ANNALI DI BOTANICA
Ann. Bot. (Roma), 2021, 11: 1–12
Journal homepage: http://annalidibotanica.uniroma1.it

MANAGEMENT OF AN INVASIVE PLANT IN A MEDITERRANEAN PROTECTED AREA: THE EXPERIENCE OF *SENECIO DELTOIDEUS* IN ITALY

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(Received 30 June 2020; received in revised form 27 October 2020; accepted 2 November 2020)

Abstract - Biological invasions are one of the most serious threats to global biodiversity and ecosystem integrity. The problem is growing year by year and a large number of protected areas worldwide are today invaded by at least one exotic species. In this study, we tested the eco-friendly and cost-effective weeding control of *Senecio deltoideus* in a Regional Protected Area in the North Mediterranean region. During a two years experiment, four techniques compatible with the local laws on protected areas (natural-herbicide, flame-weeding, mulching and mowing) were applied five times a season on sixty plots, compared with fifteen untreated controls. All techniques were effective in reducing *Senecio* covering: after the first year the maximum covering was limited to 37.93% (flame weeding) with a mean value of 10%; after second year the covering was further reduced (17.02% max; 2% mean). Interestingly, during the second year all plots submitted to a one-year treatment showed an enduring control of *S. deltoideus* covering (40.73% max; 20% mean). Taking into account feasibility and their impact on the environment, the weeding control recommendable for *S. deltoideus* is mowing. In a long-time management strategy, the selected treatment could be applied every two years with a drastic reduction in costs for the manager of the protected area.

Keywords: alien species; eco-friendly and cost; effective; management; natural environment.

Introduction

Biological invasions are one of the most serious threats to global biodiversity and ecosystem integrity (Mack et al., 2000; Essl et al., 2020; Shackleton et al., 2020). Alien species may cause huge ecological (Hulme, 2003), economical (Pimentel et al., 2000; Oerke, 2006), social (García-Llorente et al., 2011) and sanitary impacts (McNeely, 2001).

Invasive alien species are characterized by rapid growth rates, extensive dispersal capabilities, large and rapid reproductive output and broad environmental tolerance (Geesing et al., 2000). It is estimated that as many as 50% of invasive species in general can be classified as ecologically harmful, (Richardson et al., 2000) forming alien-dominated plant communities (Viciani et al., 2020). Despite invasive species mainly occur in vegetational disturbed areas, their prevalence has gone nowadays beyond these areas and they invade natural protected areas across the world (DePoorter et al., 2007). Invasions into natural habitats can produce detrimental consequences in native communities (e.g. Bais et al., 2003; Miller & Gorchov, 2004; Wearne & Morgan, 2004) and represent one of the main threats in protected areas (Ervin, 2003), becoming a threat to endangered or threatened plant species around the world (Pimentel et al., 2005). The problem is growing year by year and today at least one exotic species has invaded a large number of the protected areas in the world (Shackleton et al., 2020). For example, in Spain, more than 90% of invasive species are found in at least

doi: 10.13133/2239-3129/16852

one protected area (Andreau et al., 2009). For this reason, invasive plant control is today a major challenge for natural resource management (Kettenring & Adams, 2011). Despite effort to understand the characteristics of invasive plants (e.g., Rejmánek & Richardson, 1996; Bossdorf et al., 2005; Ellstrand & Schierenbeck, 2006) and what makes some areas more susceptible to invasion than others (e.g. Stohlgren et al., 1999; Alpert et al., 2000), the control of invasive plants in the context of ecosystem conservation have had mixed success. In particular, few studies aimed to assess the eradication and control of invasive plant species in protected areas (Child et al., 1998; Shaw, 2003; Dehnen-Schumutz et al., 2004; Nielsen et al., 2005; Křivánek, 2006). Most of them applied mechanical methods in substitution to the chemical control, forbidden within protected areas of many countries (Villaverde et al., 2014). Mechanical control allows the exhaustion of reserves, provoking withering and depriving the plant of any capacity to regenerate (Chicouene, 2007). Mowing (Milakovic et al., 2014), uprooting (Chicouene, 2007), grazing (Erskine Ogden & Rejmànek, 2005; Bandarra et al., 2012;), and burning (Kettenring & Adams, 2011) are the main controls applied in protected areas today but new weeding techniques aiming at lower environmental impact and cost are now available. However, their efficiency and applicability with invasive plants still need to be tested in protected areas.

Senecio deltoideus Less. (Asteraceae - Canary creeper) is one out of the 791 non-native naturalized plant species detected in Italy (Galasso et al., 2018). It is an extremely invasive exotic plant introduced in the Mediterranean area since the beginning of the XIX century for ornamental purposes (Zappa & Campodonico, 2005). Today the species is a casual neophyte in SE France (Fried, 2010) and Spain, but it is an invasive plant in NW Italy (Galasso et al., 2018).

In this study, we tested the best eco-friendly and cost-effective weeding control of *S. deltoideus* in a Regional Protected Area near Ventimiglia (Italy - close to the French border). More specifically, in a Mediterranean climate area, the study aimed at: a) assessing the re-growth of *S. deltoideus* in a non-native area; b) verifying the effect of different weeding techniques for the control of *S. deltoideus* invasion; c) testing the enduring effect of each technique on *S. deltoideus* after one-year treatment.

Materials and Methods

Study species

Senecio deltoideus Less. is a vigorous perennial climbing herb native from Tropical Africa, producing masses of bright yellow flower heads in early winter. In native range, it is a species of open terrain, such as bracken and ericoid scrub or bush clumps in montane grassland, where it often forms masses on the ground and it climbs on lower scrub (Hyde et al., 2020). In non-native range, the species grows mainly in open vegetation, in Mediterranean grassland and shrubs, frequently becoming invasive. The plant blooms in December and later it shows a vigorous vegetative growth favoured by its many basal gems from which many shoots sprout, or re-sprout in summer when the plant is cut.

Study site

We performed the study at Capo Mortola [Ventimiglia (IM), North West Italy - 43.781576° N; 7.554797°E] inside the Regional Protected Area Giardini Botanici Hanbury. This territory is part of the Special Area of Conservation (IT13116118 “Capo Mortola”), protected by the Habitats European Directive 1992/43/EEC, aimed to conserve natural habitats and wild fauna and flora in Europe. The territory has a Mediterranean climate, with an arid period in July (annual average rainfall 663 mm, mean annual temperature: 12.9 °C). In 1867 part of the SAC (18 ha) was bought by British merchant Thomas Hanbury (Campodonico, 2010), who transformed the land in an acclimatization garden for exotic plants (Campodonico & Zappa, 2006). *Senecio deltoideus* entered the SAC in 1902 (Zappa & Campodonico, 2005). Currently there is an extension of about 10 hectares invaded by the African plant, rapidly covering fields and shrubby places with its covering and suffocating shoots (Galasso et al., 2018; personal observations).

Experimental design

The experiment was carried out in a homogenous plane (10 m a.s.l., exp. SE, incl. 2 %, 100 m distant from seaside) within an area of about one square hectare (43.781576° N; 7.554797°E). The selected area was never previously cultivated and located in a Aleppo-pine wood (*Pinus halepensis* Mill.) in which occurs some manna ash (*Fraxinus ornus* L.) and holm oak (*Quercus ilex* L.) individuals with a sparse underwood vegetation of Mediterranean scrubs (*Rhamnus alaternus* L., *Pistacia lentiscus* L., *Coronilla valentina* L.) and some grassland parcels. In those areas infested by *S. deltoideus* with a covering area of at least 90%, we randomly placed seventy-five 1 x 1 m plots. In January 2018 and 2019 (at the beginning of vegetative growth), we mowed all plots to have the same starting covering percentages and to measure the colonization capability of *S. deltoideus*. This preliminary operation corresponds to the usual management control of an alien invasive plant performed in a protected area management (Braun et al., 2016; Weidlich et al., 2020). Fifteen plots were untreated and used as control (hereafter CTR) while the other sixty plots were treated five times during the first years with four eco-friendly and cost-effective weeding techniques (fifteen plots for each treatment). Then in the second year, we repeated six times the treatments on thirty-six plots (nine for each technique) with a timetable similar to the first year. To test the enduring effect of each technique, we did not treat any more the remnant twenty-four plots (1-year treatment), and we compared them with those treated for a second year (2-years treatment). In particular, we used the following techniques and specific application methods:

1. organic herbicide - performed with pelargonic acid (FINALSAN Professional, W. Neudorff GmbH KG, Germany) 20 L/hl per ha, applied manually with shoulder sprayer five time a year with a regular interval between each treatment (5 day/ha manpower per year). Pelargonic acid (hereafter PEL) is a contact herbicide killing the sprayed parts of the plant, which does not translocate the active substance (Muñoz et al., 2020). Thus, PEL has a local effect like fire and does not leave any polluting traces in the environment;
2. flame-weeding (hereafter FLW) - performed with a flame-weeder Pirotrolley15 Maito, fuelled by liquefied petroleum gas (LPG), 1 kg/ha, five time a year with a regular interval between each treatment (5 day/ha manpower per year). The operator made a subjective use (up to visual plant desiccation, about 3-5 sec/m^2) in order to kill herbs but not affecting woody plants and not generating a fire. Plants are exposed to ultra-high temperatures producing cellular death due to the initial thermal disruption of the cellular membranes rapidly followed by dehydration of the affected tissue (Ellwanger et al., 1973);
3. mulching (hereafter MUL) - performed with chopped wood locally produced with the management of the protected area (pruning, chopped wood, etc.). A layer of 20 cm height of chopped wood was scattered on the ground after the preliminary mowing made in January (3 day/ha manpower per year);
4. mowing (hereafter MOW), performed with a handy machine trimmer, five time a year with a regular interval between each treatment (5 day/ha manpower per year).

Data collection and analysis

Before any new treatment (MUL included), we took a high definition photograph of each plot to record *S. deltoideus* re-growth. The photographs were made with a Canon EOS 350D equipped with an EFS 18-25 mm lens, fixed on a tripod at a distance of 120 cm from the ground. Specifically, each year we took 450 photos in six sessions (a total of 900 photos in 12 sessions during the whole study): the first session was aimed to detect the starting covering, the others to quantify the re-growth. At the end of the study we uploaded: 90 photographs of CTR, PEL, FLW, MUL, MOW each belonging to 2018; 90 photos of CTR belonging to 2019; 216 of PEL, FLW, MUL, MOW after 2 years treatment belonging to 2019; 144 of PEL, FLW, MUL, MOW after 1-years treatment belonging to 2019.

The images were elaborated with ImageJ 1.52a (Wayne Rasband, National Institute of Health, USA. http://imagej.nih.gov/ij) producing a final matrix of the covering percentage of *S. deltoideus* only per plot per weeding technique. The recolonization of other plants was detected but not analysed in this study.

The repeated measures of covering proportion were analysed using a generalized linear mixed effect model by using lme4 package (Bates et al., 2015) implemented in R (R Core Team, 2020). To determine whether there was a significant effect of techniques, we set them as a fixed effect, and plot as random factor. To determine difference between CTR and 1-year treatment plots we set them as a fixed effect and plot as random factor. Then, to determine for each weeding technique any difference between 1-year treatment and 2-years treatment plots, we set them as a fixed effect and plot as random factor. The data were analysed with a negative binomial distribution because the response variable is proportion data. We performed post hoc analysis using the emmeans function in the "emmeans" package in R (Lenth, 2020).

Results

The CTR plots had a high re-growth after the shared mowing performed at the beginning of each study year (Tables 1 and 2). *S. deltoideus* covering grows constantly up to the mean value of 96.4% (sd 4.77) and 88.68% (sd 9.39) of the total surface at the end of 2018 and 2019 respectively.

The re-growth was very fast in spring and early summer, a period favoured by a sensible amount of precipitations (Figure 1). The summer aridity, on the contrary, limited the vegetative growth of the plant, with a fast restart of the vegetation colonization during the autumn (Figure 1).

During the first year of experiment, the four weeding techniques reduced *S. deltoideus* covering (Tables 1) but they had significantly different effect (Table 3). In particular, FLW was significantly different from all other treatments, reaching the highest covering value of 37.93% (sd 23.98) in late autumn (Table 1). The other techniques had a better

Table 1. Percentage of surface and standard deviation (in brackets) covered by *S. deltoideus* during the first year in the four weeding techniques. The total number of plots performed (N) is reported. The columns 1-6 correspond to the treatment applied: 1 = winter mowing as pre-treatment; 2-6 the five subsequent treatment from early spring to late autumn.

Treatments	N	1	2	3	4	5	6
MOW	15	0.28 (0.28)	7.31 (3.21)	7.31 (3.56)	3.10 (2.87)	5.17 (6.72)	4.72 (4.88)
FLW	15	0.29 (0.15)	15.50 (12.16)	22.57 (15.54)	23.13 (19.70)	24.19 (14.83)	37.93 (23.98)
MUL	15	0.20 (0.30)	0.16 (0.25)	0.40 (0.83)	2.34 (4.48)	0.22 (8.38)	5.12 (11.15)
PEL	15	0.31 (0.33)	1.32 (0.98)	4.29 (3.15)	0.59 (0.86)	0.16 (0.19)	0.22 (0.30)
CTR	15	0.23 (0.15)	19.83 (12.45)	51.46 (25.59)	90.49 (9.54)	89.99 (10.73)	96.40 (4.77)

Table 2. Percentage of surface and standard deviation (in brackets) covered by *S. deltoideus* during the second year in the four weeding techniques. Values are reported for 2-years treated plots (y-t = 2; grey stipes) on which the technique was repeated and 1-year treated plots (y-t = 1; white stripes) on which the technique was not repeated. The total number (N) of plots used is reported. The columns 1-6 correspond to the treatment applied: 1 = winter mowing as pre-treatment; 2-6 the five subsequent treatment from early spring to late autumn.

Technique	y-t	N	1	2	3	4	5	6	7
MOW	1	6	1.18 (0.73)	8.34 (4.78)	20.07 (9.48)	4.08 (3.82)	2.59 (2.11)	11.97 (13.34)	40.73 (31.15)
	2	9	0.61 (0.29)	1.54 (1.39)	2.06 (2.45)	0.05 (0.07)	0.01 (0.03)	0.05 (0.11)	0.38 (0.83)
FLW	1	6	0.75 (0.98)	8.05 (5.57)	23.84 (18.20)	8.18 (7.66)	3.61 (2.88)	9.51 (12.06)	25.32 (16.68)
	2	9	0.57 (0.43)	17.02 (11.36)	6.64 (9.51)	0.94 (0.86)	0.21 (0.34)	0.91 (1.80)	1.44 (2.15)
MUL	1	6	1.34 (0.96)	5.92 (3.75)	12.56 (11.28)	6.13 (5.77)	3.67 (3.43)	11.01 (15.20)	16.34 (23.77)
	2	9	1.25 (1.03)	1.29 (2.52)	1.47 (1.64)	0.09 (0.23)	0.05 (0.16)	0.38 (0.51)	0.70 (1.98)
PEL	1	6	0.38 (0.27)	0.39 (0.31)	13.06 (10.19)	0.07 (0.07)	0.03 (0.04)	0.03 (0.03)	0.01 (0.02)
	2	9	0.86 (0.71)	0.23 (0.43)	0.18 (0.13)	0.02 (0.02)	0.00 (0.01)	0.10 (0.24)	0.00 (0.00)
CTR	0	15	0.18 (0.13)	47.19 (19.00)	83.03 (10.45)	84.41 (10.42)	71.88 (20.85)	54.48 (26.81)	88.68 (9.39)

performance reaching a maximum covering of 7.31% (sd 3.56), 5.12% (sd 11.15) and 4.29% (sd 3.15) in MOW, MUL and PEL respectively (Table 1 and Fig. 2a).

Differently, during the second year, the effect of the four techniques was similar and not significant differences were detected (Table 2 and 3). In 2-years treatment plots the maximum covering surface was reached in FLW again (17.02%, sd 11.36), while the other techniques showed a maximum covering of 2.06% (sd 2.45), 1.47% (sd 1.64) and 0.23% (sd 0.43) in MOW, MUL and PEL respectively (Table 2 and Fig. 2b).

The 1-year treatment plots were significantly lower and different to CTRCTR plots in the proportion of *Senecio* covering (Table 4 and Fig. 3). The highest maximum covering surface was reached in MOW (40.73%, sd 31.15), while the other treatments showed maximum covering values of 25.32% (sd 16.68), 16.34% (sd 23.77) and 13.06% (sd 10.19) for FLW, MUL and PEL respectively (Table 2 and Fig. 3).

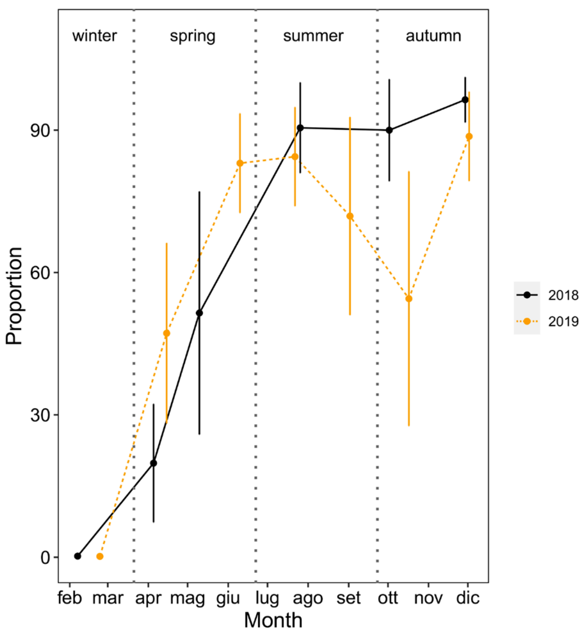

Figure 1. Natural re-growth of *S. deltoideus* in the CTR plots in 2018 (black continuous line) and 2019 (yellow dotted line), after the preliminary mowing operation corresponding to the usual management control of an alien invasive plant performed in a protected area management. Proportion indicates the mean percentage of covering area of *S. deltoideus* in the study plots used as control and never treated with any weeding techniques.

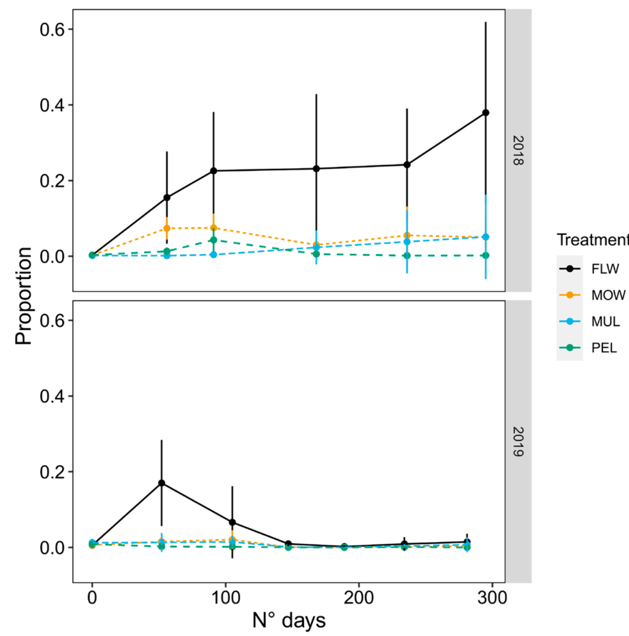

Figure 2. Comparison in covering surface (%) of *S. deltoideus* after one year and two years treatment with the four weeding techniques (MOW = mowing; FLW = flame weeding; MUL = mulching; PEL = pelargonium acid).

Table 3. Post hoc test for the difference over time of the proportion of *Senecio* covering detected in 2018 and 2019, according to the different weeding techniques (FLW, MOW, MUL and PEL) and the control (CTR). Fix terms is the interaction treatment with days after first treatment (treatment x days).

Year	Contrast	Estimate	SE	z ratio	p value
2018	CTR vs FLW	1.0362	0.2486	4.1684	0.0003
	CTR vs MOW	2.4970	0.4547	5.4914	<0.0001
	CTR vs MUL	3.3646	0.6768	4.9714	<0.0001
	CTR vs PEL	3.9226	0.9172	4.2766	0.0002
	FLW vs MOW	1.4608	0.5025	2.9071	0.0300
	FLW vs MUL	2.3284	0.7099	3.2801	0.0092
	FLW vs PEL	2.8864	0.9418	3.0649	0.0185
	MOW vs MUL	0.8676	0.8065	1.0758	0.8191
	MOW vs PEL	1.4256	1.0166	1.4023	0.6262
	MUL vs PEL	0.5580	1.1335	0.4923	0.9881
2019	CTR vs FLW	2.7412	0.6138	4.466	0.0001
	CTR vs MOW	4.5139	1.0357	4.3582	0.0001
	CTR vs MUL	4.4093	2.1447	2.0559	0.2395
	CTR vs PEL	5.7303	1.2766	4.4886	0.0001
	FLW vs MOW	1.7727	1.1968	1.4812	0.5747
	FLW vs MUL	1.6681	2.2164	0.7526	0.9439
	FLW vs PEL	2.9891	1.4136	2.1146	0.2137
	MOW vs MUL	-0.1046	2.3729	-0.0441	0.9999
	MOW vs PEL	1.2164	1.6422	0.7407	0.9469
	MUL vs PEL	1.3210	2.4918	0.5301	0.9843

Table 4. Post hoc test for the difference over time of the proportion of *S. deltoideus* covering in the 1-year treated plots with different weeding techniques (FLW, MOW, MUL and PEL) and the control (CTR). Fix terms is the interaction treatment with days after first treatment (treatment:days).

Contrast	Estimate	SE	z.ratio	p.value
CTR - FLW	1.6907	0.4693	3.6028	0.0029
CTR - MOW	1.4656	0.3513	4.1721	0.0003
CTR - MUL	1.6445	0.4602	3.5734	0.0032
CTR - PEL	3.4266	0.9313	3.6795	0.0022
FLW - MOW	-0.2251	0.5606	-0.4015	0.9945
FLW - MUL	-0.0462	0.6344	-0.0728	1.0000
FLW - PEL	1.7358	1.0322	1.6817	0.4453
MOW - MUL	0.1789	0.5529	0.3235	0.9976
MOW - PEL	1.9609	0.9842	1.9924	0.2696
MUL - PEL	1.7820	1.0281	1.7334	0.4133

The proportion of *Senecio* covering was partially different between 1-year treatment and 2 years treatment plots. In particular, MOW and MUL were significantly different between 1-year treatment and 2 years treatment plots, while in FLW and PEL no significant differences were detected (Table 2 and 5 and Fig. 4).

Table 5. Difference in proportion of *S. deltoideus* covering between 1-year treated and 2-years treated plots with the different weeding techniques (FLW, MOW, MUL and PEL), assessed using generalized linear mixed effect model with negative binomial distribution.

	χ2	df	P value
FLW	1.9873	1	0.1586
MOW	7.3703	1	0.0066
MUL	4.3117	1	0.0378
PEL	0.9088	1	0.3404

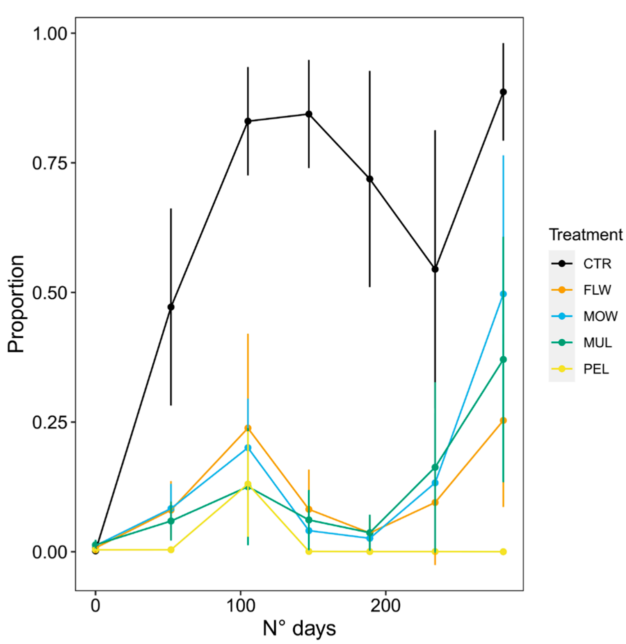

Figure 3. Natural re-growth of *S. deltoideus* in the CTR plots in 2018 (black continuous line) compared with the natural re-growth in the 1-year treated plots, verifying the enduring effect of one-year treatment (MOW = mowing; FLW = flame weeding; MUL = mulching; PEL = pelargonium acid).

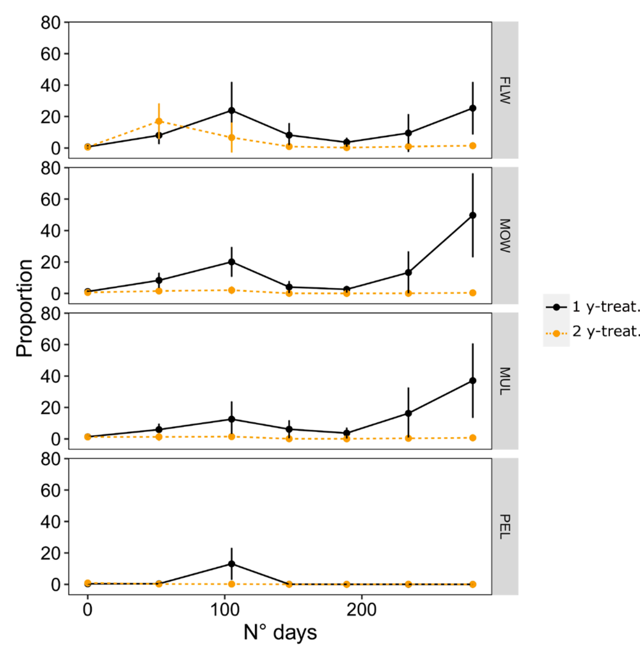

Figure 4. Comparison between 1-year (black continuous line) and 2-years (yellow dotted line) treated plots detected in 2019. The first are those no more treated during the second year, the second are those on which the 4 weeding techniques were applied a second time (MOW = mowing; FLW = flame weeding; MUL = mulching; PEL = pelargonium acid).

Discussion

In this study, we tested different eco-friendly and cost-effective weeding techniques on *S. deltoideus*, in order to define the easiest and most convenient strategy in managing this invasive plant in a protected area of the northern Mediterranean coasts. The untreated plots quantified for the first time the capability in vegetative growth of the species in a non-native area and its invasive potential toward natural vegetation: the species showed a constant, rapid and complete re-colonization of the plot after the start of the mowing operation at the beginning of the vegetative seasons (Table 1 and 2). When stimulated by a single control cutting a year (corresponding to a basic invasive control made in protected areas), the plant shows a vigorous gemmation activity at the base (personal observations) as observed in *Senecio pterophorus* DC. (alien invasive species in Italy - Barberis et al., 1998) in the same geographical area of this study. The spring and autumn precipitations of the Mediterranean climate support the plant growth and the seed germination, as already observed in the other co-generic *S. pterophorus* and *S. inaequidens* DC., alien species to Spain and Italy (Caño et al., 2007). In particular, *S. deltoideus* seems to be sensible to the summer aridity typical of the Mediterranean climate (Fig. 1) when it temporarily stops its fast and vigorous vegetative growth, similarly to other congeneric species (Caño et al., 2007).

The multiple application of all four eco-friendly and cost-effective weeding techniques during the same year resulted in a high reduction of *S. deltoideus* covering (Table 1 and 2), evidencing that to obtain effective control of perennial alien plants, more frequently repeated treatments are required (Rask et al., 2013). According to literature, a single weeding control may have a negative effect by promoting the invasion of an alien invasive species and decreasing natural vegetation competitiveness (Trtikova, 2009). On the contrary, as observed in *Senecio jacobaea* and other alien perennial plant species, consecutive cuts are necessary to achieve maximum control (Suter et al., 2007; Roos et al., 2011), depleting the reserves in the plants by repeated killing of the leaves (Raghu et al., 2006), interrupting seedling growth and causing seed bank depletion (Sebastian et al., 2017).

All four weeding techniques, applied for two consecutive years, showed a progressively and drastic reduction of *S. deltoideus* covering (Tables 1 and 2), but they had significantly different effect. During the first-year treatments, FLW was less effective but in the second-year treatment the same ineffectiveness was not detected. Among the four weeding techniques applied, PEL showed the most consistent and constant covering reduction along years. MUL and MOW showed a similar efficiency with a covering reduction during the first year treatments but definitely lower in the second year treatment.

Flame weeding (FLW) is the most common thermal weed control method used in agriculture in both organic and conventional systems (Ascard, 1995), as an alternative to herbicide applications (Peruzzi et al., 2007; Datta & Knezevic 2013; Fontanelli et al., 2013), and few times in the management of natural areas. One of the limits of FLW is that the operator has the subjective responsibility to define the sufficient quantity of heat to cause the killing of weeds. In addition, this personal assessment is also combined with the environmental conditions under which the treatment is carried out. The weather conditions of the day (wind, rain, etc.), the trend of the season (more or less dry), the characteristics of the habitat (amount of litter and undergrowth, etc.) can lead to different results in the application of FLW (Ulloa et al., 2012). For these reasons, FLW resulted in a lower effectiveness in our experiments along the first year treatments and in the inconsistency between the first and second year. Moreover, the use of FLW in natural environment is still debated and controversial: on the one hand, there is growing evidence that these management projects in wide scale in natural vegetation alter ecosystem structure in ways that promote alien plant invasion (Keeley, 2006). On the other hand, when used in altered environments, fire is likely to promote persistence of aliens (Brooks et al., 2004), and being difficult to apply to a targeted species, it may favour other alien vigorous re-sprouting plants (Keeley, 2001). However, the use of FLW to control invasive herbaceous plants in open natural spaces may be advantageous because it avoids the spreading of chemical residues in the environment and the herbicide carryover to the following season, it is effective on a very wide spectrum of weeds (Ascard, 1995; Mojžiš, 2002; Fontanelli et al., 2013).

The other two physical eradication techniques used to control *S. deltoideus* (i.e., mulching, MUL and mowing, MOW) showed an effectiveness similar to FLW but they were more constant between years. However, these techniques have two common drawbacks: they can be expensive because of the manpower involved and they disrupt the soil, creating disturbed sites prone to new invasion (DiTomaso, 2000), as also supported by the re-growth observed at the end of the second year in 1-year treatment plots. In general, MUL is most effective on controlling small seeded species and it is marginally effective on established re-sprouting perennials (Hayes et al., 2019), but in this study we recorded satisfactory results on *S. deltoideus* too (Table 1 and 2). This method has the advantage that the operator work is limited in time (the mulch layer is laid once a season) and it is made with the sustainable use of locally produced recycled material. On the other side, MUL increases the risk of summer fire in the natural environment for the huge accumulation of highly flammable material. Finally, MUL may be also hazardous in terms of introduction, promotion and establishment of further alien species (Kruse et al., 2004; Keeley, 2006). MOW is often used to control annuals but can occasionally reduce seed production and can provide suppression of biennials and perennials (Biazzo & Milbrath, 2019), if used repeatedly as we did. Timing is critical to the success of MOW and the repetition of several cuts in the year leads to a complete consumption of the plant's reserves (DiTomaso et al., 2013). The advantages of MOW are its quick and easy execution and its applicability on large surfaces.

The highest effectiveness and consistency between years was achieved using PEL, a chemical control never performed on *Senecio* before. Recent studies report the use of synthetic systemic herbicides (2,4-D, Asulam and MCPA) to control some invasive species of *Senecio* (Roberts & Pullin, 2004). They effectively reduced population density (e.g. *S. jacobaea* and *S. aquaticus*), but there are legitimate concerns over the use of herbicides in terms of potential environmental impacts. Although newer herbicides are less toxic, have shorter residence times, and are more specific, concerns over detrimental environmental impacts remain (Borokini & Babalola, 2012), especially if applied in natural protected areas. Differently, the pelargonic acid is a natural extract with a contact herbicide effect, and the plant does not translocate it (Muñoz et al., 2020). Thus, it behaves similarly to fire, and if application is timed correctly, it may be used in a targeted way on specific alien plants (Ciriminna et al., 2019). The main limitation is that the product is expensive: the suggested dosage is 170 litres of product per ha, resulting in a cost of about 1,300 euros per hectare (Muñoz et al., 2020).

The interruption of treatments on some plots during the second year showed a potential long lasting effect of the weeding techniques on *S. deltoideus*, keeping its covering reduced over time (Table 4 and Fig. 3). In particular, FLW and PEL did not show any significantly difference in the comparison between 1-year and 2-year treated plots, demonstrating an enduring effect as a control technique. This result opens interesting future perspective for *S. deltoideus* management: the control might be limited to biannual cycles of treatment, maintaining the invasion degree at a low level and reducing the cost.

However, the selection of the best strategy to control *S. deltoideus* is difficult to define. As suggested by many studies in literature, long-term and repeated control methods would be needed to effectively manage invasive plants, but it is always necessary to consider the costs and benefits of each methodology when implementing control programmes (Matarczyk et al., 2002; Wootton et al., 2005; MacDonald et al., 2007). If an exotic weed is already widespread, a species-specific organic control may be the only long-term effective method able to suppress its abundance over large areas (Mack & Lonsdale, 2002). In this context, our second-year results for no-treated plots revealed that in a long-time management strategy the selected treatment could be applied every two years with a drastic reduction in costs for the manager of the protected area.

Table 6. Comparison among the weeding techniques on their eco-friendly and cost-effective performances during an experimental year. Efficacy = mean covering resulted after 1-year treatment. Manpower = expressed as days per hectare per year for the application of the technique. Cost = referred to the material used applying the technique. Risk = potential risk applying the technique. Enduring = mean covering resulted in 1-year treated plots if untreated during the second year.

	Efficacy (%)	Manpower (day)	Cost	Risk	Enduring (%)
MOW	2-7	5	cheap	-	0-2.5
FLW	17-38	5	cheap	Wood fire	1-17
MUL	1.5-5	2	cheap	Wood fire	0-2.5
PEL	0.2-4	5	expensive	Veg. desicc.	0-13

Conclusion

Evaluating both advantages and disadvantages of the four weeding techniques and their implementation costs, mowing is the recommendable control method for *S. deltoideus* (Table 6) because it fulfils the best compromise among a good covering decrement, a lasting effect and a moderate demand of manpower, without harmful consequences for the environment. Despite sometimes more effective according to our results, the other treatments bring some important contraindications (Table 6): they are either much more expensive (PEL), or very dangerous in creating potential wood fires (FLW and MUL).

Acknowledgements

We would like to thank Francesco Ghilino for supporting the experimental set-up of the pots experiment. We are grateful to Oscar Marchelli for supporting photos sampling during 2019. This study was performed in frame of the 2014-2020 Interreg Maritime Program, Project "ALIEM - Action pour Limiter les risques de diffusion des espèces Introduites Envahissantes en Méditerranée". Gabriele Casazza gratefully acknowledges financial support from the European Union's Horizon 2020 Research and Innovation Programme [Grant Agreement No. 793226].

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