example, this technique was recently used to stem the growth of exotic annual grasses in abandoned agricultural land (Lambrecht and D'Amore 2010; Marushia and Allen 2011), control seedbanks of different invasive plant species (Cohen et al. 2008; Concilio 2013; Orr et al. 2019), as well as restore coastal prairie grasses (Holl et al. 2014) and riparian and wetland ecosystems (Hunter et al. 2016).

In this work, after the removal of the anti-weed fabrics from the tarped *Carpobrotus* experimental plots, the plants from 6 different native species and 3 invasive species (including *Carpobrotus*) were observed in the experimental plots in the summer of 2009 (Table 1). Thus, tarping *Carpobrotus* did not increase the soil temperature sufficiently to kill all the seeds present in the sand underneath the *Carpobrotus* cover. Nevertheless, fewer species emerged under these conditions compared to the plots on which glyphosate was applied (Table 1), although the number was similar to the figures obtained in the work by other authors who had applied herbicides (Hueso et al. 2005; Smyth et al. 2011).

In addition to demonstrating the effectiveness of tarping for *Carpobrotus* eradication, the obtained results also allow highlighting some practical considerations for the future implementation of this technique. First, the effects of tarping on the *Carpobrotus* plants were independent of the fabric type used (Figure 5), and the fabric coverage time was the most important factor in determining the effectiveness of the methodology. Second, over the three-month trial, all four fabrics remained intact under the experimental conditions and were suitable for reuse, thereby reducing the costs of future eradication campaigns. In contrast, others have reported that polyethylene can disintegrate over shorter periods during solarization (Concilio 2013; Orr et al. 2019).

However, tarping is an unrealistic option for eradicating invasive plant species over large areas (Orr et al. 2019). Indeed, a comparative assessment of the two eradication methods employed in this present study indicated that the cost of tarping is an order of magnitude higher than the cost of using herbicide (Holl et al. 2014). Nonetheless, the effectiveness of tarping for the elimination of *Carpobrotus* shows its potential use in certain situations, such as the areas where invasion is still in its early stages. Thus, the use of tarping for scattered spots of plants would minimize the ecological impact of eradication through other techniques. Tarping would also be a viable technique for eliminating the *Carpobrotus* regrowth that can appear after its eradication in large areas, either by mechanical means (Chenot et al. 2018) or by applying herbicides (Lazzaro et al. 2020).

CONCLUSIONS

In conclusion, the results described here established the minimum effective dose of glyphosate required to eradicate *Carpobrotus* in dune ecosystems. It was determined that a single sprayed application of glyphosate at a concentration of 4 kg/ha under autumn conditions killed these plants in dune ecosystems without regrowth. This knowledge is especially important if management programs are aiming to minimize the number of herbicide treatments used and their impact on sensitive habitats. The effectiveness of tarping for the eradication of *Carpobrotus* under winter conditions was also demonstrated by testing four different weed-control fabric types, showing that this technique could be used on a small scale to eradicate *Carpobrotus* in dune ecosystems.

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