Mechanical and manual control of prickly pear *Opuntia dillenii* in lakeside dunes at Laguna del Portil, southern Spain

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SUMMARY

We present the results of an intervention to control prickly pear *Opuntia dillenii* in an area of coastal dunes with *Juniperus* spp. and *Pinus pinea* at the 'Laguna del Portil' Site of Community Importance, Huelva, southern Spain, in 2015-2017. In the first stage, a total of 2,266 m^3 (approximately 460 MT) of the cactus was removed using heavy machinery, which was supplemented by the manual removal of 4 MT of fragments. Subsequently, as part of the periodic control and monitoring work, a total of 200 and 126 kg of shoots and saplings were removed manually after 15 and 25 months respectively. Twenty-six months after the mechanical removal, the composition of native plant species in treated and reference plots (uninvaded areas that represent well-preserved native vegetation) provided evidence of natural recovery. The economic efficiency of the different control stages was compared. The results suggest that combining mechanical and manual methods, adapted to the abundance, size and distribution of the invasive plant, was an effective approach. Additionally, subsequent annual rounds of control appear to be sufficient to provide effective ongoing control of the invasion of *Opuntia dillenii*.

BACKGROUND

Prickly pear *Opuntia dillenii* is a perennial, spiny plant belonging to the family Cactaceae. It is native to the southernmost areas of North America, the east coast of Mexico, Bermuda, the East Indies and the north of South America (Britton & Rose 1919). It has been introduced in many regions, including the Mediterranean basin, the Canary Islands, West and East Africa, Madagascar, Mauritius, Yemen, India, South East Asia and Australia (Böhm 2008). In Spain, it was introduced in the sixteenth century (Sanz-Elorza *et al*. 2004), and has since been dispersed via the consumption of the fruits by birds, small mammals and saurians (Valido & Nogales 1994, Nogales *et al*. 1999, Padrón *et al.* 2011). *Opuntia dillenii* is included in the Spanish Catalogue of Invasive Alien Species, in accordance with Royal Decree 630/2013, mainly affecting protected areas in the south of Spain (provinces of Huelva and Cádiz) and the Canary Islands (Sanz-Elorza *et al*. 2004).

Actions aimed at controlling wild populations of *O. dillenii* are considered a priority. However, documented experiences of controlling this species are scarce. In the Canary Islands, the effectiveness of mechanical and chemical elimination has been compared (Arévalo *et al*. 2015), whilst in other parts of the world, biological control has been tried using the cactus moth *Cactoblastis cactorum*, However, this involves certain risks, as this species may also parasitize other non-target *Opuntia* species, which may be either native or economically exploited (Zimmermann *et al*. 2000).

In this paper, we report the control works carried out on *Opuntia dillenii* combining mechanical and manual methods, in the 'Laguna del Portil' Site of Community Importance near Huelva, southern Spain. Specifically, our work aimed to answer the following questions: 1) did the intervention reduce the abundance of *Opuntia dillenii*?; 2) did the intervention lead to recovery of a native vegetation community? and 3) was the intervention cost effective? We evaluated the results of the work during the different stages of action, and assessed the recovery of the native plant community after 26 months, based on a comparison of the composition of plants in treated and non-invaded reference plots. The results can be used for guiding future control actions.

'Laguna del Portil' (37º12' N, 7º2' W, 10 m above sea level, Figure 1) is a lake originating from the wind causing small streams running through mobile dunes to be covered up. The soil comprises a mix of pebbles, sand, lime and quaternary clay (de Torres 1973). Around the lake, several natural habitats of community priority interest identified in the Directive 92/43 of the European Council are represented, such as coastal dunes with *Juniperus* spp. and wooded dunes with *Pinus pinea*. The vegetation in the working area is dominated by xerophilous shrubs such as *Cistus monspeliensis*, *Cistus crispus*, *Cistus ladanifer*, *Rosmarinus officinalis*, *Juniperus turbinata*, *Lavandula pedunculata*, *Ulex australis*, *Pistacia lentiscus* and reforestation pine trees *Pinus pinea*. The site was partially invaded with *Opuntia dillenii* (mean cover of 10%; total invaded surface of approximately 1.65 ha), mainly in the form of large stands (25-150 m^2 each).

ACTION

Control of *Opuntia dillenii*: From September-October 2015, all the stands of *Opuntia dillenii* surrounding the 'Laguna del Portil' (Figure 1, 15 ha) were removed. Considering the size of the stands (height and diameter > 1m) and their aggregate distribution near to old paths, the first stage of the control used a wheeled excavator. The biomass remains were removed in a

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ISSN 1758-2067

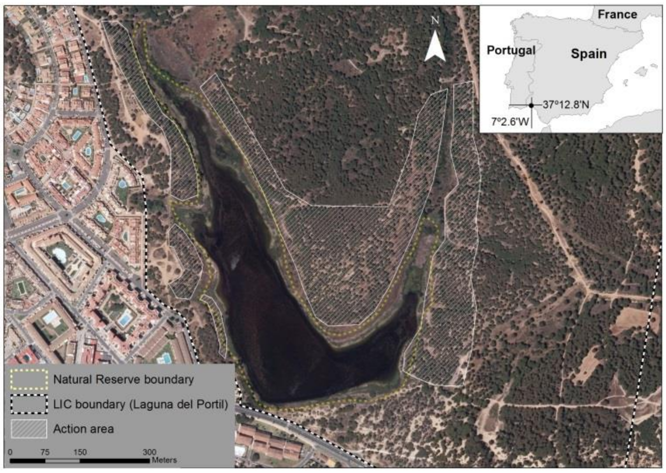

Figure 1. Area of study, indicating the areas inside the Site of Community Importance where *Opuntia dillenii* was removed.

dump truck (Figure 2) to be taken to a landfill. In order to minimise the effect of heavy machinery on the habitat, existing old paths were used. In the second stage of removal (October-November 2015), the remains of broken cladodes and stands hidden by dense vegetation that were left in the first stage were removed by hand. Also, the soil compaction and disturbance made by the heavy machinery (in the plots with sandy soil) was restored (Figure 3).

Subsequently, two further rounds of control were carried out (stages three and four) in which the shoots, resprouts and saplings that were found in the treated area were manually removed (Figure 4): the first between November 2016 and January 2017 and the second in November 2017. The remains of prickly pears from stages two, three and four were collected in raffia sacks or thick plastic sacks to avoid breakage caused by the spines, and were taken to a landfill. Tools such as pliers were necessary for the manual removal of shoots and saplings in order to avoid direct contact with *O. dillenii* spines. To estimate the removed biomass (kg or MT) from the volume (m^3) data provided by the contractor, a known volume of *O. dillenii* was weighed, resulting in a conversion estimate of 0.2 MT/m^3.

Recovery of the plant community: In February 2018, 26 months after the beginning of the action, we evaluated the composition of the plant community in five treated plots, as well as in five reference plots (uninvaded areas with well-preserved, natural vegetation) (area from 25–100 m^2).

Figure 2. First stage of mechanical removal work of *Opuntia dillenii* using a wheeled excavator (September-October 2015).

Figure 3. Fragments of cladodes of *Opuntia dillenii* (yellow arrows) remaining after the mechanical removal operations. Note the local alterations due to the passage of the heavy machinery on the plots with sandy soil.

Reference plots represent the natural state to which the treated plots should return after the action. Considering that the main objective of the action was the recovery of the ecosystem affected by the invasion of *Opuntia dillenii*, the comparison of treated and reference plots was used as an indicator to infer to what extent the main objective was reached. Reference plots with characteristics similar to the treated plots in terms of substrate type, orientation, slope and tree cover were chosen in order to make reliable comparisons.

The presence of perennial plants in 20 quadrats of 0.25 m^2 was noted for each plot (N = 200). Using this occurrence data, the relative abundance of each species was calculated as the proportion of the total number of quadrats in which each species appeared. The data were analysed using one-way Anosim and Simper multivariate analyses (Warwick 1988), grouping together the data from each plot. The Simper test calculates the percentage of dissimilarity between treated and reference plots, as well as the contribution of each species to overall dissimilarity. The Anosim test was used to test significant differences between the groups (Clarke & Warwick 2001). Both analyses were based on the Bray-Curtis similarity measure. Since the aim was to evaluate the recovery of native vegetation after the action, *O. dillenii* was excluded from the analyses. The software Past3 (Hammer et al. 2001) was used.

CONSEQUENCES

Removal of *O. dillenii*: In the first stage (mechanical removal), 2,266 m^3 of biomass (approx. 460 MT) of *Opuntia*

Figure 4. Shoots (left) and saplings (right) of *Opuntia dillenii* removed during the annual rounds of control.

ISSN 1758-2067

Figure 5. Comparative pictures of the working area, before (above) and after 26 months (below) of *Opuntia dillenii* removal, which included annual rounds of control.

dillenii were removed over 14 days (yield = 33 MT/day). The excavator operator, the truck driver and a work supervisor participated. The second stage (manual removal supplementary to the mechanical removal) took 87 work days (total time used by all the workers involved) and removed 4 MT (yield = 46 kg/day). During the subsequent manual rounds of control, a total of 200 kg and 126 kg of shoots and saplings were removed between November 2016 and January 2017 (stage three) and November 2017 (stage four), respectively. The contribution of shoots that grew from the remains of stems (cladodes) (Figure 4) was much higher (around 90% of the total) than saplings from the seed (Figure 4). Each round of control required an effort of between 11 and 13 days/year, giving yields of 10–18 kg/day. Regarding costs, the mechanical removal had a cost/volume ratio of €9.7/m^3 whilst in the second manual stage, supplementary to the mechanical removal, the ratio was €435/m^3. The manual rounds of control carried out 12 and 24 months after the beginning of the action had ratios of 1,000–2,063 €/m^3.

Figure 6. Detail of cladodes of *Opuntia dillenii* showing the groups of 6-8 strong, large spines with numerous glochids on the base.

Native plant recovery: Prior to the action, *Opuntia dillenii* stands lacked native vegetation. After 26 months, the native plant community in treated plots showed evident signs of recovery (Figure 5). Multivariate analysis revealed differences

Table 1. Results from the multivariate SIMPER analysis showing the mean occurrence of each species in treated and reference plots, and the contribution of each species in the dissimilarity between treated and reference plots. Values refer to the average cover obtained in 100 quadrats per plot. Species contributing <1% to the overall dissimilarity between plots are omitted.

Taxon	Occurrence (%) in treated plots	Occurrence (%) in reference (uninvaded) plots	Contribution to overall dissimilarity (%)	Cummulative contribution (%)
Cistus monspeliensis	26.5	18.6	23.3	23.3
Asphodelus ramosus	19.9	8.48	15.1	38.4
Cistus crispus	20	17.9	13.6	52.0
Cistus ladanifer	16.6	11.6	10.6	62.6
Rosmarinus officinalis	0.6	11.5	8.5	71.1
Ulex australis	0.6	6.8	5.1	76.2
Asparagus aphyllus	5.8	2.2	4.8	81.0
Juniperus turbinata	2.0	6.3	4.5	85.5
Lavandula pedunculata	1.1	5.2	4.1	89.6
Pistacia lentiscus	0	4.7	3.6	93.2
Pinus pinea	1.0	2.1	1.9	95.1
Inula viscosa	0	2.4	1.8	96.9
Chamaerops humilis	0	1.9	1.5	98.4

ISSN 1758-2067

in the composition of the native vegetation between treated and reference plots ($p = 0.0036$, $R = 0.026$, one-way Anosim), with a similarity of 33% (Simper). The species that first recolonised the treated plots were *Cistus monspeliensis* (26%), *Cistus crispus* and *Asphodelus ramosus* (20%), *Cistus ladanifer* (17%) and *Asparagus aphyllus* (6%). In contrast, species with higher occurrences in uninvaded, well-preserved (control) plots that hardly recolonised the treated plots were *Pistacia lentiscus*, *Chamerops humilis*, *Ulex australis* and *Rosmarinus officinalis* (Table 1).

DISCUSSION

Efficiency of the methodology employed: The methodology used in this study followed the recommendations of Sanz-Elorza *et al*. (2004), combining mechanical and manual methods. The use of biological methods with the cactus moth was ruled out, to avoid potential risks to non-target *Opuntia* species that are native in other regions or are economically exploited for food, animal fodder, or dye production (Zimmermann *et al*. 2000). The use of herbicides in the area of study was also not considered appropriate, even in combination with mechanical methods, despite their observed efficiency in the Canary Islands (Arévalo *et al*. 2014). This was for several reasons: (i) possible illegality of the method given the existence of plots of *O. dillenii* near the lake, in accordance with the current legislation in Spain (Royal Decree 1311/2012); (ii) very high doses would have been necessary for a species with such a hard cuticle (around 10g active substance/L) (Ellenberg 1989, Arévalo *et al*. 2014); (iii) as a consequence of the latter, the recovery of the native plant community could be diminished (Ellenberg 1989); (iv) presence of protected species such as *Juniperus turbinata* ('Vulnerable' in Andalusia and 'Near threatened' on a global scale); (v) length of time taken for chemical treatment to be effective on *Opuntia* spp., from 1 to 3 years (USDA 2014); and (vi) after the prickly pears have withered, their spines remain on the ground with the consequent potential impact for fauna (E. Dana & J. García-de-Lomas, unpublished results). In contrast, mechanical control was considered optimal for removing large stands of *O. dillenii* as a first stage, avoiding contact with its long spines (Berthet 1990) (Figure 6). Our results showed that the excavator was highly selective and efficient in terms of kg/day. Manual removal was considered appropriate for removing scattered, small stands that require active searching and highly selective removal to encourage the recovery of the invaded area. This method wasemployed during the second stage and the subsequent periodic rounds of control (stages three and four).

The amount removed (in terms of biomass) during stages three and four (rounds of control) represented a negligible percentage (0.03-0.04%) of the initial size of the invasion. In terms of surface, shoots and saplings also represented a negligible contribution of the initial surface invaded (approximately 1.65 ha). These results agree with those of Arévalo *et al*. (2014), who documented some recovery of *Opuntia dilleni* and *Agave americana* four years after mechanical treatment, but a much smaller quantity than in the initial invasion (0.1%). The small quantity of shoots could be explained, on the one hand, by the biological characteristics of *O. dillenii*, with a shallow root system and relatively slow growth (Böhm 2008). During annual monitoring stages, only very occasional shoots from the root were observed (for example, next to the trunk of threatened species, such as *Juniperus turbinata*, that were carefully treated during the mechanical removal). The fact that the shoots found are largely from pieces of cladodes that remained buried showed that vegetative propagation is especially effective in this species. The general recommendation for the control of prickly pears state that leaving remains must be avoided, since any piece of stem in contact with the earth will take root (USDA 2014). However, our results cannot be extrapolated to other species such as *O. ficus-indica*, with large taproot and secondary root systems with the ability to resprout (Böhm 2008).

None of the shoots or saplings removed in annual monitoring stages showed any signs of flowering or fruiting. The timing of first flowering and fruiting is not known for this species, but as a proxy, flowering in *Opuntia ficus-indica* is produced on cladodes that are one or two years old (Melgarejo 2000). The persistence of the seeds is also not known, however, some birds, rabbits and lizards (e.g. *Lacerta lepida*) present outside the working area could aid in the dispersal and colonisation of new areas. Therefore, we suggest that vegetative re-growth would be the main reinvasion mechanism of treated areas in the short term, whereas sexual reproduction and seed dispersal from neighbouring areas may be of greater importance in the long term.

In conclusion, annual monitoring seemed an appropriate frequency to achieve effective ongoing control. This frequency will allow the seed bank in the soil to be progressively reduced, thus avoiding the reinvasion of the treated area. A higher frequency of monitoring and control was not considered to be efficient, since not enough time would have passed for the shoots or saplings to reach a sufficient size that allows them to be detected.

The results documented here aim to aid the planning and budgeting of future control work on prickly pears in similar scenarios. In this regard, the difference in yields from manual control just after mechanical removal (45 kg/day) and during the annual monitoring stages (10–18 kg/day) is striking, which suggests that the use of heavy machinery may leave a number of fragments or hidden stands of prickly pear and that these remains are larger than one-year-old shoots. In any case, the results demonstrate the need to supplement mechanical work with manual work as an essential part of the initial control stages.

Recovery of the plant community after the action*:* The history of the invasion of *O. dillenii* in the 'Laguna del Portil' Site of Community Importance is unknown. The size of the removed stands suggests that the invasion started at least several decades ago. Despite this rather long history of invasion, the low R value obtained when comparing the treated and reference plots suggests a reasonably rapid recovery of the native plant community after the removal of *Opuntia dillenii.* This recovery can be explained by three distinctive features: (i) *O. dillenii* is an invasive species not an engineer species; (ii) the degree of invasion of the working area before the action was considered intermediate (average density = 146 m^3/ha); and (iii) the environment is naturally adapted to disturbance. Regarding the first point, *O. dillenii* does not fix nitrogen or cause an accumulation of leaf litter that can modify the balances of C/N, pH, or flammability (Le Maitre *et al.* 2011). The plant debris was not abandoned in situ, which also minimises the alteration of the habitat. Regarding the second point (degree of invasion), in comparable actions carried out in the Canary Islands, Arévalo *et al.* (2014) documented a certain impact of the mechanical removal of *O. dillenii* (density up to 60,000 m^3/ha) and *Agave americana* on the composition of the

ISSN 1758-2067

community, although this damage was imperceptible after four years. Arévalo *et al.* (2014) also indicated heterogeneity in the vegetation response to the treatment, depending on rainfall patterns, as well as the incorporation of annual plants and other alien plants after the action. This effect was not observed in this study, which could be due to the lower degree of invasion present in this work. Lastly, regarding the resilience of the ecosystem to disturbance, species such as *Cistus monspeliensis*, *Cistus crispus* and *Cistus ladanifer* rapidly recolonised the spaces previously occupied by *O. dillenii*. Similar results were observed after a control programme in shrubland communities of northern Spain, dominated by *Cistus ladanifer* (Calvo *et al*. 2005), that recovered 70% of the plant cover in just one year. This recovery rate was not observed in other plant communities (Calvo *et al*. 2005). Therefore, shrubland communities rich in *Cistus* spp. appear to respond better to occasional physical disturbance such as that carried out during the mechanical control stage.

Finally, although the methods employed have been effective, the results suggest the need to keep up annual rounds of control for a longer time. Also, we recommend removing *Opuntia dillenii* stands near the treated area to avoid reinvasion due to dispersal by animals.

ACKNOWLEDGEMENTS

This project has been financed with the LIFE CONHABIT ANDALUCÍA PROJECT (LIFE13/NAT/ES/000586), coordinated by the Regional Ministry for the Environment and Land Planning of the Regional Government of Andalusia, and is 60% co-financed via the Life+ programme, an EU financial instrument for the environment. We thank P. Millán and rangers for supervision during the mechanical removal.

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ISSN 1758-2067