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Note

Removal of water hyacinth (*Eichhornia crassipes*) and native plant recovery in a Mediterranean permanent pool

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INTRODUCTION

Water hyacinth (*Eichhornia crassipes* (Mart) Solms) is one of the world's most invasive plant species, introduced for use as an ornamental and responsible for a plethora of negative impacts for aquatic ecosystems (Villamagna and Murphy 2010). It was included in the list of Invasive Alien Species of Union Concern (The European Union 2016). In the case of rivers or large lakes, eradication is unrealistic because of the rapid growth rate, vegetative spread, cost, and restrictions on chemical or mechanical means of control. For example, in the Guadiana river in southwestern Spain, 40 million euros have been spent between 2004 and 2018 without achieving eradication, whereas other cases were successfully controlled or eradicated as part of early detection or rapid response plans (Ministerio para la Transición Ecológica [MITECO] 2019). Vegetative propagation is the most common mode for spread, but seeds can also be a source of new infestations or re-infestation (Pieterse 1978). Despite the large number of ecosystems invaded by water hyacinth around the world and the significant management expenditures in many sites, there have been no published studies evaluating the recovery of native flora after its elimination. Additionally, a lack of data on preinvasion conditions impedes the assessment of how much the water hyacinth altered the invaded ecosystems (Villamagna and Murphy 2010). However, removal experiments may provide opportunities for inferring the impact of plant invasions on the remnant or recovering native community and ecosystem functioning (Díaz et al. 2003). In this paper, we document the results of water hyacinth removal in a Mediterranean pool, and the subsequent recovery of native plants. Notice of the presence of water hyacinth was obtained from a park ranger, and the proximity of the river Guadiaro downstream from the pool motivated a rapid response plan. Specifically, we will investigate the following questions: (1) What are the requirements and costs of eradicating water hyacinth in a lotic mountain ecosystem? and (2) What is the recovery pattern of native plant species after eradication? Based on the results, we shed light on the impact of water hyacinth on the native plant community.

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MATERIALS AND METHODS

The water hyacinth removal was carried out in a permanent, freshwater pool (36.5347°N; 5.407705°W; elevation = 305 m; conductivity = 140 μS/cm) at Los Alcornocales Natural Park, which is included in the Natura 2000 Network as a Special Protection Area and Special Area for Conservation (code ES0000049). The pool is 79 m^2, and has a maximum depth of 0.85 m. It is fed by a natural upwelling (total N $<$ 0.5 mg/L; total P $<$ 1 mg/L) and surrounded by shrub bushes (*Cistus salviifolius* L., *Erica arborea* L., *Lavandula stoechas* L., *Pistacia lentiscus* L., *Calicotome villosa* (Poir.) Link) and a cork oak (*Quercus suber* L.) forest. The pool water is partially retained by a stone dam located in the outlet. It is an isolated pool, with no other pond or watercourse connected upstream. The closest river (Guadiaro) is located at ca. 525 m, and within the same watershed downstream. Thus, the pool water could connect to the river in an eventual flood. The climate is Mediterranean, with dry, hot summers and mild, wet winters. The average temperature and precipitation at El Colmenar (located 1.8 km from the study area) for the 1982 to 2012 series is 15.2 C and 582 mm, respectively (https://es.climate-data.org/). Winter frosts are practically nonexistent. The average temperature is above 8 C (the growth threshold of water hyacinth; Wilson et al. 2005) throughout the year, except in January.

The entire biomass of the invasive species was removed in June 2010. Before removal, the pool was completely covered by water hyacinth (Table 1). Workers equipped with waterproof fishing waders proceeded mainly by hand because of the shallow depth of the pool. A hand net was occasionally used for removing isolated plants in order to minimize sediment disturbance. The biomass was left to drain for 24 h to reduce weight and facilitate transport to a landfill. Park rangers took the biomass to an accessible point in the closest village (at ca. 20 km away from the study area) before transport to a landfill. As the work was being carried out, two people carried out a thorough search of the pool shoreline looking for hidden and rooted plants. Once the

Table 1. Abundance (% plant cover) of native plants before the action (pretreatment), 3 mo after treatment (MAT), 6 MAT, 9 MAT, and 12 MAT. Relative abundance of water hyacinth and native plants, native species richness and diversity index, and overall dissimilarity in plant community composition between the invaded and treated conditions are shown.

Species	Pretreatment	3 MAT	6 MAT	9 MAT	12 MAT
Alisma plantago-aquatica	2	20	40	30	5
Apium nodiflorum	2	–	–	–	–
Baldellia ranunculoides	1	–	–	1	1
Cyperus fuscus	–	–	–	5	5
Holcus sp.	–	–	5	45	11
Juncus bulbosus	–	2	5	5	10
Lemna minor	–	2	10	70	50
Lythrum junceum	1	–	–	–	–
Mentha suaveolens	–	–	–	–	2
Nerium oleander	1	1	1	1	1
Paspalum sp.	–	–	2	–	10
Pteridium aquilinum	2	2	2	2	2
Ranunculus hederaceus	–	–	–	2	–
Rorippa nasturtium-aquaticum	2	–	4	40	10
Rubus ulmifolius	2	2	2	2	2
Relative abundance ($p_i = n_i/N$) of water hyacinth	0.88	0.03	10^{-4}	0	0
Relative abundance, p_i, of native plants	0.12	0.97	0.99	1	1
Native species richness	8	6	9	11	12
Shannon-Weaver diversity index, H'	0.48	1.11	1.50	1.63	1.84
Overall dissimilarity (%) (Simper analysis)	–	67	79	91	84

water hyacinth was removed, quarterly visits were undertaken during the following 12 mo to confirm the complete removal and to assess the native plant recovery. At each visit, we assessed the abundance visually (% cover) of the native flora. Therefore cover % in Table 1 represents the coverage of each species for the entire pool. We measured the native species richness and calculated the Shannon-Weaver diversity index, $H' = -\sum p_i \cdot Lnp_i$, where $p_i = n_i/N$, n_i is the abundance of species i and N is the sum of the abundances of all the species. The former indices value all species equally and do not evidence shifts in composition. For this reason, multivariate test SIMPER was applied to get complementary information of plant community composition. The SIMPER test calculates the percentage of dissimilarity between pairs of plots (invaded versus treated conditions), as well as the contribution of each species to overall dissimilarity. The software Past3® (Hammer et al. 2001) was used.

RESULTS AND DISCUSSION

A total of 1,880 kg (fresh weight) was removed. This translates to 24 kg/m^2. Water hyacinth was densely packed. This value is within the range of plant biomass density found in other reports (8.3–67 kg/m^2; Wilson et al. 2005 and references therein). Most plants removed were ca. 0.7–1 m (total length, including roots). This size is rather smaller than those reported in other warm-climate regions and nutrient-rich waters where only the petioles can reach up to 1 m in length (EPPO 2008, MITECO 2019). Thus, the lower size was likely because of the depth (0.85 m) and nutrient concentration of the studied pool (Wilson et al. 2005, Yu et al. 2019). Only three plants with flowers were observed before removal. Several water hyacinth individuals were found rooted on the banks, hidden among the riverside vegetation. This observation suggests sexual reproduction and the ability of seedlings to root and grow in saturated soils (Barrett 1980). Rooting can also occur in adult specimens as an adaptation to withstand stranding and fluctuating water levels (Venter et al. 2017). Like the seedlings, the rooted plants can abscise when an inundation event occurs (Penfound and Earle 1948). Although these small individuals represent a negligible amount in terms of total biomass removed, their removal is an essential step to achieve eradication (Ruiz-Téllez et al. 2008). In our experience, this task requires a very thorough and repeated search along the banks. The presence of water hyacinth in a private pond 1.1 km away from the studied pool suggests that the invasion could have been the result of deliberate introduction.

Climatic conditions in the studied habitat are suitable for a net growth of water hyacinth during most of the year (e.g., lack of winter frosts and average temperatures above 8 C; Bock 1969, Wilson et al. 2005). Considering the environmental conditions in the studied pool (average temperature of 15.2 C and a low water nitrogen concentration), the time for a water hyacinth infestation to grow from 0.1 kg fresh weight/m^2 (that may represent conditions close to the incipient invasion) to 10 kg/m^2 (that may represent conditions of total coverage of the pool surface), is ca. 100 to 400 d (Wilson et al. 2005). As we removed 24 kg/m^2 in early June (average temperature = 20.8 C), and average temperatures in April (13.1 C) and May (16.3 C) allowed a net positive growth of water hyacinth, we hypothesize that the habitat could have been completely invaded by water hyacinth for ca. 2 or 3 mo before removal (the minimum and the maximum temperatures for water hyacinth growth are 8 and 30 C, respectively). This relatively short time of total coverage may favor a faster recolonization of the native flora than in case of longer invasions (de Winton and Clayton 1996).

During monitoring, 5 kg of water hyacinth were detected 3 mo after the removal (relative abundance = 3%), whereas only one small floating plant was detected after 6 mo (Table

1). The monitoring visits carried out at 9 and 12 mo showed no more water hyacinth, as well as the progressive colonization of native flora. Some of the first species to recolonize the pool were *Alisma plantago-aquatica* L.; *Rorippa nasturtium-aquaticum* (L.) Hayek, Sched; *Juncus bulbosus* L.; and *Lemna minor* L., which remained the dominant species after 9 mo (Table 1). Unlike the water hyacinth, *Lemna minor* is compatible with the development of other aquatic plants and helophytes because of its smaller size and complexity (Driever et al. 2005). After 12 mo, the plant richness increased from 8 to 12 plant species and the diversity index increased 3.8 times with respect to the invaded state (Table 1). These species are typical of Iberian freshwater wetlands (Cirujano et al. 2014). Simper analysis revealed that plant community composition was progressively more different with time between the treated and invaded state. Dissimilarity percentages between invaded and treated conditions reached values of up to 91 and 84% after 9 and 12 mo, respectively (Table 1). The conditions or species composition of the pool were not documented prior to water hyacinth invading the pool used in this experiment. We thus cannot compare the posttreatment species composition to any baseline preinvasion reference point (Villamagna and Murphy 2010). However, the relatively rapid increase in the percent cover of native plants, species richness, and the Shannon-Weiner diversity index observed after the removal experiment suggests that water hyacinth was outcompeting the native species.

Recruitment of native plants could have occurred from three different sources: (1) remnant populations (some of the species that recolonized the pool after water hyacinth removal were present in the invaded state); (2) the local propagule bank, especially herbaceous and helophyte species (Nishihiro et al. 2006, de Winton et al. 2000); and (3) by animal-mediated dispersal from neighbor pools. For example, mammals and birds are known to use the freshwater pools and ponds that are scattered within the Natural Park for drinking. This way they may carry species such as *Lemna* spp. attached to their legs and feathers or transport plant propagules within their guts (Keddy 1976, Coughlan et al. 2015, Green et al. 2016). Dispersal by water was unlikely because the studied pool is fed by a natural upwelling that emerges from the subsoil, with no other pool or watercourse connected upstream. Wind dispersal seems also unlikely in the short term because the pool is inside a dense cork-oak forest.

Surprisingly, four small water hyacinth plants (size range = 7.5–16 cm; number of leaves = 4–9) growing over moist mud, were found during a monitoring visit carried out 10 yr after the initial removal, coinciding with an abnormally low water level. This observation agrees with the long seed viability of this species, that may reach up to 20 to 28 yr (Matthews et al. 1977, Sullivan and Wood 2012). Germination conditions were coincident with those described by Obeid and Tag el Seed (1976). Thus, the absence of new plants for several consecutive months was not enough to verify eradication. According to previous reports, periodic monitoring for water hyacinth should last up to 20 to 30 yr.

In sum, the water hyacinth control cost in total 2,900 euros, which included salary for 12 working days and biomass removal.

During the water hyacinth removal, several species of amphibians were also found, such as the southern marbled newt (*Triturus pygmaeus*), long-snouted salamander (*Salamandra salamandra* subsp. *longirostris*), Iberian green frog (*Pelophylax perezi*), common toad (*Bufo bufo*), and Iberian parsley frog (*Pelodytes ibericus*), as well as the grass snake (*Natrix natrix*). Some of these species (the southern marbled newt, the long-snouted salamander, and the Iberian parsley frog) are protected by current regulations (Royal Decree 139/2011 and Decree 23/2012).

Water hyacinth has been successfully eradicated in other Spanish localities, where it formed incipient populations in small streams or lentic, confined wetlands (MITECO 2019). Our results support that hand weeding is an adequate method when applied for removal of small early infestations, clearing small areas, or follow-up removal of remnants after other treatments. The rapid response prevented the invasion from eventually reaching the Guadiaro river, 80 km long, also included in the Natura 2000 network as a Special Area for Conservation (codes ES6120031 and ES6170031), and separated from the treated pool by only 525 m. The rapid response also avoided further flowering and fruiting of water hyacinth, thus minimizing the probability of reinvasion from seed production (Albano et al. 2011). However, some seeds may have remained after removal, being responsible of the incipient reinvasion found 10 yr later.

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