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Asphodelus fistulous L., a newly discovered plant invader in South Africa: Assessing the risk of invasion and potential for eradication

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Background: Naturalised populations of *Asphodelus fistulosus* (onion weed) were recorded in South Africa for the first time during the early 1990s. Initial records lodged in 2012 indicated the presence of two populations. Five additional populations were found between 2012 and 2016, as a result of surveys and the distribution of awareness materials. All populations in South Africa occurred along roadsides, but in other parts of the world the species has demonstrated the ability to spread into adjacent native vegetation and crop fields.

Objectives: The aim of this study was to assess the risk of invasion and potential for eradication.

Method: A risk assessment tool was used to establish invasion risk. Of the seven known populations, five test populations were selected to gather data on the feasibility for eradication. Randomised fixed plots were used to monitor the response of *A. fistulosus* populations to mechanical and chemical plant control methods and to track spread over time. The germinability of seeds was also tested.

Results: The Standard Australian Risk Assessment method for invasive alien plants gave a relatively high score for the threat posed by this species. In this assessment, a threshold score is used to indicate sufficient invasive risk to fail a species as part of a preborder risk assessment. Invasiveness elsewhere (Australia and USA) contributed to the relatively high score. The bioclimatic modelling map highlighted the south-western region of South Africa as most suitable climatically for *A. fistulosus*. Both mechanical and chemical control methods were shown to be effective in killing live plants. Results, based on plant removal and monitoring, over a four-year research period suggest that suppression of reproduction is possible, partly as a result of high detectability and ease of control.

Conclusion: It is recommended that *A. fistulosus* be listed as a *National Environmental Management: Biodiversity Act* 10 of 2004 1a invasive species (eradication target) under national legislation, thus requiring compulsory management. We estimate that extirpation of all known populations of *A. fistulosus* may be possible with continual effort at an annual investment of approximately ZAR 50 000 per year. Further surveillance for undiscovered populations and monitoring of known populations must be conducted to produce a definitive comment about the feasibility of countrywide eradication.

Keywords: *Asphodelus fistulosus;* biological invasion; early detection; eradication; extirpation; invasive alien plants; invasion potential.

Introduction

Globally, invasive species cause significant environmental problems where incursions impact on biodiversity, economies and human health (Pyšek & Richardson 2010; Wallace & Bargeron 2014). Following preborder prevention of entry of potentially invasive species, early detection and eradication is the most cost-effective management option as compared to containment or long-term management (Fitzpatric et al. 2009; Rejmánek & Pitcairn 2002).

South Africa has a long track record of managing invasive alien plants (Macdonald 2004; Richardson & Van Wilgen 2004; Zimmermann, Moran & Hoffmann 2004). More recently a national programme dedicated to biosecurity and the detection, assessment and control of invasive introductions was established (Wilson et al. 2013). When invasive alien species are discovered and their taxonomic identification affirmed, establishing the level of risk (Rejmánek & Pitcairn 2002) and eradication feasibility (Panetta 2015) are essential steps towards informing future management actions. In South Africa, to date, the focus of scientific and management expertise has traditionally been on woody and succulent invasive plant species and aquatic weeds (Richardson & Rejmánek 2011; Richardson & Van Wilgen 2004), with less emphasis on understanding the invasive character and management options for herbaceous plants. This paper addresses this knowledge gap and contributes to an understanding of the risk associated with the grass-like herb *Asphodelus fistulosus* and the feasibility of control of this recently discovered non-native species in South Africa.

Asphodelus fistulosus is currently not listed under the *National Environmental Management: Biodiversity Act* (no. 10 of 2004), and its invasive status and eradication feasibility should be assessed. The focus of this study was directed by the lack of published guidelines to support the understanding of potential impacts of *A. fistulosus* and limited available guidance about its practical management. In this paper, we aim to (1) describe the potential of *A. fistulosus* to become a potentially harmful invader if left unmanaged; (2) assess feasibility of extirpation (i.e. local eradication) and (3) to comment on the policy and management implications of eradication potential of the target species at a national scale.

Species description

Asphodelus fistulosus L. is an annual or short-lived perennial grass-like herb native to the Mediterranean region and Macronesia (Días Lifante & Valdés 1996). The plant can grow up to 0.8 m in height and has yellow, fibrous roots (Figure 1a). Plants bear conspicuous flowers that are white to pink with brown midribs, spreading but suberect and weakly clawed in the basal area (Figure 1b). Flowering occurs during winter and spring (June to October in South Africa and December to June in its native range). A full botanical description of *A. fistulosus* is provided by Boatwright (2012). It is uncertain how and when the species was introduced into South Africa, but it is thought to have arrived via contaminated crop seeds or hay (Boatwright 2012). The main method of dispersal appears to be by seeds (Figure 1c), which may be moved around by animals, water and along roadsides by vehicles (Figure 1d) and other human activities (Boatwright 2012). *Asphodelus fistulosus* has become widely naturalised in Australia, New Zealand and Mexico, as well as in some of the more arid states of the USA such as Arizona and California (Patterson 1996; Randall 2007; Russel 2008).

Initial discovery of the species in South Africa

The species was first formally noted near the town of Velddrif, along the West Coast of South Africa, in the early 1990s during a botanical survey (Boatwright 2012). In 2011, a second population was discovered further inland, near the town of Hopefield (Boatwright 2012). To date, seven populations have been recorded, all in the Western Cape province.

The existence of known populations of *A. fistulosus* was brought to the attention of the South African National Biodiversity Institute (SANBI) in 2012 (Boatwright 2012). Since 2008 SANBI has conducted a programme responsible for the assessment and control of invasive alien species that are not yet widespread but that are considered to pose a high risk of becoming invasive (Wilson et al. 2013).

Materials and methods

Invasion risk of *Asphodelus fistulosus*

Risk assessment

The Australian Weed Risk Assessment Protocol has been modified to suit other contexts, in which it has consistently proven to be accurate and is able to identify 90% of major invaders and 70% of non-invasive species (Gordon & Gantz 2008). A score of more than six indicates sufficient invasive risk to fail a species as part of a preborder risk assessment (Pheloung, Williams & Halloy 1999). The modified Australian Weed Risk Assessment Protocol (Pheloung et al. 1999) was used to assess the potential invasion risk of *A. fistulosus* and to collate relevant literature on the species' invasive characteristics. This method was designed to establish species risk prior to prospective introduction into a country; however, it can also be usefully applied to species that have entered the country and are in the early stages of establishment (e.g. Hickley et al. 2017; Zenni et al. 2009). In this study, the guidelines for application outside Australia as outlined by Gordon et al. (2010) were followed. A bioclimatic model was developed and used to answer risk assessment questions that relate to biogeography and potential invasive range in South Africa.

Species distribution and bioclimatic modelling

The potential distribution of *A. fistulosus* in South Africa was generated using two different presence-only data bioclimatic models: Bioclim (Busby 1991) and Domain (Carpenter et al. 1993). Predicting potential invasive species' distributions using presence-only data is a valid alternative when species absence data are unavailable. The use of false absences can compromise the model's reliability and possibly underestimate the complete potential invasion area (Araujo & New 2007; Jimenez-Valverde et al. 2011). The two presence-only models were fitted using the presence records from the species' native range and presence records from places where the species has been introduced. Fitting the model using all the available presence records for this species (from its native and introduced range) will provide to the model a wider range of potential suitable climatic conditions for the species. Presence records of *A. fistulosus* were gathered from the Global Biodiversity Information Facility database (GBIF 2015). As explanatory variables, we used the 19 climatic variables (30-s resolution; the variables were rescaled to a 1-min resolution) provided by the WorldClim website (Hijmans et al. 2005). Prior to analysis, all records were checked and only records with a precision of at least 1 km were included. To avoid pseudo-replication, only one record per 1 min grid cell was used for model calibration (4800 records, which includes the seven records from South Africa, were used). Environmental data for all occurrence records were extracted from the 19 bioclimatic variables. The climatic variables were first analysed using principal component

FIGURE 1: *Asphodelus fistulosus* invasion in the Western Cape of South Africa: (a) yellow fibrous roots, (b) white to pink flowers with brown midrib, (c) seeds from multiple pods and (d) plants spreading along the roadside.

analysis and the first five orthogonal axes (principal components; cumulative explained variance = 93%) were used as environmental predictors of species occurrence. Principal component analysis allows reduction of the number of variables into fewer uncorrelated dimensions while still retaining most of the variation in the initial data (King & Jackson 1999). Each model was projected onto the South African environmental space and one distribution map was generated by averaging the predicted output maps from the two models.

Eradication feasibility

Delimitation surveys

Efforts were made to discover new *A. fistulosus* populations through active surveillance (i.e. roadside surveys) and passive surveillance (i.e. distribution of information pamphlets requesting an alert if the species is detected).

Active surveillance: Roadside surveys are effective and efficient ways to discover new populations of species that are limited to roadsides (Maxwell et al. 2012). We employed this method by driving at 40 km/h (Milton & Dean 1998), carefully looking for *A. fistulosus* plants on both sides of the road, covering all roads within a radius of 20 km from the known populations. This surveillance method was employed twice during a growth season, during spring and autumn when species detectability is highest, between the spring of 2013 and autumn of 2016. This method was used because all known *A. fistulosus* populations in South Africa are confined to roadsides (Figure 1d).

Passive surveillance: Approximately 400 pamphlets describing the plant and its potential threat were developed and distributed, requesting sightings of the plant to be reported to SANBI (see Online Appendix 1). Initially, all known populations were located within the Velddrif municipal area along the West Coast of South Africa. Therefore the pamphlets were distributed to Velddrif municipality staff, to local residents through the Velddrif library and to the wider West Coast community via pamphlet distribution at the Darling Flower Show and West Coast Biosphere Reserve staff, between 2013 and 2016.

Plant removal methods

Both mechanical and chemical approaches were used in order to explore the effectiveness of each plant control method. There is no registered herbicide for *A. fistulosus* in South Africa and so no official guidance exists around the herbicidal control of the species in the country. The choice of herbicide for use on *A. fistulosus* in this study was based on expert advice (Dr Graham Harding, pers. comm. Plant Invader Specialists), as well as records of successful plant control carried out in Australia (Moore & Wheeler 2008). The largest population of *A. fistulosus*, which initially occupied 4860 m^2 (2095 plants estimated), was selected for foliar herbicide application. The first application used at a rate of 60 g/ha metsulfuron herbicide and water mix, dispensed using a 42 L knapsack with a spray nozzle. To date, four follow-up foliar sprays of metsulfuron have been applied to this population during the growth season, once in spring and once in autumn immediately following data collection. All other smaller (by area) test populations were manually controlled, either by hand-pulling or digging out plants using small spades. All plants were removed twice a year in spring (always before seed set in any given year) and with a follow-up in autumn. Removed plants were bagged and incinerated. Plant control measures always immediately followed data collection.

Population monitoring

An exploratory phase of the study was conducted between September 2012 and December 2013 to debate and establish the best method for monitoring populations of the target species. During this phase, basic estimates of population extent and density were made to describe the initial status of the five test populations. In all known *A. fistulosus* populations, plants were distributed across both sides of the road, but it was decided to sample only the road side that had the highest density of plants because of limited resources and time and in order to attain more conservative results. Conservative results guard against a potentially premature conclusion that success in population suppression has been achieved. Data were collected from the side of the road with the densest population, but both sides of the road were chemically or manually removed.

From March 2014 to September 2016, randomised fixed plots of 0.5 m × 0.5 m were positioned parallel to the road edge, where the number of plots varied according to population size. The data collected within each plot were used to describe and monitor the recovery of *A. fistulosus* for the five test populations along the West Coast. This method was selected because all known *A. fistulosus* populations were confined to the edge of the road and grew linearly along the edge of the road. Routine monitoring was instated and repeated every spring and autumn because plants are most detectable during these times. Random fixed plots were established, spanning the whole of each test population, ensuring that plots were positioned through dense and less dense areas and also covering the tail ends of the population where fewer to no plants were observed (e.g. Arévalo et al. 2010; Lembrechts, Milbau & Nijs 2014). Starting from the tarmac edge of the road, the plots were positioned perpendicularly from the road edge at 50 cm, 150 cm and 200 cm. Descriptive data were gathered for all plants in the fixed plots (i.e. we recorded the number of plants, number of flower stalks, flower stalk height, foliage height, foliage widths and whether the plant had fruits and/or flowers). The number of plants with reproductive structures is a proxy for population reproductive potential. The inverse – reduced reproductive potential – can be interpreted as a contributor to suppressed invasive potential. Plants that were found inside the fixed plots and plants that grew outside the fixed plots were dug out and carefully bagged during every monitoring visit to each population. Subsequent searches were made on the other side of the road, and all plants found were also dug out or treated with herbicide. All bagged plants were later incinerated outside the study area following a strict protocol.

Examination of the soil seed bank

Plant species with small or short-lived seed banks are better candidates for eradication than those with large and/or long-lived soil seed banks (Simberloff 2003). In order to estimate the size of the seed bank of *A. fistulosus* over time, soil samples were collected annually between 2015 and 2016 during autumn after plants had had a chance to set seed, from each of the thirty-four 50 cm × 50 cm quadrats during randomised sampling for the largest and most dense population (i.e. at Carinus Bridge). In addition, during a trial experiment in 2013, to establish the best approach to data collection, 30 soil samples were collected from the densest area of the Carinus Bridge population, as well as 30 soil samples 3 m away from the densest area and at a right angle to the linear road. During the autumn of 2015 and the autumn of 2016, soil sampling always followed the routine descriptive plant data gathering for each plot, as described in the population monitoring section. This soil core collection procedure involved a short rod (i.e. 20 cm long) being dropped in the middle of each half meter square and a soil sample being collected from where the end of the rod fell within the square. Soil samples were taken using a soil corer with a radius of 3.6 cm to a depth of 15 cm. The collection of soil cores was facilitated by the deep sandy soils of this area.

Soil samples were dried indoors at ambient temperature. The seeds were manually separated from the soil through sieving using a 1 mm mesh. The seeds are 3 mm in length, tear-shaped and easily distinguishable from the light-coloured sandy soil (Figure 1c). The seeds were counted and retained for incineration. The soil was returned to the site. The number of seeds found per sample of soil was used to estimate the size of the soil seed bank, expressed as the number of seeds per square meter to a depth of 15 cm.

Seed germinability

Two sets of *A. fistulosus* seeds were used to test seed germinability. The first set of 80 seeds was sourced from the soil (below ground) and was therefore of indeterminate age, and the second set of 80 seeds comprised ripe seeds (i.e. from open seed capsules) from the standing plants (above ground) collected at the Carinus Bridge population in October 2013. Both sets of seeds were used to test the proportion of seeds that would germinate under controlled laboratory conditions during 2014. This was done to investigate what proportion of the seeds is likely to germinate during spring. We assumed that seed germinability in the Carinus Bridge population might be representative of at least the *A. fistulosus* populations occurring along the West Coast.

Seeds were treated with an antifungal agent prior to germination trials. Treated seeds were placed over four caps of filter paper, in 8.5-cm diameter plastic Petri dishes (20 seeds in each Petri dish) (Perez-Garcia 1997; Thanos et al. 1992). Petri dishes were placed in a walk-in growth chamber under a temperature of 20°C with a 10-h day, 14-h night regime, which has been shown to be suitable for plants with Mediterranean origin (Valbuena et al. 1992). Two temperature and humidity loggers (i.e. iButtons) were placed in the chamber to affirm the chosen temperature and humidity regime. Seeds were kept moist by adding 3 mL – 4 mL distilled water per Petri dish, every two to three days for the duration of germination trial. Germination rate over time was recorded, by checking the Petri dishes every two days. Germinated seeds were counted and removed from the plastic Petri dishes. Trials continued for a period of two weeks, at which time all seeds had germinated.

Results

Invasion risk of *Asphodelus fistulosus*

Risk assessment

Asphodelus fistulosus scored 27 points out of a maximum of 50 on the Australian Weed Risk Assessment (Online Appendix 2). Using the literature and the bioclimatic model produced as part of this study, 40 out of the 42 questions in the risk assessment were answered. The score obtained for *A. fistulosus* comprised 15 points for bioclimatic suitability, 3 points for the undesirable attributes and 9 points for aspects of the biology or ecology of the species, respectively. This high score (27) (i.e. more than 6) means that *A. fistulosus* would be rejected in a preborder assessment.

Bioclimatic distribution modelling

The potential distribution of an invasive alien species reflects the risk of establishment and further invasion. The bioclimatic modelling map shows the south-western region of South Africa to be climatically most suitable for *A. fistulosus*. This includes the western part of the Eastern Cape, the Western Cape and the south-western part of the Northern Cape (Figure 2).

Eradication feasibility

Delimitation surveys

At the beginning of this study, two populations were known (Boatwright 2012). Five additional previously unrecorded populations of *A. fistulosus* were discovered through this study. Three of these new populations were discovered by a naturalist photographer who became aware of *A. fistulosus* through the flyer distributed to the Velddrif municipality. The fourth (S33 13.028; E18 12.193) new population was discovered by SANBI staff during road surveys south of Velddrif. One false record was lodged, which was identified to be the indigenous *Trachyandra divaricata*, similar in appearance to *A. fistulosus*. A fifth new population of *A. fistulosus* was most recently discovered near Caledon by a SANBI staff member. In summary, there are seven known populations. Six populations of *A. fistulosus* occur in deep sandy soils along disturbed roadsides between the towns of Langebaan, Vredenburg, Hopefield, Malmesbury and Velddrif on the West Coast of South Africa, while the seventh, the Caledon roadside population (34.210718, 19.342797), occurs in the Western Rûens Shale Renosterveld vegetation type (Figure 3). All known populations occur within the high invasion risk areas of South Africa (see Figure 2).

Population status, extent, density and phenology of *Asphodelus fistulosus*

Of the seven known populations, five populations were selected as test populations where baseline information was collected (Table 1). The size and density of each population are presented (Table 1).

Based on our knowledge of the species, our expectation was that *A. fistulosus* would respond strongly to rainfall, with a

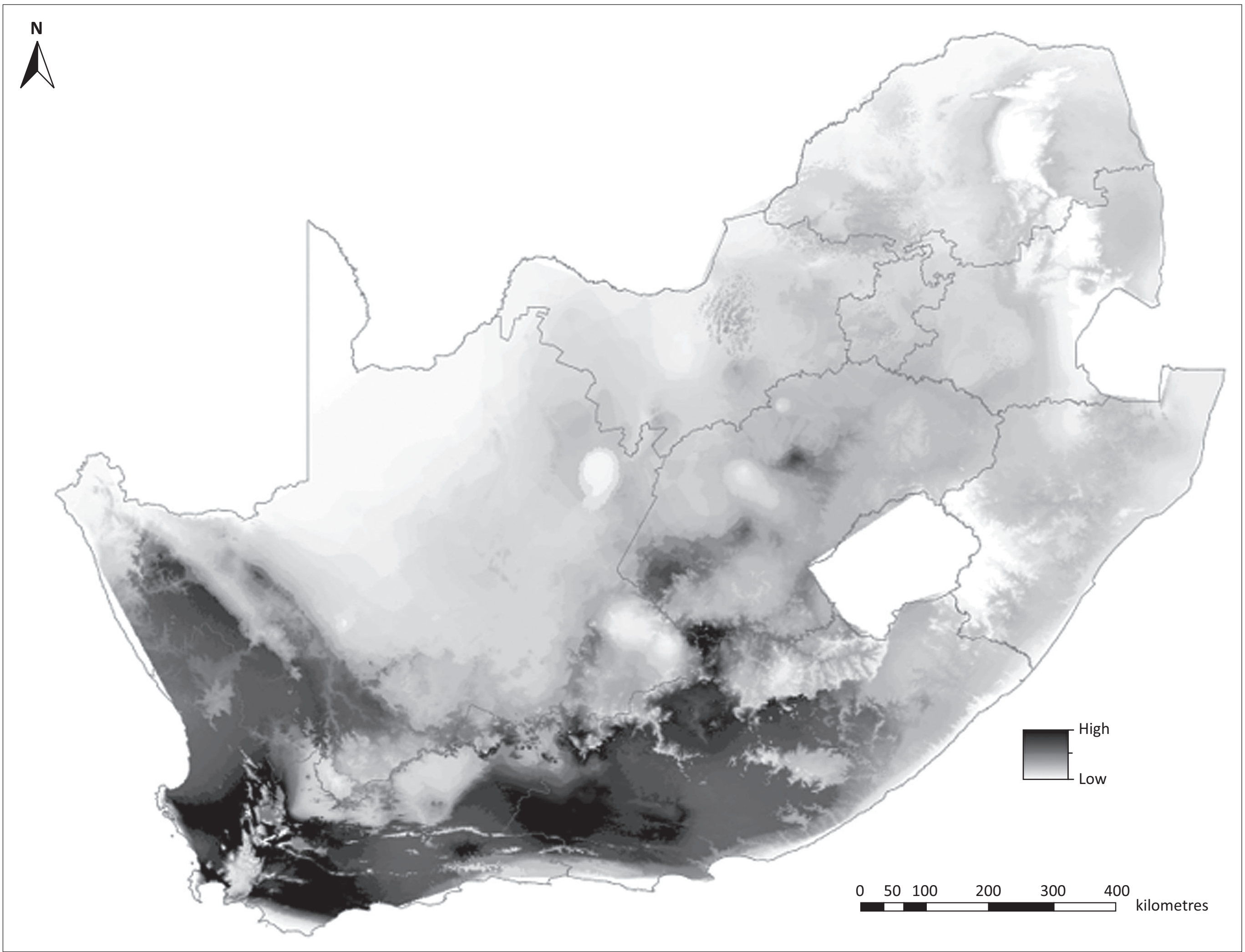


FIGURE 2: Potential distribution of *Asphodelus fistulosus* in South Africa; darker shades represent areas with higher potential for the establishment of *A. fistulosus*.

flush of germination (i.e. many seedlings) and growth in the early spring. Figure 4 provides a summary of aggregated data reflecting the number of plants summed across all sample plots for all test populations over time, plotted together with rainfall. The number of plants observed generally followed the rainfall pattern, with abundant germination occurring after the winter rains. By exception, the spring 2016 plant numbers (collective across all test populations) were relatively low following the winter rains of 2016. We speculate that this might reflect the effects of two years of plant removal and the suppression of seed set across all test populations.

Figure 4 shows results based on aggregated data from the five test populations. To clarify the patterns shown in Figure 4, Figure 5 shows the total number of sampled plants per test population over time. The St Helena Bay population is the only population showing a steady decline in individuals over time. This is probably because this is the smallest population. For the St Helena Bay population and the second-smallest population ('T-junction') (refer also to Table 1), the total number of sampled plants has been less than 20 individuals per population since 2016. Apart from other possible explanations such as the Allee effect and lack of pollination opportunity, it is possible that these two populations (St Helena Bay and T-junction) have not accumulated a substantial seed bank, such that recruitment is easily suppressed with the plant control methods used in this study. For the three larger test populations (Carinus Bridge, Hopefield and Feedlot), the number of sampled individuals increased during April 2016, possibly in response to a rain event as shown in Figure 4, but all populations showed a decline in the number of individuals during the next monitoring session (September 2016), where less than 40 individual plants per population were found.

The number of plants per population for *A. fistulosus* shows a relatively dynamic trend over time (Figure 5) that is probably a consequence of the species' sensitivity and rapid response to rainfall events and the timing of monitoring of these populations. Given this sensitivity to rainfall, long-term monitoring will be critical in order to discern real trends over time. A good additional indication of progress in population suppression is the incidence of plants with reproductive structures measured over time. There was a decline in the frequency of the number of plants with reproductive structures, aggregated across populations, over a two-year time period (Figure 6).

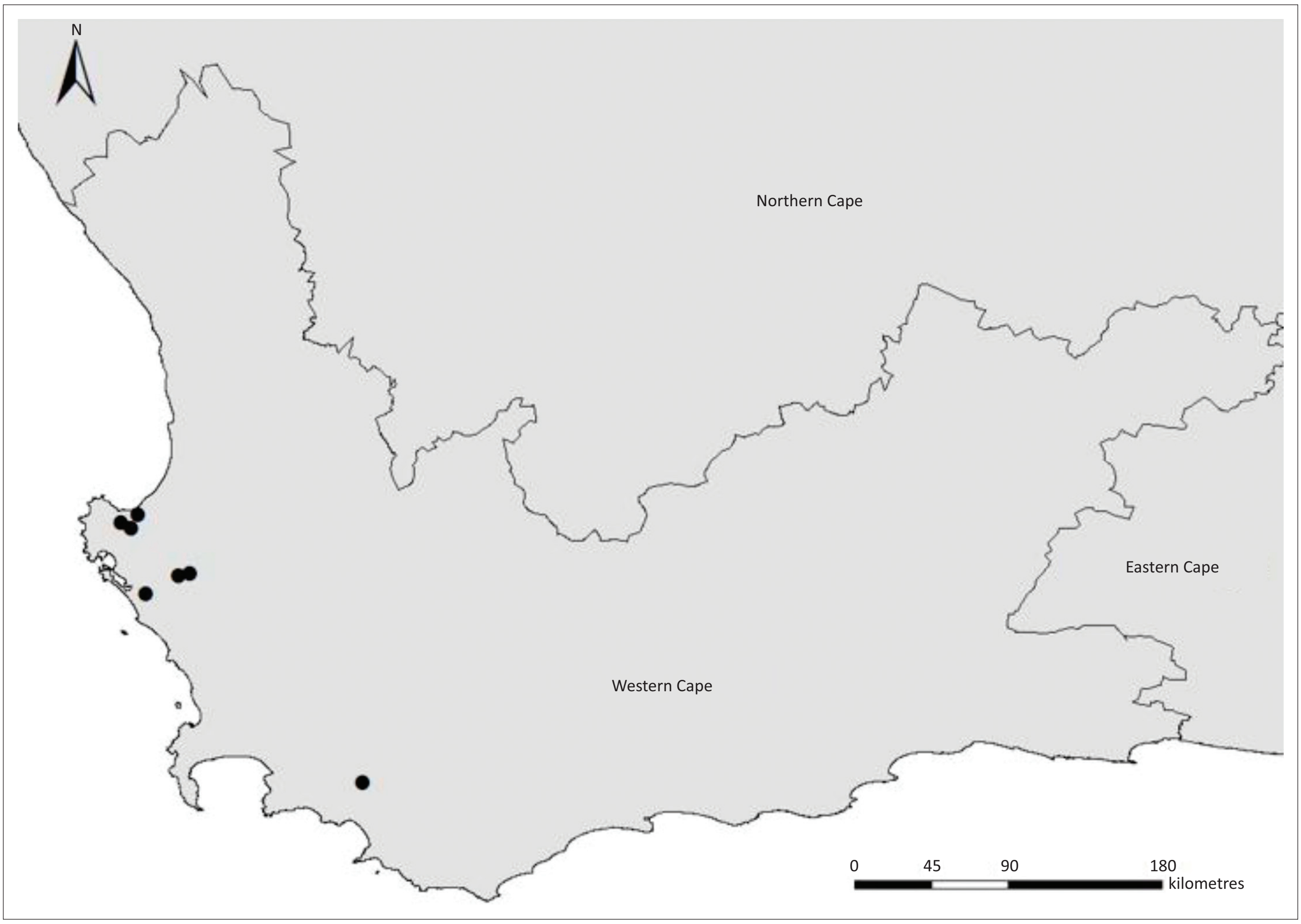


FIGURE 3: Known localities of *Asphodelus fistulosus* populations in South Africa. All known populations occur in the Western Cape province.

TABLE 1: Summary of initial extent, density and treatment of the test populations in South Africa.

Population name	Population extent	Population density averaged over the population extent	Estimated total number of plants in population	Treatment (May 2014 to May 2016)	Geographical coordinates for each population
St Helena Bay junction	4 m^2	13.000 plants/m^2	52	Hand-pulled	S32.88161; E18.11742
Vredenburg T-junction	800 m^2	0.250 plants/m^2	200	Hand-pulled	S3248.228; E18 09.596
Vredenburg feedlot	500 m^2	1.600 plants/m^2	800	Hand-pulled	S32.84817; E18.07171
Hopefield	598 m^2	0.363 plants/m^2	217	Hand-pulled	S-33.11327; E18.43386
Carinus Bridge	486 m^2	4.310 plants/m^2	2095	Foliar sprayed (metsulfuron)	S-32.79037; E18.16902

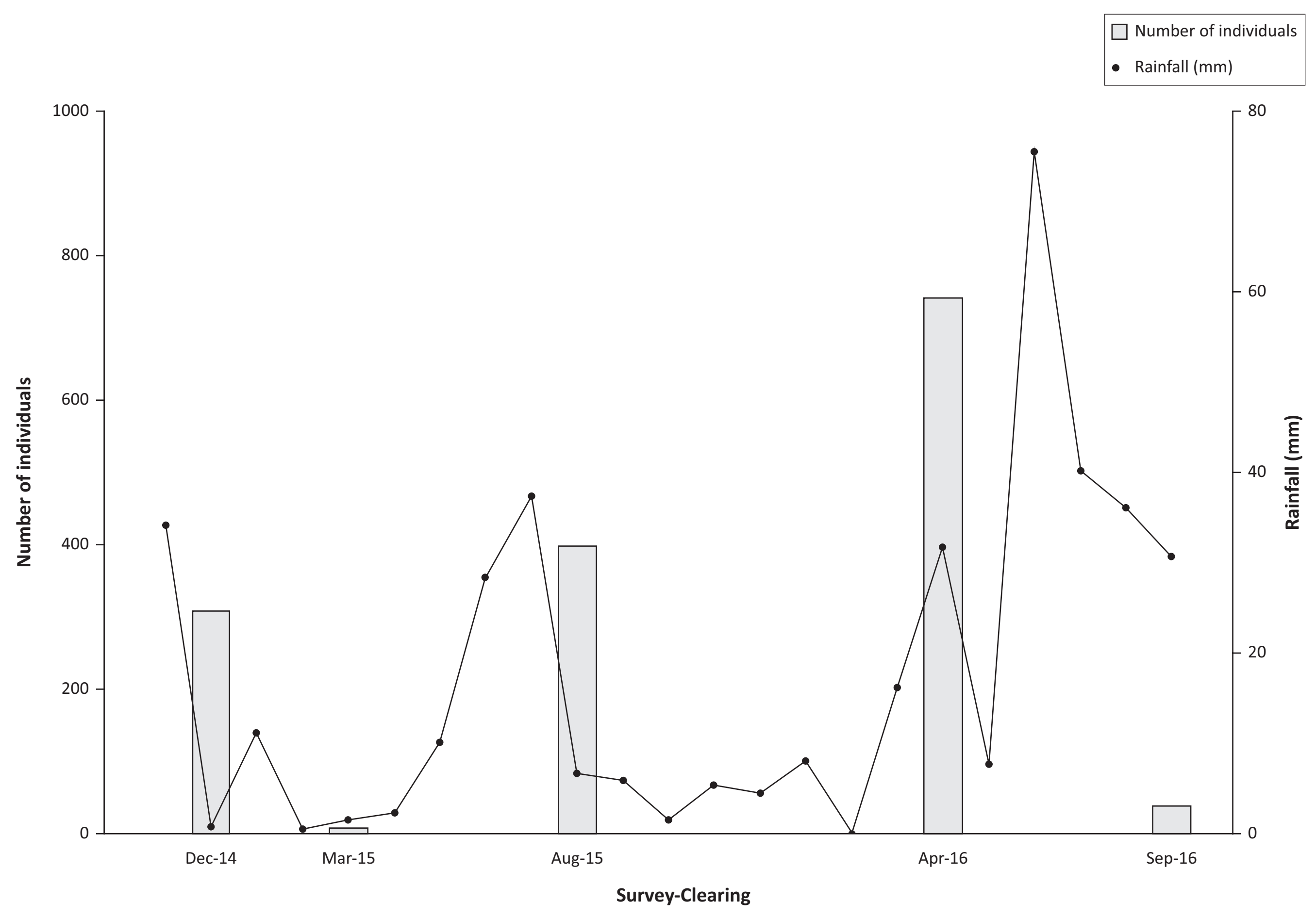
Note: The data were collected from the spring of 2012.

Examination of the extent of the soil seed bank

The soil seed bank was estimated at the beginning of the project. At that time, soil seed density inside (dense portion) the Carinus Bridge (densest) population (collected in September 2013) was 3309 seeds per m^2 of soil. In the less densely infested part of the same population, 3 m outside the densest parts, seed density was two orders of magnitude lower, at 49 seeds per m^2 of soil. This indicates the importance of plant density to the seed bank and also that the seed bank was considerable. Following this initial investigation, we continued to collect seed data from the half-meter squares in the Carinus Bridge population during the autumns of 2015 and 2016. Based on these data, the average soil seed density was 646 seeds per m^2 from the Carinus Bridge population in 2015 (standard error = 364.088) and 111 per m^2 in 2016 (standard error = 49.26). In summary the seed bank has decreased from 3309 seeds per m^2 to 111 seeds per m^2 in the densest part of the largest population over a two-year period. This suggests that with persistent control efforts, the seed bank can be reduced relatively quickly – over a control time period of two years.

Seed germinability

Germination results from the controlled chamber experiment were obtained within the first two weeks of the germination trial. Thereafter no germination was observed in both sets of seeds tested. Most of the seeds germinated during the first week of the experiment. The seed germination experiments showed that 63% of seeds collected from the soil (of unknown and probably diverse seed ages) germinated, while 86% of the younger seeds (a few months in age) collected from standing plants during 2013 germinated. The relatively high spontaneous germination rate is encouraging from a species control point of view. These results also suggest a loss of seed



Source: Rainfall data were sourced from Weather SA 2016

FIGURE 4: Total number of *A. fistulosus* individuals per survey-clearing session plotted together with rainfall. The number of individuals represents the total number of individuals (all sizes) collected in each population using the sampling methodology described in the Methods section.

viability over time and/or possible seed dormancy, but these questions will require further study.

Management of *Asphodelus fistulosus*

Field observations indicated that both mechanical and chemical methods of control are effective. No vegetative regrowth was observed at the populations where plants were hand-pulled or dug out. This finding emphasises the importance of the seed bank (as opposed to vegetative reproduction) for recruitment in this species. All plants that were foliar sprayed with metsulfuron herbicide showed initial signs of sickness, and eventually death. These results indicate that both methods are equally effective for controlling *A. fistulosus*. Because both methods are effective, the decision to use one or the other or a combination of the two is informed by practical considerations and the need to limit the use of herbicides where possible. We recommend a control approach whereby a foliar spray application is used where large numbers of seedlings are found. The reason for this is that the likelihood of missing individual plants is high with mechanical removal when removing thousands of small seedlings. Mechanical removal is appropriate for all other situations.

We propose that extirpation (i.e. local eradication) may be feasible because all observed populations occur along roadsides, which make them easily accessible and detectable, and large plants can be easily hand-pulled because of their shallow root systems. In addition, the seed bank data suggest that population suppression is possible. As a precaution, we also recommend that surveillance methods in future should include searches away from road edges, as it is not known at this stage whether populations occur away from road edges.

Retrospective cost of control over a five-year period including cost of personnel, travel, equipment and effort are shown in Table 2. Assuming a cost of approximately ZAR 50 000 per year and a total infested area of 3000 m^2, the cost for *A. fistulosus* removal and monitoring comes to approximately ZAR 16.67 per m^2. This can be compared to the costs of extirpation attempts for *Spartina alterniflora* (approximately ZAR 11.08 per m^2 in 2016) (Riddin, Van Wyk & Adams 2016) and for *Melaleuca quinquenervia* (approximately ZAR 236.35 per m^2 in 2015) in South Africa (Van Wyk & Jacobs 2015).

Discussion

The risk assessment result in this paper supports the notion that *A. fistulosus* is a species of concern in South Africa. We propose that it should be listed on the *National Environmental Management: Biodiversity Act* (NEM:BA) as a Category 1a invasive species. This listing would require compulsory

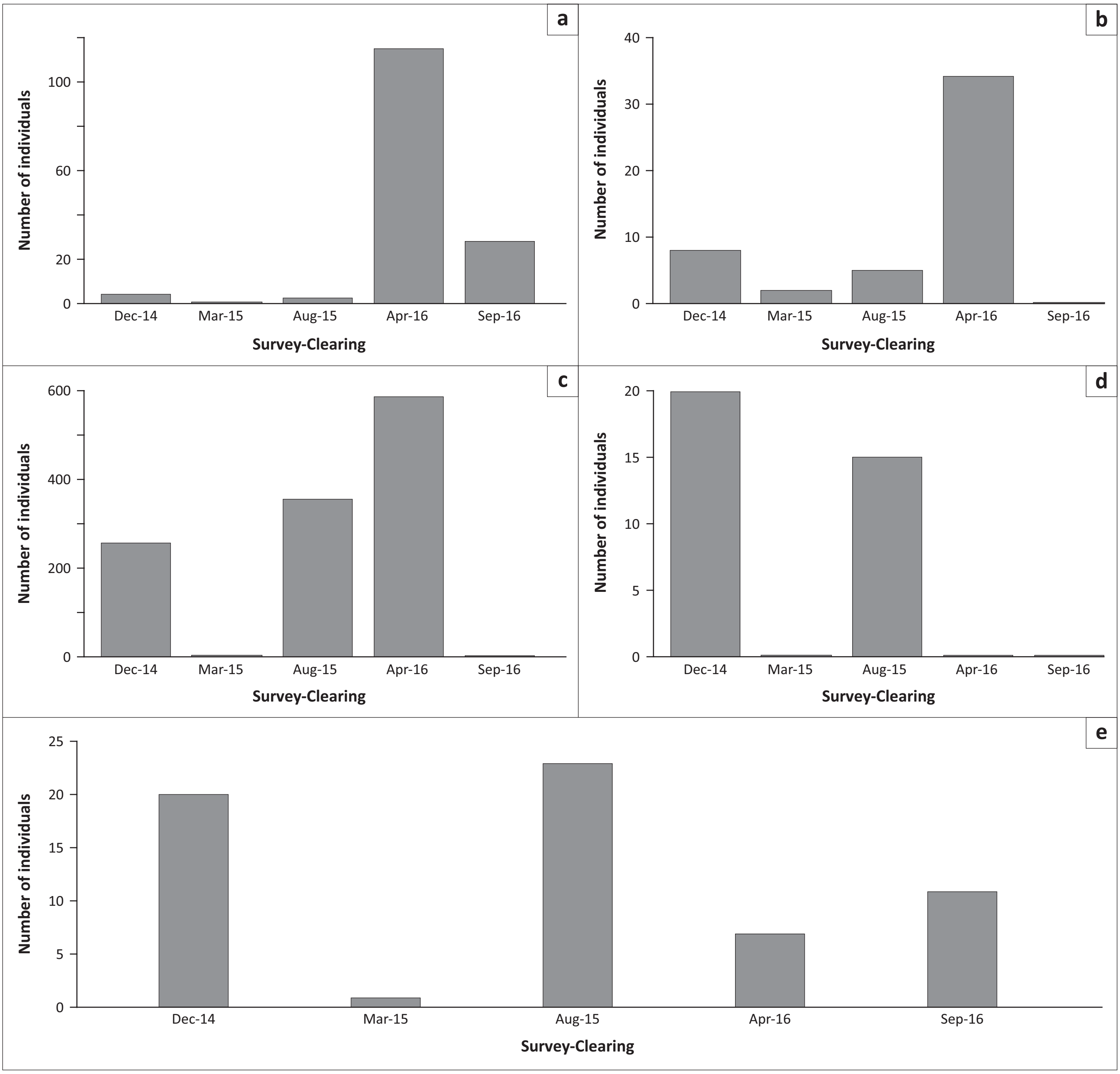


FIGURE 5: Total number of individuals across each of the five sites after implementing control methods for three years. (a) Carnius, (b) Feedlot site, (c) Hopefield, (d) St Helena Bay and (e) T-junction.

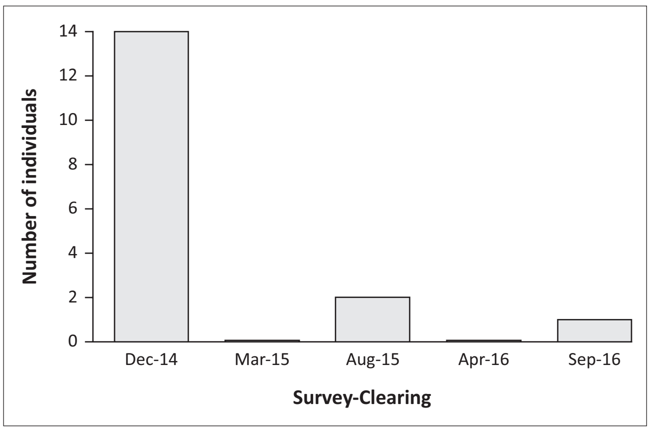


FIGURE 6: Total number of standing plants with fruits and/or seeds post-clearing over 3 years.

management of the species until eradication is achieved or until it can be proven that eradication is not a feasible management objective.

Several studies have recognised roads as a driver of the introduction and spread of invasive alien species (Gelbard & Belnap 2003; Kalwiji et al. 2008; Lembrechts et al. 2014). Roadside characteristics such as frequent disturbance, nutrient-rich soil and exposure to sunlight have been shown to contribute to the spread of invasive alien plants in several ecosystems (Flory & Clay 2006; Lembrechts et al. 2014). In addition, increased exposure to storm water runoff and vehicle traffic along roads facilitates the easy movement via other dispersal mechanisms such as wind, water and animals that transport seeds (Flory & Clay 2006; Milton & Dean 1998).

TABLE 2: Summary of expenditure (in ZAR) and effort associated with the management of seven known *Asphodelus fistulosus* on the West Coast, Western Cape.

Item	2012	2013	2014	2015	2016
Contractor cost including transport (six people)	0	62 830	63 626	63 626	54 582
Accommodation	3756	0	0	0	0
Travel (three to four researchers)	1560	4640	2125	1275	1275
Herbicide	0	0	4827	0	0
Person days (researchers)	2	8	8	8	8
Person days (contractor)	0	409	358	189	176
Total cost/year (ZAR)	**R5316**	**R67 470**	**R70 578**	**R64 901**	**R55 857**

Asphodelus fistulosus may pose a risk to agriculture and conservation in South Africa if allowed to spread from the current roadside localities. In South Africa, all known *A. fistulosus* populations are distributed along roadsides that are close to agricultural lands. *Asphodelus fistulosus* has the potential, if left unmanaged, to spread from the roadsides, as evidenced by Smith and Smith (n.d.) in Blanchetown, Australia. Indeed this pattern of spread has been found in other roadside invaders (Lembrechts et al. 2014). In addition, *A. fistulosus* does not offer any benefits to agriculture as it is not palatable to livestock (Stretch 2002). All known occurrences of *A. fistulosus* populations coincide with either West Coast coastal lowland vegetation types or shale renosterveld. Both vegetation types are considered conservation-worthy, with high levels of plant endemism and diversity, but both suffer from fragmentation and other anthropogenic effects such as agricultural, pastoral, coastal resort and urban development, as well as alien plant spread (Heijnis et al. 1999; Rutherford, Mucina & Powrie 2012). Bioclimatic results indicate that *A. fistulosus* has the potential to spread into other climatically suitable regions of the country, impacting on other vegetation types.

Several factors favour successful local control and even countrywide eradication of the target species if diligence is applied. All known populations of *A. fistulosus* are relatively small, easy to identify and occur along roadsides. From a plant control point of view this is favourable regarding detectability and access. Results from this study indicate that with persistent effort (i.e. at least two control sessions during the growth season, especially following rainfall events in the areas of infestation), reproduction and population spread is likely to be suppressed. The annual or short-lived perennial nature of the target species does present challenges because of the likelihood of opportunistic reproductive events in response to rainfall or mowing and therefore a likelihood of fluctuations in the number of reproductive structures over seasons. This may lead to difficulty in detecting real trends in the data over time, and this draws attention to the need for long-term monitoring. It also highlights that this issue will tend to be associated with short-lived herbaceous invasive species that respond opportunistically to rainfall events, in contrast to woody invasive species, which do not respond at such short intervals to climatic events. A relatively longer time frame, with budget implications, should be considered when designing monitoring programmes for invasive plant species that recruit opportunistically. Because *A. fistulosus* populations are currently small, it takes three field researchers approximately two days to collect data and remove plants from each population. An additional contracted team of six people assisted with mapping and removing plants from the R47 population, which does not form part of the test populations. The results also show that good progress can be made by persistent removal of plants through mechanical and herbicide control. The number of plants per population was very low at the time of writing, but whether this can be sustained will depend on diligent, ongoing plant control efforts. Plant control efforts may be hampered by dispersal of *A. fistulosus* seeds away from the known populations, by vehicles, which may establish new populations. In addition, occasional mowing of some road verges (excluding the research populations) by the provincial roads authority may facilitate the spread of plants, especially because mowing encourages flowering (based on observations from this study).

We recommend applying a mechanical or herbicidal (in the case of mass germination) control approach to all populations of *A. fistulosus* in South Africa. Plant material should be bagged and removed from the site in particular to ensure the removal of seeds. Follow-ups are essential. The timing of control is extremely important so as to prevent seed set. We recommend an early spring control followed by a mid-spring and early summer control to ensure that all new germinating plants are removed. The seed bank and population results from this study showed that it is possible to reduce the number of plants, as well as the seed bank over a fairly short time period (i.e. two years) by removing plants and thereby removing reproductive structures. However, overall success will depend upon effective control of known populations as well as detection of new populations.

The discovery of the Caledon population is of concern as it is relatively far from the West Coast populations and indicates that *A. fistulosus* can grow and spread in shale soils. This finding suggests that more populations may yet be detected. Therefore greater effort should be put into detection of the target species in the Overberg area as well as the West Coast, as well as other areas that may be climatically suitable for invasion as indicated by the bioclimatic map (Figure 2). This study shows that the publicity flyers were successful in prompting the discovery of three new populations (through one spotter) out of the seven known populations thus far. It furthermore suggests that focusing on awareness raising among members of the public with a degree of botanical interest (e.g. CREW; http://www.sanbi.org) may facilitate further detection. The data in this paper suggest that more medium- to long-term information is needed to understand whether local or countrywide eradication might be achieved. Longer-term plant control, monitoring of known populations and surveillance for possible new populations will be needed to understand prospects for eradication.

Conclusion

Asphodelus fistulosus is a species of concern, but it is not yet widespread within South Africa. Despite encouraging results from a substantially reduced seed bank over a two-year plant control period, the current findings do not provide compelling evidence that extirpation of this species can be achieved. However, local extirpation of *A. fistulosus* may be feasible if diligent detection and plant control is continued and if there is commitment to medium- to long-term monitoring to be able to detect trends with confidence. Management of the species involves a relatively low cost and effort. Based on these results, we recommend that *A. fistulous* be tentatively listed as a Category 1a under the under NEM:BA regulations. A NEM:BA 1a listing (eradication target) is preferred to a 1b listing (containment target) so as to keep focused attention on eradication potential until further insights are gathered. This listing should be revised once wider surveillance has been conducted and further evidence of reduction of known populations can be shown.

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Competing interests

The authors declare that they have no conflicts of interest with regard to the writing of this article.

Authors' contributions

N.J. and E.v.W. were involved in the fieldwork, data capturing and seed studies, risk assessment and drafting of the manuscript with input from all other authors. J.L.R. analysed the data and produced the bioclimatic model. D.M. developed a refined field monitoring protocol for *A. fistulosus*.

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Data availability statement

Data sharing is not applicable for this article.

Disclaimer

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