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A vulnerability index for successful eradication of IAPs targets interventions at their most vulnerable stages

Abstract

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Invasive alien plant species (IAPs) are non-native plant species whose introduction and spread outside their natural range poses a threat to biodiversity. Their removal is often financially and environmentally costly from repeated interventions. Tackling IAPs at their most vulnerable stages can be a cost-reducing and effective strategy. A vulnerability index has been devised to plan an IAPs removal strategy based on attacking the most vulnerable stages of a species and focuses on the ease and effectiveness of removing aerial and root biomass as well as propagules. The need for repeated interventions is also factored in the vulnerability index since this forms part of the weakening strategy.

Key words: alien species, invasiveness, plant management.

Introduction

Anthropogenic impacts on natural habitats including Natura 2000 (N2K) sites, are a major concern for the Maltese Islands. A huge economic burden arises from the intentional or unintentional introduction of invasive alien plant species (IAPs) (EC 2011, 2019; Egoh & al. 2014). IAPs are establishing and spreading in many parts of the world, including the Mediterranean Basin which hosts some 13000 endemic plant species, causing the decline of indigenous biodiversity, and having negative impacts on ecosystems, the economy and human health (Fritts & Rodda 1998; Myers 2000; Miller & Hobbs 2007; Pimentel & al. 2011; Lockwood & al. 2013). IAPs are invasive to different degrees, and an eradication strategy depends in part on propagule pressure comprising propagule size and frequency of introductions, as well as difficulty to permanently remove the biomass of the established IAPs including their rooting apparatus. For certain species, eradication is straightforward and a one-time exercise but for others, it becomes a daunting task that needs several months if not years of repeated interventions (Kohli & al. 2004; Hulme 2007; Hulme & al. 2009). Ziller & al., (2020) proposed a priority-setting scheme for the management of IAPs in protected areas based on three criteria – species risk of invasion, invasion stage and species frequency. But this only goes so far as to decide which IAP takes priority for intervention. Though much has been written on strategies for eradication of IAPs, it appears that not much importance has been given to tackling effective and cost-cutting eradication of IAPs at their most vulnerable life cycle stages. The importance of choosing the correct strategy for eradication of IAPs at their most vulnerable stages varies by family and species knowing fully that IAPs are vulnerable to different degrees. It is therefore imperative to identify their strengths and weaknesses and much akin to warfare, attack the IAPs at their most vulnerable life cycle stages.

Vulnerable stages may relate to both life cycle stages and choosing the right time of the year when to tackle certain actions focused on weakening the plant to reduce growth, as well as vegetative and propagule spread, is crucial. IAPs tissue composition is a prime vulnerability consideration aimed at reducing growth and biomass. Thus, the initially weak herbaceous growth in invasive climbers such as *Cardiospermum* sp. pl. is vulnerable to wilting when the main stem is severed (Gildenhuys & al. 2013; Chapman & al. 2017) whereas leaf and stem succulence in species of the genus *Aptenia, Carpobrotus, Aloe* and *Opuntia* render them vulnerable to rotting when cut and rolled or piled in a heap without need of removing biomass off-site thus helping to reduce effort and cost. Reduced propagule spread by cutting out inflorescences and harvesting seeds before maturation and dispersal, the prompt removal of tillers and suckering or creeping offshoots, as well as eradication of seedlings before establishment, are all strategies that target vulnerable stages. Conversely, IAPs with a dormant soil seed bank, root suckering, bulbil formation and subsoil rhizomes are harder to eradicate and require multiple strategies and interventions for complete eradication. Tackling these vulnerable life cycle stages at the appropriate time helps to reduce chances of reinvasion, and speed up the eradication process.

IAPs have been recorded for the Maltese Islands from at least 19 families with the number of species constantly growing due to the unrestricted importation of exotic plant species for the horticultural trade and use as landscaping ornamentals (MEPA 2013; Roy & al. 2020; EPPO Global Database). Additional invasions have resulted from the past use of exotic species for a rapid greening strategy of the Maltese Islands in the 1970s. The aim of the project was to investigate the use of different IAPs removal strategies targeting the most vulnerable stages for the eradication of a selection of IAPs. Experience gathered from different eradication strategies helped to establish a vulnerability index for a range of IAP species, including the three species selected for intervention sites, as part of the SiMaSeed INTERREG V-funded seed bank and habitat restoration project.

Materials and Methods

Our project focused on the removal of IAPs in eight different plant families shown in Table 1, using a multidisciplinary approach mainly divided into three phases: Assessment, Intervention and Monitoring. The assessment started with species identification and a search in the European and Mediterranean Plant Protection Organisation (EPPO) database to establish the recorded invasiveness of the IAPs across Europe. This was followed by a preliminary assessment of the extent of invasiveness in the chosen N2Ks intervention site. One such site was Wied Babu, an incised valley and associated garrigue in the limits of

Zurrieq Malta which is shown in Fig. 1. It is good to note that we focused on four IAPs in three families occurring on this site, though other IAPs were present as well. The extent and rate of IAPs invasion in N2K sites were next studied using historical and more recent aerial survey photographs, the oldest dating back to 1957, satellite images and drone surveys followed by walk through ground-truthing and digital imaging. Information was additionally gathered from interviews with stakeholders, all of which contributed precious information on the rate of spread. A study of the IAPs' growth characteristics and reproductive cycle including its phenology, helped to identify growth, anatomical and tissue vulnerabilities as well as to calculate propagule load in order to assess the extent of a potential invasion by these IAPS if left unchecked. Crucially it allowed us to identify, assess and prioritise the most vulnerable stages. These studies served as a preparation for the intervention phase by assigning a vulnerability index as to how easy or difficult the eradication process will be. Their eradication vulnerability index was calculated using a 10-point scale, subdivided into five vulnerability categories. The least vulnerable and hence most difficult to eradicate was assigned a 1-2 value, whereas the most vulnerable and hence easiest to eradicate being assigned a 9-10 value as shown in Fig. 2. The intervention stage involved applying the best strategy for each IAPs removal using informed management decisions based on the vulnerability index followed by monitoring over a period of several months to assess the success of our intervention strategy.

In order to assign an IAP to one of the vulnerability categories, five critical contributors to the vulnerability index shown in Fig. 3, were selected namely:
A. ease of weakening the plant to reduce its above-ground growth;
B. ease of weakening the plant to reduce its below-ground growth;
C. ease for collection of propagules;
D. ease of eradication of soil seed bank and/or uprooting of seedlings or rhizomes;
E. ease of suppression of regrowth and re-invasion from residual propagules.

Each contributor was ranked with a value of 2, 1 or 0 with the critical contributor value of 2 signifying a high vulnerability and therefore an easy IAP removal task for that contribution, 1 signifies a moderate vulnerability contributor and 0 signifies a low vulnerability contributor and therefore a difficult IAP removal task. Based on the contributor assessment, the established index allowed different strategies to target the most vulnerable stages.

Table 1. List of invasive alien plant species (IAPs) studied with families and common names.

Plant Family	**Invasive Alien Plant Species**	**Common Name**
Aizoaceae	*Carpobrotus acinaciformis* (L.) L. Bolus	Hottentot Fig
Asparagaceae	*Agave Americana* L.	Century Plant
	Agave sisalana Perrine	Sisal
Euphorbiaceae	*Ricinus communis* L.	Castor Oil Plant
Fabaceae	*Acacia saligna* (Labill.) Wendland	Blue-leaved Wattle
	Leucaena leucocephala (Lam.) de Wit	Lead Tree
Oxalidaceae	*Oxalis pes-caprae* L.	Cape Sorrel
Poaceae	*Arundo donax* L.	Giant Reed
Sapindaceae	*Cardiospermum grandiflorum* Swartz	Balloon Vine
Simaroubaceae	*Ailanthus altissima* (Mill.) Swingle	Tree of Heaven

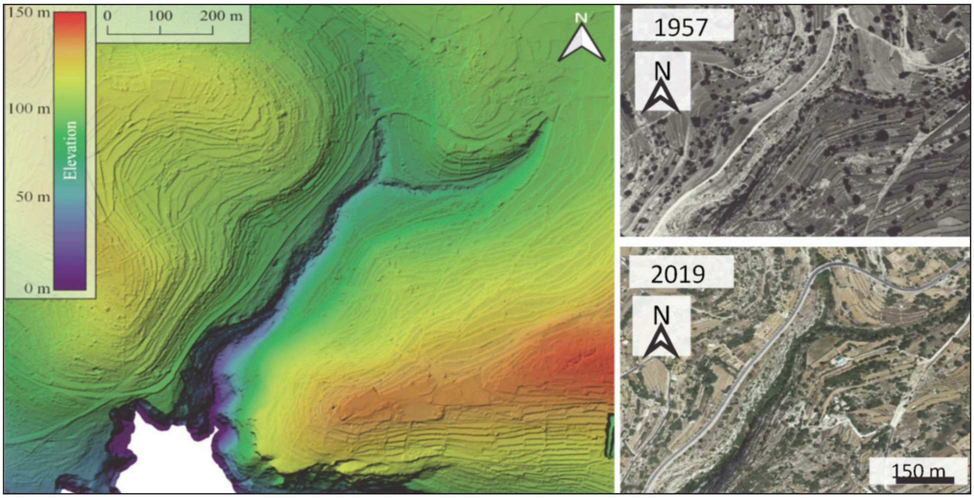

Fig. 1. QGIS elevation map of the Wied Babu, N2K site (left). Cloudisle elevation ranges from 0 m (purple) to 150 m (red). Historical aerial photos of Wied Babu from 1957(top right) when still cultivated and from 2019 (bottom right) when valley bed had become almost completely covered with a canopy of the IAP climber species *Cardiospermum grandiflorum*. Retrieved from PA Mapping unit and Google Earth (2021) respectively.

Results and Discussion

A comparison of the extent of invasion of four IAPs and the different strategies employed for their removal from N2K sites is given in detail below. Other IAPs are also included though these apply for very small trials and associated observations. All interventions related to removal of IAPs were carried out during the period June 2020 to June

1-2	3-4	5-6	7-8	9-10
Very low vulnerability VERY DIFFICULT TO ERADICATE	Low vulnerability	Medium vulnerability	High vulnerability	Very high vulnerability VERY EASY TO ERADICATE
Soil Bulbils & Rhizomes	Root fragmentation and suckering	Floating seeds and Soil seed banks	Bulbous plants	Leaf, stem and root Succulents

Fig. 2. Vulnerability index for eradication of IAPs subdivided into five vulnerability categories with 1-2 showing least vulnerability and therefore highest difficulty to eradicate and 9-10 showing the highest vulnerability and therefore the greatest ease for eradication. Examples are given for each vulnerability category.

	Contributors to Vulnerability Index	2 = High	1 = Moderate	0 = Low	TOTAL
A	Removal of above ground biomass				
B	Removal of below-ground biomass				
C	Collection of propagules				
D	Uprooting of seedlings/Rhizomes				
E	Suppression of regrowth/reinvasion				

Fig. 3. Five contributors to the vulnerability index of an IAPs marked A to E in table. A vulnerability contributor value of 2 indicates the species has high vulnerability in that contributor category, 1 a moderate vulnerability contributor whilst 0 indicates very low vulnerability for that contributor.

2021. The intervention stage initially focused on simple management decisions such as if seeds or other propagules could be collected before they are dispersed, at what stage would such a collection be made efficiently and with the minimum of labour input? Wherever possible, if seeds or other propagules were available for collection, this was the first practical intervention made followed by removal of above-ground biomass whilst minimizing labour and negative intervention impacts such as trampling on site. Our interventions were mostly dedicated to individuals of *Agave sisalana* Perrine, *A. americana* L., *Acacia saligna* (Labill.) H. L. Wendl. and *Cardiospermum grandiflorum* Sw. on several test plots in the Wied Babu and other N2K disturbed habitat sites. A description of eradication actions on these three species studied in detail follows together with how the vulnerability index of these three species was arrived at. The value of the different contributors to the vulnerability index is indicated in Table 2. Further data are given in Fig. 4. The vulnerability index of six other species has also been included though data for this is limited to field observations for limited trials.

Agave sisalana and *A. americana* growing over much of the upper reaches of the Wied Babu valley, limits of Zurrieq and an N2K site, were planted as an ornamental plant or possibly as a preventive barrier against accidental falls into the valley some six to five decades ago. The original mother plants have formed large clonal stands through extensive suckering each covering areas of several square meters. Furthermore, the mature mother plants produce tall inflorescences (totem poles) which when mature are covered with seed capsules and aereal bulbils that arise as a modification of the flower bud somatic tissue through vivipary (Frankel & Galun 1977). The monocarpic mother plant will eventually die but its suckers as well as the bulbils shed before or after the tall inflorescence collapses, will persist and contribute to further colony expansion. The seeds, though dispersed, are not known to germinate in our environment. The strategies employed for the local eradication of this species involved attacking its most vulnerable stages namely the removal of the developing inflorescence before the bulbils are formed and systematically cutting the fibrous blade-like leaves at their bases to reveal a cylindrical trunk. The cutting of the leaves at their bases may sound like a formidable task but in effect, this is difficult only in so far as removing the first few succulent leaves using a hand saw followed by severing the rest around the trunk as illustrated in Fig. 3a. The removal of the developing inflorescence at an early stage of its formation when it is some 1 to 2m tall will save a lot of work in the eradication strategy since postponement will lead to the development and dispersal

Table 2. Table showing the value of the different contributors to the vulnerability index of nine IAPs. Five vulnerability categories are shown with the most vulnerable to eradication in green and the least vulnerable to eradication in red with additional notes on vulnerable stages.

IAP Species & Contributor Value	A	B	C	D	E	Index	Ease of Eradication	Vulnerable stage of intervention
Carpobrotus acinaciformis	2	2	2	2	2	10	Very Easy	Severe plant from roots, roll up and allow to rot
Agave sisalana	2	2	2	2	1	9	Easy	Remove totem, propagules, leaf bases and offsets
Leucaena leucocephala	2	1	2	2	1	8	Moderately Easy	Collect pods when still green, severe tree at base
Cardiospermum grandiflorum	1	1	2	2	1	7	Needs persistence	Collect capsules, severe & uproot stem, seedlings
Ricinus communis	1	1	1	1	1	5	Difficult	Collect semi ripe inflorescence and seed capsules
Acacia salignia	2	0	0	1	1	4	Difficult	Lop off main trunk, remove tillers & seedlings
Ailanthus altissima	1	0	1	1	0	3	Very Difficult	Lop off trunk and suckers before leaf emergence
Oxalis pes-caprae	1	0	0	1	0	2	Extremely difficult	Use herbivores and light exclusion to weaken plants
Arundo donax	1	0	0	0	0	1	Extremely difficult	Cut off canes & remove new shoots

of some 600 bulbil propagules per mother plant, all sufficiently developed and ready to establish since they have fully formed roots and leaves. Collection of these propagules is easy if they have just fallen but will be time-consuming if they root. Mature totem poles may also have capsules with seeds but locally at least, the seeds are not known to germinate. The next task is the removal of the rooted stump of the mother plant and all clonal suckers. This is a time-consuming task but not hard to perform with the right tools. Removal of the voluminous biomass offsite may be a challenge. Since it is easy to overlook suckers, periodic site visits to uproot overlooked plantlets need to be carried out. The vulnerability index contributors for this species have been assigned a value of 2 for vulnerability categories A to D and 1 for category E giving a total vulnerability index of 9 and thus classifying the eradication of this species as easy.

Cardiospermum grandiflorum Swartz growing in the dry river valley section of Wied Babu is by far the most invasive. Its climbing habit drapes a continuous cover, thus blotting out light and weakening the underlying indigenous arborescent species including *Ceratonia siliqua*, *Pistacia lentiscus* and *Ficus carica* as well as threatening native assemblages of smaller indigenous perennials. Its vine-like stem allows it to spread, rooting wherever this touches the ground further fuelling the invasion but the species also produce a huge seed load most of which germinates readily. Eradication strategies involved two, time-consuming but not labour-intensive strategies, one of which again centres on the reduction of propagule dispersal as a vulnerable stage in the life cycle of this species. Mature seed capsules were collected when still wet from rain or dew (early in the morning) thus reducing seed dispersal from an otherwise fragile capsule that dehisces easily when dry. This helped to reduce the further shedding of seeds in the intervention area. The collection of seedlings about three to four weeks after periods of heavy rain and concurrently severing main stems of mother plants or rooted suckers some 30 cm above the ground not only kills the climbing vines but allows an easy handle for uprooting the remaining poorly-anchored root apparatus. All remaining aerial parts were left to wither and decay on the supporting shrubs. Based on the time-consuming but not labour-intensive work involved in the eradication of *C. grandiflorum*, vulnerability contributors A, B and E were assigned a value of 1 each whilst C and D were assigned a value of 2. This species, which has therefore been

Fig. 4. Morphological and life cycle stages for four different IAPs on which the invasiveness vulnerability index was based. From left to right, *Agave sisalana, Cardiospermum grandiflorum, Ricinus communis* and *Oxalis pes-caprae*. Different types of propagules produced by the species were key considerations to arrive at an informed management decision followed by morphological and tissue characteristics of above and below ground biomass. The colours correspond to four out of five vulnerability categories with green showing the most vulnerable to red showing the least vulnerable to eradication.

assigned a total vulnerability index of 7, is placed between moderately easy and difficult to eradicate since eradication requires frequent, repeated, and persistent interventions for seed collection, seedling uprooting, severing of the main and removal of the remaining rooted stump.

Acacia saligna (Labill.) Wendland was introduced in the 1970s as part of a fast greening project for the Maltese Islands and though the original scheme called for the use of these fast-growing and resistant species as nurse trees for the indigenous but slower-growing trees, this part of the scheme was never put into practice. The *Acacia* trees have persisted contributing to invasions, especially after the mother tree dies out naturally or after burning. The reason for this is the presence of an extensive soil seed bank under the mother tree which is stimulated to germinate only after the mother tree ceases to produce ethylene gas that acts as a seed germination inhibitor. Whereas for the previous two species, eradication focused on the vulnerability of the propagule production and dispersal stages, this does not apply here for even if the seed pods are collected before they dehisce, the soil seed bank will not be eliminated. As indicated earlier, once the main trunk of the mother plant is sawed off at ground level, ethylene production is suppressed and the seed bank is activated. Thus, since seed germination is triggered by a decline in ethylene production, it renders the species vulnerable to eradication if timed close to the start of the rainy season in September, where germinated seedlings can subsequently be easily uprooted. If the cutting down operation is timed before the onset of the dry season, then the stage is set to subsequently eradicate the plant using two fronts. Several tillers may be produced from the remaining stump but these can be easily pulled off when still young. This process will help to remove the source of sugars needed to nourish the roots which will eventually die. The summer drought will also help to desiccate the exposed soil further weakening the remaining root apparatus. On the other front, the seeds forming the soil seed bank will now readily germinate with the first rains in September being a warm and humid period of the year. These seedlings will grow rapidly and need to be uprooted in their entirety when about 20 to 30 cm high. One may try to uproot earlier but these may break off and if left to establish beyond 30 cm they will be hard to uproot or incompletely so. It is good to note that the seeds germinate in waves and the seed bank may persist for several years after the removal of the mother tree. The tiller removal and seedling uprooting process need to be repeated at frequent intervals over many months if not years. This species has been assigned a total vulnerability index of four comprised of a 2 for contributor A, two 0s for contributors B and C and two 1s for contributors D and E. This makes the species difficult to eradicate compared to the previous two. It is good to note that different environmental situations may call for different eradication strategies. Bachetta & al. (2018) refer to the use of germination-inhibiting sheeting (and indirectly light-excluding) to suppress regrowth, as well as sieving to reduce the seed bank but this may well apply for *Acacia* species growing on sandy beaches which would be difficult to apply on soil.

Amongst the other species included in Table 1, it is good to comment on the vulnerability index of two species that are extremely difficult to eradicate namely *Oxalis pes-caprae* and *Arundo donax*. The latter has become a highly invasive plant in valleys whilst the former which has overrun the entire Mediterranean basin and beyond, is now considered an impossibility to eradicate. And for both, the low vulnerability of their propagule stage is key. Though *Oxalis* suffers from repeated disturbance as when the soil is tilled in cultivation or when grazed upon by goats and sheep, it will thrive when left undisturbed and the production of a huge number of clonal bulblets renders it impossible to eradicate. Likewise, *Arundo donax,* whose subsurface rhizomes are very hard to uproot and even have the capacity to survive burning. With a vulnerability index of 2 and 1 respectively, the lack of appropriate vulnerable stages renders the two species extremely difficult to eradicate.

Conclusion

The use of a vulnerability index for IAPs removal helps to provide an informed management decision to plan a strategy for eradication. Key conclusions from this exercise are:
- A species may have multiple or a limited number of vulnerable stages;
- IAPs with a limited number of vulnerable stages are most difficult to eradicate;
- A good knowledge of the biology of IAPs especially their phenology helps successful eradication;
- Planning interventions to coincide with vulnerable stages can reduce work effort and expenses;
- Plants with a vulnerability index of 1-2 will need repeated eradication procedures and possibly mechanical and chemical intervention, though the latter is the least desirable.
- Finally, it is good to stress that the vulnerability to eradication for different IAPs must be considered in the context of the specific habitat as well as the prevailing environmental and climatic conditions in which that IAP is found. Therefore, these results/conclusions cannot be automatically generalised to a wider context but refer only to the conditions observed in Malta and only to species considered in this study.

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