Management in Practice

Lessons learnt from large-scale eradication of Australian swamp stonecrop *Crassula helmsii* in a protected Natura 2000 site

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Citation: van der Loop JMM, van de Loo M, de Vries W, van Veenhuisen LS, van Kleef HH, Leuven RSEW (2022) Lessons learnt from large-scale eradication of Australian swamp stonecrop *Crassula helmsii* in a protected Natura 2000 site. *Management of Biological Invasions* 13(1): 101–117, https://doi.org/10.3391/mbi.2022.13.1.06

Received: 3 June 2021
Accepted: 4 November 2021
Published: 23 December 2021

Thematic editor: Calum MacNeil

Abstract

The eradication of the aquatic invasive Australian swamp stonecrop *Crassula helmsii* in North-western Europe usually fails. This is especially true for areas where this plant species is abundant and wide spread or the probability of re-infestation is high due to hydrological connectivity with other infested surface waters or wetlands. Therefore, the large-scale eradication of this invader is often assumed not to be cost-effective. In 2018, *C. helmsii* was eradicated in a wetland of 4.5 ha covering interconnected humid dune valleys on the Wadden Island of Terschelling in the Netherlands. The total costs of this large-scale project were estimated to be 1.5 million euro. The applied method was excavation of infested locations and replenishing these areas with clean (uncontaminated by *C. helmsii)* sand to restore boundary conditions suitable for recovery of the treated habitats in this Natura 2000 site. An eight step approach was implemented to eradicate the invasive plant species. Aftercare consisted of a monitoring program with six-weekly vegetation surveys for early detection of any regrowth of *C. helmsii* and assessment of the effectiveness of the eradication measures. The eradication of *C. helmsii* was regarded successful since this fast growing plant species was not observed in the areas of concern during a period of at least two years. The results of a strength, weaknesses, opportunities and threads (SWOT) analysis revealed that the method for eradication of this invasive plant species was effective to secure nature values but also complex, time consuming and costly. Our lessons learnt and recommendations for management will help other nature managers making the right decisions in determining appropriate eradication measures for *C. helmsii*.

Key words: alien plant, amphibious weed, costs, effectiveness, elimination, non-native plant, Wadden Island

Introduction

The invasive Australian swamp stonecrop (*Crassula helmsii* (Kirk) Cockayne) is rapidly expanding in Northern Europe (OEPP/EPPO 2007; Scheers et al. 2020; Smith and Buckley 2020; Van der Loop et al. 2020a). Effectiveness of eradication measures for this aquatic weed is low (e.g. Dawson and Warman 1987; OEPP/EPPO 2007; Van der Loop et al. 2018;

Smith and Buckley 2020). An extensive review showed that only 10% of the reported measures yielded a successful eradication of the species (Van der Loop et al. 2018). Combined eradication measures are more effective than separate measures (8% and 14%, respectively) on the long term (> 1 year). Implementation and effectiveness of measures were often insufficiently documented and/or monitored (Van der Loop et al. 2018). This is also the case in studies on eradication of other invasive plant species (Van Wilgen 2012). Sharing of expert knowledge on management of biological invasions needs to be encouraged and implemented on a more regular basis, to improve the quality and predictability of outcomes from the management actions (e.g. Caffrey et al. 2014; Schmiedel et al. 2016; Sarat et al. 2017; Hussner et al. 2017).

This paper evaluates a large-scale project for eradication of *C. helmsii* in a Natura 2000 site on the Wadden Island of Terschelling (The Netherlands). In 2013, the species was first recorded during monitoring of a recently excavated area within a natural dune valley. It possibly originated from a former garden pond. In the past, this pond was an isolated water body. However, it became hydrologically connected to the study area due to excavation of the dune valley within an earlier nature restoration project. In 2016 an attempt was made to eradicate this invader by salinization of the area with sea water following the approach of Charlton et al. (2010). This method was insufficient due to several unforeseen factors, such as dilution by the influx of fresh water and the growth of *C. helmsii* in non-inundated areas (Van der Loop et al. 2018). After this, the small-scale and partial removal by excavators of the species did not prevent rapid regrowth, and the spread to nearby natural dune pools, located in the Natura 2000 site "Duinen van Terschelling". Plant fragments were left behind and native plant species became quickly overgrown by *C. helmsii*. A study on the effects of *C. helmsii* on the Natura 2000 site concluded that this invasive plant species posed a threat to the conservation goals imposed by the European Habitat Directive and eradication was required to prevent deterioration of vegetation with unique protected and endangered species (Van der Loop and Van Kleef 2017). It was reasonable to expect that the invader would spread to all freshwater systems on the Island of Terschelling and would also pose a serious threat to other freshwater ecosystems that are among others used for extraction and storage of fresh water. Terschelling is important for its nature values and inhabitants are largely dependent on nature-oriented tourism and livestock farming. *C. helmsii* poses a threat to tourism and farming because nature areas lose their attractiveness to visitors and water storage and discharge for agricultural purpose are reduced. In order to eliminate all these risks, a plan for large-scale eradication of the plant species was developed in the course of 2017 and 2018, with involvement of experts on ecology and management of biological invasions and the commitment of responsible authorities to organize

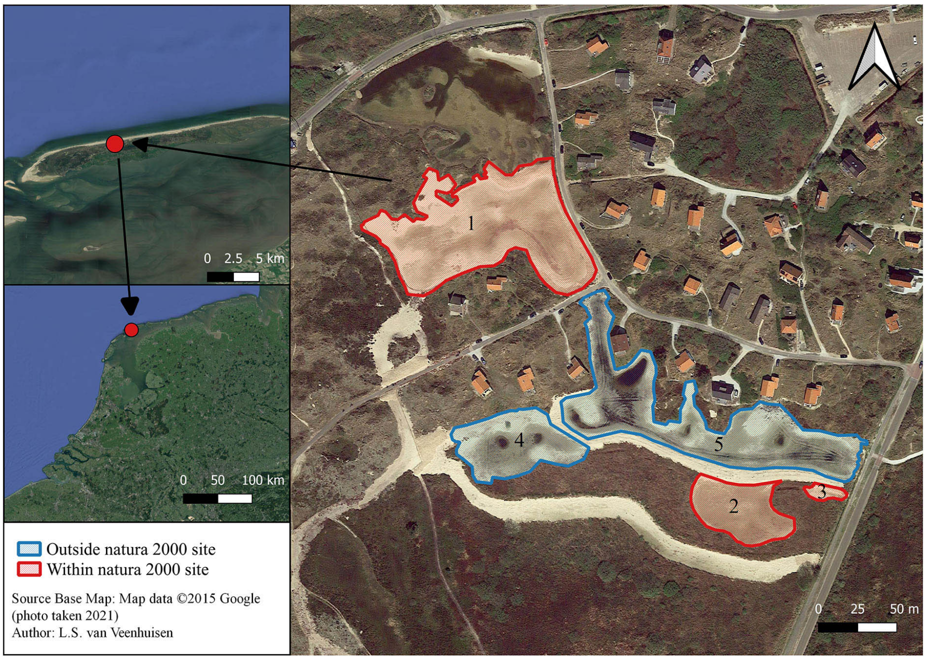

Figure 1. Locations of the dune slacks (1–5) where measures for eradication of *Crassula helmsii* were taken.

finances. This has resulted in large-scale project for eradication of *C. helmsii* in the winter of 2018–2019. The goal of this paper is to outline the approach and to assess the effectiveness of the large-scale eradication of *C. helmsii* on the Island of Terschelling. The effectiveness of measures against *C. helmsii* depends on site specific characteristics of the infestation and area of concern. A strength, weaknesses, opportunities and threads (SWOT) analysis has been performed to identify whether the eradication approach is applicable to other sites. The lessons learnt and opportunities for application of this approach in other infested areas will be discussed.

Materials and methods

Study area

Measures against *C. helmsii* were taken in five dune slacks (numbered as 1–5 in Figure 1) on the Island of Terschelling in The Netherlands (53°24′01.47″N; 5°16′57.22″O). The total area of this site is 4.5 ha. Part or the site is designated as Natura 2000 site according to the European Habitat and Bird Directives (Meijer et al. 2016). *Crassula helmsii* was present in the Habitat Type H2170 "Dune slacks marked with dominance of creeping willow (*Salix repens*)" and H2190A "Humid dune slacks (open water)". However, the main vegetation in this infected location was part of a pioneer *Littorellion* community with banks consisting of bare mineral soil or covered with *Phragmites australis* (Cav.) Trin. ex Steud. (1840).

In winter, the water stagnates in all water bodies as they have a water storage function and also receive run off of rain water in their catchment areas, inlet from other water bodies and groundwater seepage. To avoid damage of buildings in the neighbouring area, the maximum water level is artificially maintained at 3 m above average sea level. The excess of water runs off through a large wetland and artificial drainage system to the Wadden Sea. In summer, water levels are low and the water bodies are reduced to small puddles or even completely run dry. During high tide, the study area is an important resting site for waterfowl, such as goose, duck, wader and gull species. The dune slacks also form part of a large network of breeding sites of the endangered toad species *Epidalea calamita* (Laurenti, 1768). This toad and its habitat are protected under the European Habitat directive (Council of the European Communities 1992).

Based on visual detection of presence and abundance of *C. helmsii* during vegetation surveys in the period January–August 2018, the infestation of *C. helmsii* had a total cover of 1.78 ha and this surface area was measured using the program ArcGIS Map Service (39.55% of the area of concern). The invasive plant was most abundant on the banks of dune slack 4 and 5 (Figure 1). On the 28th of February 2017 a water sample was taken from one of the artificial ponds and the results of water quality analyses were compared with reference values for infected locations of the Netherlands (for methods see Supplementary material Appendix 1 Table S1). These data give insight in driving abiotic factors of the infestation (Van Kleef et al. 2017; Brouwer et al. 2017; Van der Loop et al. 2020b). Conditions favouring the invasiveness of *C. helmsii* on the infested sites of Terschelling are a high concentration of CO_2 in the water compartment, the presence of bare soils, fluctuation of water levels throughout the year and a disturbed ecosystem by former salinization and excavation measures (see for complete analysis Appendix 1).

Management measures

Planning and preparation

When the characteristics of the infestation were clear, an action plan was developed by a team of experts from different disciplines, e.g. ecologists, policymakers and engineers. Goals were: 1) eradication (100% removal) of *C. helmsii*, 2) restoring the ecosystem after taken measures, 3) ensuring that the function of water storage and draining remains intact, and, 4) creating awareness among local residents in surrounding areas of the infested water bodies and among islanders and tourists to prevent possible future introductions, and to assist with early detection of regrowth or new infestations of *C. helmsii*. The latter is important because the spread of this species often results from human introductions and "early detection and rapid response actions" against the species increase the effectiveness of the measures taken (e.g. Rejmánek and Pitcairn 2002; Simpson et al. 2009; Van der Loop et al. 2018; Reaser et al. 2020). Previous research has shown that the eradication of *C. helmsii* is only possible, and therefore justifiable, when establishment of the species is in an early stage, when the infestation is present

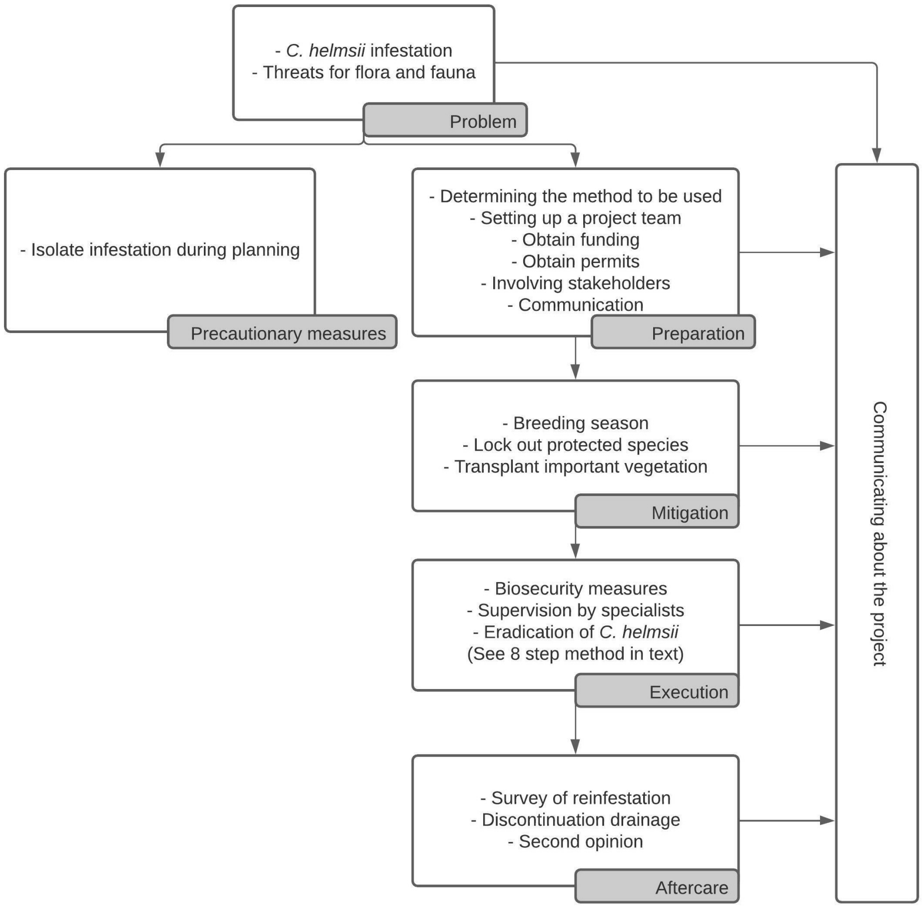

Figure 2. Flow chart of the process for large scale eradication of *Crassula helmsii* on the Island of Terschelling.

in isolated or isolatable, water systems, when the locations can be drained, and when chances of recontamination of the sites are low (Van der Loop et al. 2018). During planning all of these requirements were met, except for one. The establishment of the species was not in an early stage. *Crassula helmsii* had already been present on the island for more than 5 years and was found in an area of 1.78 ha. According to the knowledge of the authors, large-scale eradication of *C. helmsii* was only attempted with salinization at the time of the launch of the present project (Charlton et al. 2010).

Out of more than 50 known eradication methods for *C. helmsii* (Van der Loop et al. 2018), only two were considered for the study site: 1) Covering of the total waterbody (filling-up) with clean mineral sand, and 2) the excavation of soils with *C. helmsii* combined with refilling the excavated sites with clean sand. The first option will lead to successful eradication by the removal of suitable habitat for *C. helmsii*. However, in this area filling up of the wet areas will also disrupt the hydrology of the area and will lead to the permanent loss of a characteristic humid dune landscape and Natura 2000 habitat for protected and endangered species. Therefore, the only suitable method turned out to be excavation of the infested areas and refilling with clean soil. Figure 2 shows a summary of the process of the eradication and Table 1 summarises all key figures of this project.

Table 1. Key figures of the project for large scale eradication of *Crassula helmsii* on the Island of Terschelling.

Time	
Date of execution	September 2018
Duration (weeks)	14
Study area	
Infestation surface (ha)	1.78 ha
Total surface (ha)	4.51 ha
Drained water volume (m^3)	80,000
Soil movements in the infested area (m^3)	14,240 (1,100 truckloads)
Soil movements in the depot (m^3)	40,000
Materials	
Mitigation fence (km)	2.75
Construction fence (km)	2.10
Dewatering pumps (#)	8
Drainage pipes without filters (m)	1,100
Drainage pipes with filters (m)	800
Wellpoint filters for extracting groundwater below surface (#)	200
Waste water hoses (m)	1,500
Steel road plates (m)	4,000
Machines	
Crawler excavator 40 tons weight long reach (#)	3
Crawler excavator 35 tons weight long reach (#)	2
Wheel excavator 18 ton tons weight (#)	1
Lorries (#)	4
Labour (man hours)	
Planning	2,300
Mitigation	700
Execution	6,000
Supervision	2,500
After care	470
Total	11,970
Hired companies (#)	7
Finance (€)	
Planning costs	347,000
Mitigation costs	89,000
Supervision and control costs	198,000
Execution costs	874,000
Aftercare costs	45,000
Total costs	1,553,000

Because *C. helmsii* is capable of fast expansion, a quick start of the operation was necessary. This way, efforts, ecological effects and costs would be kept as low as possible. However, a quick response proved to be unfeasible for several reasons. One small fragment of *C. helmsii* can result in colonization and fast expansion of the plant species (Dawson and Warman 1987). Therefore, additional measures were necessary to avoid cross-contamination between infested and clean areas. To avoid spreading of *C. helmsii* a geotextile (mesh size < 0.1 mm) filter construction was designed and installed to obstruct plant fragments from superficial drainage water between dune slacks. The high regeneration capacity also makes combatting *C. helmsii* a precise operation. Developing a plan of action, without any experience on large-scale eradication of *C. helmsii* proved time consuming because of the need of drawing hygiene protocols and accurately instructing people executing the measures. The operation was carried out in a protected nature area and included the transportation of 54,324 m^3 soils and draining of 80,000 m^3 water (Table 1). This required legal permits and exemptions for performance of the work in a Natura 2000 site, and consultations of stakeholders and cooperation with several (non)governmental parties (e.g. owners of adjacent properties) about the upcoming disturbance of the area. A consultancy and engineering firm was involved to ensure that this process was carefully conducted.

Prior to the eradication, several mitigating measures were required to protect flora and fauna during the implementation process in accordance with European and national legislation (the Dutch Nature Conservation law) nature conservation as the area is designated as a Special Area of Conservation (SAC) and a bird directive area (Special Protection Areas, SPA), harbouring several Habitat Directive species (Meijer et al. 2016; European Commission 2021). The eradication was implemented outside the breeding season of birds and herpetofauna. In order to mitigate harm to amphibians (i.e. *E. calamita,* and *Lissotriton vulgaris* L. 1758) and a lizard species (*Zootoca vivipara* Jacquin, 1787), the area was completely fenced off with a plastic screen (2.75 linear km) to block entry of these animals (Figure 3A). Buckets were placed on 15 m intervals on the inside along the screen to trap these species in the project area. Trapped animals were released in suitable habitats at safe distance. Additionally lizards were lured using artificial shelter, in the form of tapestry tiles. Here they were caught and relocated to safe distance from the eradication site as well. *Viola tricolor* subsp. *curtisii* (E. Forst.), the host plant of multiple protected butterfly species (*Argynnis aglaja* L. 1758, *A. niobe* L. 1758, *Boloria selene* Denis and Schiffermüller, 1775, *Issoria lathonia* L. 1758), was transplanted outside the project area. During drainage of the dune slacks, several fish species, *Gasterosteus aculeatus* (L.), *Pungitius pungitius* (L.) and *Anguilla anguilla* (L.), were caught. The fish were kept in quarantine for five days to ensure that they could not spread attached or ingested fragments of *C. helmsii*, and subsequently released in other suitable habitats on the island.

Eradication approach

Implementation of the eradication plan started on 3 September 2018 and lasted for 14 weeks. A myriad of safety and biosecurity precautions were put in place to make the process of eradication successful. The work proceeded according to strict work protocols to prevent spread of plant fragments. The fenced work area could only be entered with vehicles that were not used outside the project area. Moreover, entry was only allowed with footwear that was only used in the infested area. Infested and already cleaned areas were clearly separated. The latter were accessible only with clean vehicles, footwear and equipment. In addition, all involved employees, from crane operator to management, followed a training on how to work in infested areas with *C. helmsii*, i.e. recognizing the species of concern and

Figure 3. Photo impressions of the large scale eradication of *Crassula helmsii* on the Island of Terschelling. A. The dominant infestation of *C. helmsii* in an artificial lake (location 5). B. Installing a mitigation fence in order to prevent entry by amphibians and reptiles (2.75 linear km). C. Drainage installation and steel road plates tracks. D. Excavation of 40 cm topsoil (Step 4 of the described eradication approach). E. Recolonization of characteristic native plant species in excavated area 2.5 years after the eradication of *C. helmsii* (March 2021). F. Guided tours in the study area to inform those concerned.

cleaning materials and footwear, and how to prevent spread of this weed. An ecologist specialised in invasive species management and nature legislation of Natura 2000 sites supervised the excavations to ensure complete removal of *C. helmsii* and enforcement of biosecurity measures. An 8 step approach for eradication of this species was developed.

1. Prior to the excavation, all waterbodies were drained using construction dewatering with below and above ground filters.
2. The area to be excavated was marked by an expert, trained in finding and recognising *C. helmsii*, using poles and warning ribbon. The infested area was marked including an additional buffer zone of five meters to reduce the risk of leaving plant fragments. The size of this buffer zone was determined pragmatically, with the additional costs and available budget playing a decisive role.
3. Steel roa plate tracks were installed to guarantee low impact of driving with heavy machinery for nature, to reduce the risk of machines sinking down in humid and filled in areas. Additionally they maintain visibility for hygienic working to prevent unintentional spread of *C. helmsii* by machines as well.
4. Excavators were used to remove 40 cm of the top soil including vegetation from the infested locations. This depth guarantees removal of all roots, shoots and plant fragments and potential released seeds of *C. helmsii* (Dawson and Warman 1987; D'hondt et al. 2016). Soils were excavated in three separate layers (15, 15 and 10 cm) in distinct working sequences using two different excavator buckets. The first layer contained all visible plants and top soil with *C. helmsii*' roots and was removed with a so-called "dirty" excavator bucket. After inspection and any necessary correction, consisting of additional removal of any incompletely excavated soil with vegetation, the bucket was manually cleaned with a brush and used for excavation of the second layer. In the final course a third layer was removed with the so-called "clean" excavator bucket (a second bucket) ensuring that any remaining undetected plant fragments were removed.
5. The excavated material was either directly placed into lorries for transport or placed on piles that were removed by another excavator. To avoid spilling soil with plant fragments on the steel road plates or non-infested areas, the excavation buckets were cleaned again. The transportation of the contaminated material took place in liquid-tight lorries, closed by valves. Before permission to drive, the outside of the dump-body, chassis and wheels of tipper lorries were always carefully checked for contamination. The contaminated soil was transported to a nearby dune valley and under supervision dumped into an area that had been dug for controlled storage of contaminated soil. The dumped material was covered with highly permeable geotextile and buried under a layer of dune sand of at least 1 m to prevent the potential spread of *C. helmsii* by wind.
6. Before refilling with clean dune sand, the excavated area was thoroughly inspected by the expert in *C. helmsii*. After any adjustments, a final survey was performed. This way, it was guaranteed that no fragments of *C. helmsii* remained in the area.

7. The excavated areas were refilled with clean dune sand. To restore the original profile and hydrology a crane model, used for the 3D control of machines, was developed on the basis of areal images (taken before the removal). Excavators were shaping the sand using a GPS. Covering the excavated parts provided additional security in the case any plant fragments were left behind and was required to avoid disturbing hydrology and habitat of the dune slacks and the surrounding dunes.
8. Stimulating succession of native vegetation to increase resilience of the ecosystems in case of a possible re-infestation of *C. helmsii*. Previous research has shown that the introduction of native plant species, a so-called ecosystem-oriented measure, increases the resilience of disturbed systems against invasions of alien species (Van Kleef et al. 2017; Van der Loop et al. 2020b). In this project, *Ammophila arenaria* (L.) Link (1827) was planted on higher banks and on lower parts vegetation clippings obtained from other humid dune pools were applied. Preventing dusty soils to blow away was an additional benefit of this measure.

Aftercare

Three months after the excavation and replenishment of soils, the drainage was terminated and the water naturally rose to the target level according to local water management agreements. During and after the eradication, the entire area has been surveyed every six weeks by invasive species experts to monitor vegetation succession and to detect any re-infestations of *C. helmsii.* With this frequency newly colonizing *C. helmsii* is rapidly detected during the early phases of plant re-growth and eradication measures can be limited (i.e. manual removal). Each survey required the efforts of two specialists during a full workweek (40 hrs per person; in total 80 hrs). It was visually determined whether the species was present or not. Focus was not only on treated areas but also on all waterbodies that were potentially suitable for colonization by *C. helmsii.*

Multiple measures to minimize probability of reintroduction of *C. helmsii* on the treated areas and other parts of the Island of Terschelling. Areas with suitable habitat for the plant species have been made inaccessible to recreational users and free roaming cattle by the placement of wired fences. Suitable habitats are frequently used by waterfowl which potentially reintroduce and contribute to spreading of *C. helmsii* (Denys et al. 2014). However, as birds are heavily protected they cannot be disturbed from their resting areas. Therefore no measures could be taken to account for this risk.

Additionally, a scientific staff member of the Dutch Food and Consumer Product Safety Authority (NWVA), charged with invasive species management, peer reviewed the project and gave a second opinion about the effectiveness of the eradication measures. In March 2020, it was concluded that the large-scale eradication at the three infested locations had been successfully carried out. *Crassula helmsii* had not been observed in the treated areas for two years. After these two years, we can conclude that the implementation has been successful because: 1) the seed bank has been excavated and all vegetation has been removed, 2) frequency of surveys is high (6 weekly), 3) regrowth of plant fragments (even under suboptimal conditions) becomes sufficiently visible within a few weeks, 4) no records of regrowth during more than one growing season therefore indicates with a high degree of certainty that all (fragments of) plants have been removed. During the planning phase, the plant was recorded, however, in three previously un-infested dune systems on the Island of Terschelling. Measures, in line with the ones described here, are currently taken to eradicate these infestations as well.

SWOT analysis by experts and stakeholders

The authors (N = 6) compiled a SWOT-analysis following Kotler et al. (1991) and Pickton and Wright (1998). All authors of this manuscript were involved in the execution of the large-scale eradication of *C. helmsii* on the Island of Terschelling (The Netherlands). This data was supplemented with data from stakeholders (N = 10) of this eradication project (Table S2). The stakeholders were anonymously asked to name their work field and give their views about the execution of the project. An interview resulted in their opinions about strengths, weaknesses, opportunities and threats of eradication approach. A search on 18 February 2021, using Google and Google Scholar, for newspaper articles and other media items appeared in the media, was carried out to compile information about the measures and peripheral matters of the large-scale eradication of *C. helmsii* on the Island of Terschelling. For each search query, the relevance of the first 30 hits was assessed. Tables S3 and S4 show the results of the search and selection process for suitable literature. In total 15 articles, all in Dutch, were obtained.

Results

The eradication of *C. helmsii* in two lakes and three moist dune slacks with a total area of 4.5 ha was successfully executed by an eight step approach and a duration of eight weeks. After two years *C. helmsii* was still absent at the project site. Unfortunately, *C. helmsii* has spread during the planning process via natural vectors (e.g. waterfowl) or (unintentional) human introductions to some other sites on the island.

The implementation of large-scale eradication measures caused ecological damage, i.e. the excavation, in the treated areas. In areas with *C. helmsii*, the native vegetation was removed and this measure initially created a distinct habitat for fauna species. However, as indicated earlier, the expectation was that the presence of *C. helmsii* would cause more damage to the vulnerable nature values and economics coming from tourism and livestock farming on the Island of Terschelling on the longer run (Karbet and Van der Loop 2017). About 2.5 years after the eradication measures, native vegetation was thriving again (Figure 3C), and amphibians (*E. calamita*) and several birds species were breeding in the treated areas (J. van der Loop *pers. observation*).

The implementation of large-scale measures on the Island of Terschelling, in the middle of a recreational area, also caused concern among residents, owners of holiday homes and tourists. Therefore, information signs were placed. Many meetings and guided tours were organized before, during and after the eradication to inform people about the objectives and the current state of affairs. In addition, the project received a lot of attention in the media, which was handled by a communications consultant.

A large-scale eradication, with an extensive planning process, high deployment of manpower and equipment, duration of 14 weeks and aftercare results in high financial costs. The cost for the planning, eradication measures and aftercare on an area of 4.5 ha with an infestation of 1.78 ha amounted approximately 1.5 million euro in total (resulting in 33.33 and 84.27 euros per m^2 for the area of concern and infested area, respectively).

The execution of this eradication project gained experience to combat *C. helmsii* at other sites with large scale infestations of this plant species. In the Netherlands, our approach has already been applied for eradication of other infestations on the Island of Terschelling and in dune systems of the Island of Texel.

SWOT-analysis

A variety of methods has been developed for eradication and control of *C. helmsii* and there is no single solution that is suitable for every situation (Van der Loop et al. 2018). The approach described in this study is evaluated by performing a SWOT-analysis (see for description and method Appendix 2), taking the findings of all involved stakeholders (N = 10) and scientists (N = 6), including statements by stakeholders brought via various media (N = 15). The results of the SWOT-analysis help to evaluate the applied method and can support to make the right decisions for eradication *C. helmsii* in other areas (Table 2).

Discussion

Lessons learnt and recommendations

The large scale eradication of the invasive plant species gained multiple experiences, lessons learnt and recommendations for replication in other cases of *C. helmsii* infestations (Table 3).

Table 2. Strengths, weaknesses, opportunities and threats (SWOT) analysis to identify issues of concern for replication of eradication measures in other areas (N indicates the number of individuals that brought forward a statement; N_{total} = 31). The top five statements per SWOT section are summarized. All other statements are included in the Table S5.

Internal	**External**
Strengths	Opportunities
Secure ecological values (flora and fauna, water storage, Natura 2000 objectives) (N = 20)	Gain experience for management of other infected areas (N = 17)
Successful eradication of *C. helmsii* (N = 15)	Tackle other *C. helmsii* infestations (N = 12)
Well-developed strategy available (N = 14)	Gain experience for combatting other invasive species (N = 9)
Multidisciplinary consulting leading to strong administrative decisions (N = 6)	Development of nature areas (N = 9)
Taking into account all other socio-economical values of the area (e.g. water storage, tourism and nuisance in residential area) (N = 6)	Prevent spreading to other areas (N = 8)
Weaknesses	Threats
High financial costs (N = 18)	Reintroduction of *C. helmsii* (via for example water fowl or visitors (N = 13)
Time consuming planning and execution (N = 15)	Rapid response (quick start of eradication) not possible (N = 12)
The need of permits and exemptions (N = 14)	Eradication fails (N = 11)
High administrating and planning load (N = 14)	Conditions for eradication are not met (N = 10)
Specific working method (N = 14)	Lack of cooperation between parties (N = 10)

Table 3. Lessons learned from the large scale eradication of *Crassula helmsii* on the Wadden Island Terschelling, coupled with appropriate recommendations.

Nr.	Lesson learnt	Recommendation
1.	There are only a few options of eradication measures. Selection of the most suitable measure depends on the characteristics of the infested areas (Van der Loop et al. 2018)	Conduct more research on cost-effective eradication (and population control) measures to eliminate treats and problems caused by *C. helmsii*. Describe and publish the results of these studies, even if they turned out to be unsuitable for eradicating the plant species, so other people can learn from these implementations
2.	The necessary rapid response against infestation is often not achievable because of a time consuming planning, long duration of procedures for environmental permits and exemptions, required mitigation measures and the need of extensive communication with stakeholders, among others	If possible, involve the right parties with experience in combating *C. helmsii*. Adopt (calamity-like) exemptions in nature legislation and avoid conflicting laws to save time for obtaining appropriate permits for eradication of invasive alien species in Natura 2000 sites. On the short run, eradication measures for invasive species may temporary affect native flora and fauna, however, on the long run these measures will contribute to biodiversity conservation
3.	Continuous commitment of involved authorities during the entire eradication process is important. Stopping the implementation in the middle of the process or not conducting the proper aftercare can lead to greater problems with *C. helmsii* than not implementing measures in the first place	Ensure the involvement of various parties in the project in advance. Discuss a priori the size of the project and risks of dropping out prematurely or not taking the work serious enough. Drafting a risk assessment for the entire project helps to provide insight into potential future problems. Keep people involved during the implementation and identify problems that could lead to the failure of an involved party in time
4.	Even with a thorough planning, it is possible that the project will have to be adapted to changing circumstances during implementation to ensure successful elimination	Initiate quick response actions during the execution. A proactive management, with a complete overview of all aspects of the project, is thereby important
5.	The media can contribute to raising awareness about *C. helmsii* and the importance of the measures taken. However, it can also lead to resistance to the project when the usefulness and necessity of the project are not shared by the public	Make communication very broad; make sure every stakeholder has sufficient opportunities to actively participate in the decision-making and make information accessible and focused on all public parties, i.e. residents, tourists, nature organisations, lay man and specialists. Be open to providing explanations and answering additional questions, but also ensure that this does not delay the project or modify the implementation in such a way that the effectiveness of the eradication is reduced
6.	The costs of the implementation are high. This can lead to postponement or even cancelation of eradication and may result in a high impact in the infested area as well as other nature areas when the species spreads	In addition to financial constraints, consider the absolute impact and costs of the invasive species as well. Include the loss of ecosystem services and the loss of tourism when attractiveness of the nature area is reduced by a dominance of *C. helmsii*. When doing so, bear in mind that when current problems are only local, and therefore harming only a small part of the total nature area, these infestations are still a source for spread to other nearby nature reserves and may eventually result in a greater loss at a larger spatial scale
7.	Aftercare monitoring requires a serious investment in manpower	Start training local experts and volunteers in recognising and carrying out small-scale aftercare measures for the species as soon as possible

SWOT analysis

Based on the results of the SWOT we concluded that securing ecological- and socio-economical values justify the large scale eradication of *C. helmsii* on Terschelling. A well-developed plan in which the costs and benefits have been assessed in advance, a thorough implementation with skilled people and frequently determining the effectiveness of the measures taken are vital success factors for large scale eradication of *C. helmsii*. A large majority of the respondents indicates the conservation of ecological values by eradication of the invasive species as strengths of the project. The eradication approach is recognized as well thought out and involving many peripheral matters. However, the process to eradicate the species by this method is very specific, and requires specialists for i.e. administration, communication and the obtainments of the right legal paperwork, and is therefore time consuming and costly. This has to be taken into account when replicating this method on other infested areas. Despite many threats, of which the one with the highest risk is eradication failure, we think the project contributed to gaining experience for combating and managing this invasive species in other areas and if the conditions are right we would repeat the process to eradicate *C. helmsii* in other infected areas. Especially because the eradication turned out to come with other positive side effects on the dune systems, i.e. rejuvenation and reduction of nutrients and organic material in the top layer.

Preconditions for successful eradication

When planning the complete removal *C. helmsii* from a location, it is important to consider in advance whether eradication of the species at a specific location is technically feasible and cost-effective. If potential dispersal vectors cannot be ruled out and fast resettlement of the species is expected, eradication measures will not be effective on the short or long run. Thus it may be best to choose alternatives, such as population control of the invasive species to mitigate significant impacts and to prevent spread to neighbouring areas (Van der Loop et al. 2018). However, the approach described in this paper proves that *C. helmsii* can be completely mechanically removed from large-scale infested locations. The success of such a major task depends on sound planning and execution, aftercare, thorough administrative decision-making, cooperation of all involved parties, public support and sufficient financial resources.

Rapid response

Taking rapid response actions, which is important for effective eradication of invasive species at low cost, proved impossible because of conflicting legislation protecting the Natura 2000 site and species within this area. These conflicts are the result of rules concerning the prevention of disturbance of the area and on the other hand the need of combating invasive species resulting in a disturbance of the area. Although it was obvious that a rapid response was required, the project preparation with planning and administrative processes took over one and a half year, resulting in bigger infestations in both surface area and biomass. Drawing a plan of action, the process of obtaining environmental permits and exemptions, and obtaining agreement within the project team, took about one year in total. Obtaining legal permission after application alone was a procedure of half a year. Meanwhile, *C. helmsii* increased in biomass and spread to other areas. This case study is illustrative for the importance of accelerating legal (environmental) procedures when combatting an invasive alien species in order to protect endangered biodiversity and ecosystems.

Controversies

Several outsiders, directly to the project group or via media, have criticized the eradication by putting forward arguments regarding, for instance, benefits and necessity of the eradication, high impacts on the ecosystem and high financial costs. This led to political upheaval. In the local council and national parliamentary, questions were posed about the project and responsibilities for invasive alien species management. For many alien species, it is unclear or uncertain to what extend they harm ecosystems and economics (Simberloff 2013). However, in our case it was clear to policy makers and nature managers of the Natura 2000 site that *C. helmsii* posed a significant threat to both biodiversity and functioning of the dune ecosystem, and eradication was necessary. Those interested and opposed were invited to join public excursions and information meetings. In most cases, the in-depth explanations led to adjustments of their opinion on the contribution of the project to achieving conservation goals of the Natura 2000 site.

Conclusion

The large-scale eradication of *C. helmsii* in the five dune slacks on the Island of Terschelling was successful. Our approach included planning, execution and aftercare. The eight-step method can be replicated in other areas after adaptation to site-specific preconditions. Planning, fund raising, acquiring environmental permits and communication with stakeholders were time consuming and resulted in delay of the rapid eradication actions and expansion of the infestation. A faster process of legal permission is necessary to prevent the invasion problems from getting worse and to prevent spread to other areas. Evaluation of the project with a SWOT–analysis shows that our eradication approach secured the natural values of the area but the process is complex with a long duration and high expenses. The main threat when performing this approach is a failure of the eradication, but even in such a case, thorough evaluation of failure and success factors provides knowledge and experience to combat and manage this invasive species. Our lessons learnt and recommendations can support decision making for other infested areas.

Acknowledgements

The eradication measures were financially supported by the European Third Rural Development Programme (POP3) grant 1696520, the Province of Friesland, Staatsbosbeheer, the Municipality of Terschelling and the Waterboard of Friesland. Furthermore, we are grateful to nature managers of the Natura 2000 site "Duinen van Terschelling" for cooperation during execution of these measures. The authors would like to thank Jelle Bijlsma Gytsjerk and the staff of Radboud University (Nijmegen), Stichting Bargerveen (Nijmegen), Soontiëns Ecology (Eindhoven), TAUW (Assen), TripHek (Terschelling) and Van Tongeren (Apeldoorn) for their advices and technical assistance during the implementation of management measures. We thank Femke Soontiëns, the thematic editor Dr. C. MacNeil and two anonymous reviewers for their constructive comments on the manuscript.

References

Brouwer E, Denys L, Lucassen ECHET, Buiks M, Onkelinx T (2017) Competitive strength of Australian swamp stonecrop (*Crassula helmsii*) invading moorland pools. *Aquatic Invasions* 12: 321–331, https://doi.org/10.3391/ai.2017.12.3.06

Caffrey JM, Baars JR, Barbour JH, Boets P, Boon P, Davenport K, Dick JTA, Early J, Edsman L, Gallagher C, Gross J, Heinimaa P, Horrill C, Hudin S, Hulme PE, Hynes S, MacIsaac HJ, McLoone P, Millane M, Moen TL, Moore N, Newman J, O'Conchuir R, O'Farrell M, O'Flynn C, Oidtmann B, Renals T, Ricciardi A, Roy H, Shaw R, van Valkenburg JLCH, Weyl O, Williams F, Frances E. Lucy FE (2014) Tackling invasive alien species in Europe: The top 20 issues. *Management of Biological Invasions* 5: 1–20, https://doi.org/10.3391/mbi.2014.5.1.01

Council of the European Communities (1992) Council directive 92 /43 /EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Communities* L206: 7–50

Charlton PE, Gurney M, Lyons G (2010) Large-scale eradication of New Zealand pygmy weed *Crassula helmsii* from grazing marsh by inundation with seawater, Old Hall Marshes RSPB reserve, Essex, England. *Conservation Evidence* 7: 130–133

Dawson F, Warman E (1987) *Crassula helmsii* (T. Kirk) Cockayne: is it an aggressive alien aquatic plant in Britain? *Biological Conservation* 42: 247–272, https://doi.org/10.1016/0006-3207(87)90071-1

Denys L, Packet J, Jambon W, Scheers K (2014) Dispersal of the non-native invasive species *Crassula helmsii* (Crassulaceae) may involve seeds and endozoochorous transport by birds, *New Journal of Botany* 4: 104–106, https://doi.org/10.1179/2042349714Y.0000000046

D'hondt B, Denys L, Jambon W, De Wilde R, Adriaens T, Packet J, van Valkenburg J (2016) Reproduction of *Crassula helmsii* by seed in western Europe. *Aquatic Invasions* 11: 125–130, https://doi.org/10.3391/ai.2016.11.2.02

European Commission (2021) The Habitat Directive. https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm (accessed 13 September 2021)

Hussner A, Stiers I, Verhofstad M, Bakker E, Grutters B, Haury J, van Valkenburg J, Brundu G, Newman J, Clayton J (2017) Management and control methods of invasive alien freshwater aquatic plants: A review. *Aquatic Botany* 136: 112–137, https://doi.org/10.1016/j.aquabot.2016.08.002

Karbet J, van der Loop JMM (2017) Watercrassula Terschelling; Scenariostudie bestrijding Watercrassula Terschelling. Report R001-1260302KBJ-rrt-V01. TAUW, Assen [In Dutch]

Kotler P, Saliba S, Wrenn B (1991) Marketing management: Analysis, planning, and control: Instructor's Manual. 4th edition. Prentice-Hall, Mishawaka, 165 pp

Meijer J, Vriens G, Lammerts EJ (2016) Natura 2000-ontwerpbeheerplan Terschelling (4). Ministerie van Economische Zaken Directie Natuur and Biodiversiteit, Den Haag [In Dutch]

OEPP/EPPO (2007) Data sheets on quarantine pests. *Crassula helmsii*. *EPPO European and mediterranean Plant Protection Organization* 37: 225–229, https://doi.org/10.1111/j.1365-2338.2007.01111.x

Pickton DW, Wright S (1998) What's swot in strategic analysis? *Strategic Change* 7: 101–109, https://doi.org/10.1002/(SICI)1099-1697(199803/04)7:2<101::AID-JSC332>3.0.CO;2-6

Reaser JK, Burgiel SW, Kirkey J, Brantley KA, Veatch SD, Burgos-Rodríguez J (2020) The early detection of and rapid response (EDRR) to invasive species: a conceptual framework and federal capacities assessment. *Biological Invasions* 22: 1–19, https://doi.org/10.1007/s10530-019-02156-w

Rejmánek M, Pitcairn MJ (2002) When is eradication of exotic plants a realistic goal? In: Veitch CR, Clout MN (eds), Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, IUCN [World Conservation Union], Gland Switzerland, and Cambridge, pp 249–253

Sarat E, Dutartre A, Soubeyran Y, Poulet N (2017) A French working group on biological invasions in aquatic environments: Towards an improvement of knowledge and management of freshwater invasive alien species. *Management of Biological Invasions* 8: 415–424, https://doi.org/10.3391/mbi.2017.8.3.15

Scheers K, Denys L, Packet J, De Knijf G, Smeekens V, Leyssen A, Adriaens T (2020) Leidraad voor het beheer van watercrassula - *Crassula helmsii* - in Vlaanderen. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2020 (32). Instituut voor Natuur- en Bosonderzoek, Brussel [in Dutch], https://doi.org/10.21436/inbor.18650299

Schmiedel D, Wilhelm EG, Roth M, Scheibner C, Nehring S, Winter S (2016) Evaluation system for management measures of invasive alien species. *Biodiversity and Conservation* 25: 357–374, https://doi.org/10.1007/s10531-016-1054-5

Simberloff D (2013) Invasive Species. What Everyone Needs to Know. Oxford University Press, 352 pp, https://doi.org/10.1093/wentk/9780199922017.001.0001

Simpson A, Jarnevich C, Madsen J, Westbrooks R, Fournier C, Mehrhoff L, Browne M, Graham J, Sellers E (2009) Invasive species information networks: collaboration at multiple scales for prevention, early detection, and rapid response to invasive alien species. *Biodiversity* 10: 5–13, https://doi.org/10.1080/14888386.2009.9712839

Smith T, Buckley P (2020) Biological Flora of the British Isles: *Crassula helmsii*. *Journal of Ecology* 108: 797–813, https://doi.org/10.1111/1365-2745.13336

Van der Loop JMM, de Hoop L, van Kleef HH, Leuven RSEW (2018) Effectiveness of eradication measures for the invasive Australian swamp stonecrop *Crassula helmsii*. *Management of Biological Invasions* 9: 343–355, https://doi.org/10.3391/mbi.2018.9.3.16

Van der Loop JMM, Beringen R, Leuven RSEW, van Valkenburg JLCH, van Kleef HH, Verhofstad M, Odé B (2020a) Risk assessment of Australian swamp stonecrop (*Crassula helmsii*) in Europe. https://english.nvwa.nl/documents/plant/plant-health/pest-risk-analysis/documents/risk-assessment-australian-swamp-stonecrop

Van der Loop JMM, Tjampens J, Vogels JJ, Van Kleef HH, Lamers LP, Leuven RSEW (2020b) Reducing nutrient availability and enhancing biotic resistance limits settlement and growth of the invasive Australian swamp stonecrop (*Crassula helmsii*). *Biological Invasions* 22: 3391–402, https://doi.org/10.1007/s10530-020-02327-0

Van der Loop JMM, Van Kleef HH (2017) Watercrassula problematiek Terschelling. Inventarisatie huidige besmetting en nodige vervolgstappen. Stichting Bargerveen, Nijmegen, The Netherlands [In Dutch]

Van Kleef HH, Brouwer E, Van der Loop JMM, Buiks M, Lucassen ECHET (2017) Systeemgerichte bestrijding van watercrassula. Stichting Bargerveen, Nijmegen, The Netherlands [In Dutch]

Van Wilgen BW, Forsyth GG, Le Maitre DC, Wannenburgh A, Kotzé JD, Van den Berg E, Henderson L (2012) An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. *Biological Conservation* 148: 28–38, https://doi.org/10.1016/j.biocon.2011.12.035

Supplementary material

The following supplementary material is available for this article:

Appendix 1. Method chemical analysis.

Table S1. Chemical properties of surface water of the artificial lake in comparison with concentrations of other infested areas.

Appendix 2. Method for strengths, weaknesses, opportunities and threats (SWOT) analysis.

Table S2. Data of expert judgement and anonymous stakeholders.

Appendix 3. Data search of media items.

Table S3. Data search media performed on 18 February 2021.

Table S4. Added data to the SWOT-analysis data obtained from media.

Table S5. Total SWOT-analysis to identify issues of concern for replication of eradication measures in other areas.

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