RESEARCH ARTICLE

Recovery of Native Plant Communities following Control of Terracina Spurge (*Euphorbia terracina*): Three Case Studies from South-west Western Australia

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ABSTRACT

Terracina spurge or Geraldton carnation weed (*Euphorbia terracina*) is an invasive weed that impacts native plant communities across southern mainland Australia and in the United States (USA), including southern California and Pennsylvania. There are, however, few published accounts of appropriate control techniques or recovery of native vegetation following removal of this species. We report here on the results of three adaptive management projects investigating effective control of Terracina Spurge and subsequent recovery of Banksia woodlands, coastal shrublands, and sedgeland communities in the Swan Coastal Plain bioregion, south-west Western Australia. In Banksia woodlands the herbicide metsulfuron-methyl (600g/kg) (Brush-Off®) in combination with hand removal of adult plants was effective at controlling Terracina spurge. Although there was some initial off target damage to native flora, after five years of repeated application the Banksia woodland within the treated area is regenerating. In sedgelands of the Holocene dune swales and in coastal shrublands 750g/kg triasulfuron (Logran®) was very effective, reducing Terracina spurge populations significantly in the first two years. The treatment resulted in little damage to native flora. At both sites a significant difference in species abundance between years was attributed mostly to a decrease in the cover of Terracina spurge but also an increase in cover of several species of native flora. The results indicate triasulfuron is an effective tool for the management of Terracina spurge in coastal plant communities potentially leading to the protection and restoration of significant areas of the conservation estate within the Swan Coastal Plain bioregion and beyond.

Keywords: Banksia woodland, invasive species, Logran®, Swan Coastal Plain, triasulfuron

One of the primary objectives of managing invasive species in high conservation value natural areas is the protection and restoration of native plant communities (Zavleta et al. 2001, Hulme 2006, Lesica and Hanna 2009). Control techniques employed often influence native plant community recovery (Flory and Clay 2009). It is therefore important to measure not only the effectiveness of control treatments on the target species but also their impacts on native flora and plant communities. A focus on longer term (more than 2–3 years) recovery of the plant community is also necessary to assess the effectiveness of the restoration program over time (Lesica and Hanna 2009). In addition, when effective control measures are not well established, managing highly invasive weeds in high value conservation reserves requires an adaptive management approach including development and implementation of an experimental framework, monitoring to evaluate effectiveness, and on-ground implementation of results to improve conservation outcomes. Varying levels of invasion, different plant communities, and conservation values of reserves may require a range of approaches and management objectives (Margolius and Salafsky 1998, Shea et al. 2002, Lindenmayer and Burgman 2005, Keith et al. 2011).

Terracina spurge (*Euphorbia terricina*) is an herbaceous perennial native to southern Europe, western Asia and north Africa, where it occurs on sand dunes and shallow calcareous soils (Smith and Tutin 1968, WCSP 2012). Terracina spurge was first recorded as naturalised in Australia early in the 20th century (Western Australian Herbarium 1998, Australia's Virtual Herbarium 2012). Today it is a serious invader of native plant communities on calcareous soils across the southern states of Australia where it is difficult to control or eradicate (Parsons and Cuthbertson 2001). In recent years it has been recognized as a serious environmental weed in parts of the USA,

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including Pennsylvania and southern California (Riordan et al. 2008). In California and in south-west Western Australia there is evidence that where Terracina spurge invades native plant communities it forms dense monocultures and has significant negative impact on native species abundance and diversity (Keighery and Keighery 2007, Riordan et al. 2008, Bettink 2009). The species possesses numerous traits that have been associated with invasive plants including rapid establishment in disturbed sites, phenotypic plasticity, high reproductive output, and seeds lacking dormancy. These are also traits that contribute to the difficulty of control of established populations (Riordan et al. 2008, Dorsey et al. 2010). Terracina spurge was nominated an Australian weed of national significance in 2010.

South-west Western Australia is an area recognized as one of 25 global biodiversity hotspots (Myers et al. 2000) and is renowned for its floristic diversity and high level of endemism. However, this area is subject to a range of threatening processes including fragmentation of natural habitat and invasion by introduced species. The entire region has experienced high rates of habitat loss through urban and agricultural land use change and in particular the Swan Coastal Plain bioregion has been heavily impacted by urban development (Government of Western Australia 2010) with remaining remnant native vegetation highly fragmented. Terracina spurge is invading remnant natural areas across the region, including many of conservation significance: nature reserves, national parks and regionally significant bushlands (Bettink 2009). Particular habitats at risk include offshore islands and plant communities on calcareous soils (Keighery and Keighery 2007).

In south-west Western Australia the current strategy for management is to contain spread by controlling outlying populations and to protect high conservation value assets from invasion (Bettink 2009). There is little published information on effective control techniques for Terracina spurge, or on the recovery and restoration of invaded plant communities. At the commencement of this study, the standard recommended chemical control methods for Terracina spurge invading native vegetation (Brown and Brooks 2002), were only effective on seedlings and plants less than one year old. Hand removal was recommended for adult plants.

In the US, preliminary studies have identified the herbicides chlorsulfuron and glyphosate as providing effective control of Terracina spurge (Dorsey et al. 2010). These studies, in open riparian woodlands in Solstice Canyon, California, indicate both glyphosate and chlorosulfuron are effective at reducing cover of Terracina spurge (Dorsey et al. 2010). However, the authors did not investigate impacts on native vegetation. Glyphosate is a non-selective herbicide and would be expected to cause considerable off target damage to native flora. Chlorsulfuron would be expected to be more selective in native vegetation (Brown and Brooks 2002), but there are few published studies.

Our objective in this study was to investigate the potential effectiveness of the herbicide metsulfuron-methyl (Brush-Off®) combined with hand removal and of triasulfuron (Logran®) on the control of Terracina spurge and to assess the impacts of treatments on co-occurring native species. We present here three case studies covering six years of an adaptive management program for Terracina spurge including developing appropriate control techniques while monitoring the associated response and recovery of the flora of Banksia/eucalypt woodlands, sedgelands in dune swales, and coastal shrublands, on the Swan Coastal Plain of south-west Western Australia.

Methods

Study Sites and Experimental Design

Case study 1: Banksia and eucalypt woodlands, Paganoni Swamp

The Banksia/eucalypt woodlands on deep quaternary sands are the dominant vegetation of the Swan Coastal Plain. Originally covering around 280,000 ha, more than half have been cleared for urban development (Government of Western Australia 2010), and many that remain have become highly fragmented. The first case study was located in a 700 ha remnant of Banksia/eucalypt woodland on the dunes and ridges surrounding Paganoni Swamp, 100 km south of the City of Perth. The woodlands are in excellent condition and one of the key threatening processes is invasion from Terracina spurge.

In 2005, the Department of Environment and Conservation and a community group 'Friends of Paganoni Swamp' initiated a control program employing the recommended control method at that time, spraying 600g/kg metsulfuron-methyl (Brush-Off®) at 0.2 g/10L plus the penetrant (Pulse®) on seedling and younger plants in July/August (winter) and hand weeding the more difficult to kill adults in November (late spring). Fifteen 1 m × 1 m plots were placed across the population on the western boundary of the reserve to monitor the effectiveness of this treatment, to measure the impacts of the treatment on the native plant communities, and to monitor changes following removal of the weed. Cover estimates (Braun-Blanquet 1965 modified scale; 0 = 0, 1 = < 1%, 2 = 1–5%, 3 = >6–25%, 4 = >26–50%, 5 = >51–75%, 6 = >75% cover) of Terracina spurge and all native and introduced species in each plot was recorded before the control program began in July 2005 and then each July before the annual control program, until July 2010. The midpoint of the Braun-Blanquet cover estimates were used to determine average percent cover (0 = 0, 1 = 0.5%, 2 = 3%, 3 = 15.5%, 4 = 38%, 5 = 68%, 6 = 87.5%). The management objectives were to protect intact uninvaded plant communities, to restore disturbed sites and to eradicate Terracina spurge from the reserve. It was therefore not appropriate to establish untreated control sites.

Case study 2: Sedgelands in Holocene dune swales, a threatened ecological community, Point Becher

The sedgelands in the Holocene dune swales are mostly restricted to the coastal wetland depressions (swales) occurring between parallel sand ridges of the Rockingham Becher Plain, 80 km south of the City of Perth (Gibson et al. 1994). The dominant species at the site included bare twig rush (*Baumea juncea*) and knotted club rush (*Ficinia nodosa*). The distribution of these sedgelands is very limited and all known occurrences are extremely vulnerable to threatening processes including changing hydrology and weed invasion. As a result they are listed as an endangered community under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (Department of Environment and Conservation 2011). Terracina spurge invades the calcareous soils of the dune swales and forms dense stands in the sedgelands. In 2004, funding was made available to undertake restoration of the impacted dune swales.

With extensive and dense populations of Terracina spurge at this site, hand removal of adult plants was not a practical option. Consequently, a study into alternative control techniques for Terracina spurge was initiated. Preliminary trials were carried out on five different herbicides at two different rates. Herbicides included Glean® (750 g/kg chlorsulfuron), Broad Strike® (800 g/kg Flumetsulam), Brush-Off® (600 g/kg metsulfuron-methyl), Eclipse® (100 g/L metosulam) and Logran® (750 g/kg triasulfuron). The results indicated 750 g/kg triasulfuron (Logran®) was the most effective with little impact on co-occurring native species in the Holocene dune swales (K. Brown, unpublished data). In July 2005, as a result of this preliminary work, triasulfuron at 12.5 g/100 L plus the penetrant Pulse® (2 mL/L) was trialled across a 2 ha discrete population of Terracina spurge invading the sedgelands.

In July 2005, before the first triasulfuron treatment, five 50 m transects, 15 m apart, were placed across the occurrence of the community where Terracina spurge was present. The point intercept method (Bonham 1989, Elzinga et al. 2001) was used to measure cover of all native and introduced species along each transect. For each transect, a 50 m tape was run between two permanently placed steel bars. An 8 mm diameter fibreglass rod was dropped perpendicular to the tape every 10 cm along the tape and each species (leaves, stems or inflorescence) intercepted by the rod at each point was recorded and reported as percentage overlapping cover. This provided an objective measure of abundance (Elzinga et al. 2001). In late July, adult and juvenile plants of Terracina spurge across the 2 ha site were sprayed with triasulfuron at a rate of 12.5 g/100L plus the penetrant Pulse® (2mL/L). The transects were rescored each year, prior to a follow up triasulfuron treatment until 2008. In February 2007 a large fire in the reserve burnt across the entire study site. Again the management objective was eradication so it was not appropriate or practical to establish untreated control sites.

Case study 3: Coastal Shrublands, Burns Beach

The third case study was located on coastal dunes near Burns Beach, a 400 ha remnant of coastal shrubland often dominated by *Acacia* spp., and coastal honey myrtle (*Melaleuca systena*), with an understory of herbs and native grasses. The site lies approximately 25 km north west of the City of Perth. Ninety hectares of the reserve was mapped for Terracina spurge and of this more than 80% had some level of invasion, with the majority having 5–75% cover of the weed (Department of Environment and Conservation, unpublished data). From the work at Point Becher it was clear that triasulfuron was a useful tool for control of Terracina spurge in native plant communities, however trials over a broader range of native species was required before triasulfuron treatment could be recommended as a control method across the range of plant communities invaded by Terracina spurge. The coastal shrublands at Burns Beach have considerably higher species richness than the sedgelands in the Holocene dune swales at Point Becher (Gibson et al. 1994). Burns Beach therefore provided an opportunity to conduct a replicated, controlled herbicide trial over a broad range of species in the habitat most at risk from invasion.

Ten pairs of 10 m transects, each pair a control and a treatment transect, separated by 5 m buffer, were placed across 3 ha of coastal shrubland in the reserve where cover of Terracina spurge was between 5 and 75%. Pairs of transects were approximately 30 m apart. The point intercept method was used to measure percentage overlapping cover of all native and introduced species along each transect at 10 cm intervals, a total of 101 points were scored along each transect. The transects were scored in early July 2009 before treatment. Triasulfuron at a rate 12.5 g/100 L plus the penetrant Pulse® (2 mL/L) was applied to the treatment transects in late July 2009 and the transects were rescored in July 2010.

Data Analysis

For case studies 1 and 2 (Paganoni Swamp and Point Becher) an analysis of similarity (ANOSIM, Clarke 1993) was undertaken to determine if there was significant change in species abundance following treatment over time and, where significant, a post-hoc pairwise comparison was undertaken between years. ANOSIM is a non-parametric method which uses rank values from dissimilarity matrix

Table 1. Modified Braun-Blanquet classes of species that contributed to more than 90% of the changes in species abundance at Paganoni Swamp over six years. Average Bray-Curtis similarity was used to estimate homogeneity in species composition between plots within years. *denotes non-native species.

Species	Mean cover class					
	2005	2006	2007	2008	2009	2010
*Terracina spurge (*Euphorbia terracina*)	>26–50%	1–5%	>6–25%	1–5%	< 1%,	< 1%
Dichopogon capillipes	>6–25%	>6–25%	>26–50%	>26–50%	>26–50%	>26–50%
yellow buttercup (*Hibbertia hypericoides*)	>6–25%	>6–25%	>6–25%	>6–25%	1–5%	>6–25%
berry saltbush (*Rhagodia baccata*)	>6–25%	1–5%	1–5%	1–5%	0	< 1%
bull banksia (*Banksia grandis*)	1–5%	1–5%	1–5%	1–5%	1–5%	>6–25%
zamia palm (*Macrozamia riedlei*)	1–5%	1–5%	1–5%	1–5%	0	0
weeping grass (*Microlaena stipoides*)	1–5%	1–5%	1–5%	1–5%	>6–25%	1–5%
red ink sundew (*Drosera erythrorhiza*)	1–5%	< 1%	1–5%	0	0	0
Lasiopetalum membranaceum	< 1%	1–5%	1–5%	1–5%	1–5%	0
native geranium (*Geranium retrorsum*)	< 1%	< 1%	1–5%	1–5%	1–5%	>6–25%
*blowfly grass (*Briza* spp.)	< 1%	1–5%	1–5%	1–5%	>6–25%	>6–25%
Average similarity within years	**23.7**	**37.2**	**35.3**	**35.4**	**33.1**	**36.1**

calculated from species abundance data to test for differences between a priori groups (years in this case). The Bray-Curtis dissimilarity measure was used and significance tested by permutation (n = 999). Species that contributed to significant differences were identified using similarity percentage analysis (SIMPER, Clarke and Gorley 2006), which decomposes the average Bray-Curtis dissimilarities between contrasting groups into percentage contribution from each species. In addition average similarity by year was calculated to elucidate any temporal trends in species abundance data. All analyses were undertaken using the PRIMER 6 software package (Clarke and Gorley 2006).

For case study 3, a before and after control/impact (BACI) model (Underwood 1992) was used to assess impacts of the herbicide treatment on species abundance between 2009 and 2010. This was a multivariate analysis of variance (PERMANOVA+; Anderson et al. 2008), based on a Bray-Curtis dissimilarity matrix calculated from species abundance data. In this model, year was treated as a random factor and treatment as fixed, and significance was tested using 999 permutations of residuals under the reduced model (Anderson et al. 2008). The analysis was undertaken using the PERMANOVA+ extension of the PRIMER 6 package (Anderson et al. 2008). In addition average similarity by year was calculated to elucidate any temporal trends in species abundance data.

Change in mean and standard deviation of native vegetation cover at Point Becher (Case study 2) and Burns Beach (Case study 3) was calculated from point intercept data. At Paganoni, change in mean cover of native vegetation was estimated from the midpoint of the Braun-Blanquet cover values, therefore standard deviations were not calculated.

Results

Case Study 1: Banksia and eucalypt woodlands, Paganoni Swamp

On average, plots at Paganoni Swamp were quite heterogeneous (Table 1). We found significant differences in species abundance across the five years of treatment (ANOSIM Global R = 0.278, p = 0.001). Pairwise tests between years revealed a significant difference in species abundance between 2005 (before treatment) and 2006 (R = 0.376, p = 0.001) and between 2006 and 2007 (R = 0.499, p = 0.001). From 2007 until the end of the study in 2010 there was no further significant change in species abundance. The plots became less heterogeneous after the first year of treatment but subsequently little change in overall similarity within years was observed (Table 1).

The greatest contribution to the significant change that occurred in species abundance between years was a decrease of Terracina spurge cover from an average of 26–50% cover to less than <1% over the five year period of the project (Table 1). Total cover of native species dropped from an average of 51–75% cover following the first herbicide application to 26–50% and then recovered the following year, remaining within the same cover class (51–75%) over the next four years of treatment (Figure 1). Cover of berry saltbush (*Rhagodia baccata*), a native shrub dominant in the understory of these woodlands, dropped following the first herbicide application and cover continued to decrease in following years with some seedling recruitment in 2010. Another dominant understory shrub, yellow buttercup (*Hibbertia hypericoides*), decreased in cover between 2008 and 2009 and then increased in cover in 2010. The other native shrubs, herbs, and grasses that contributed to the changes between years were initially low in cover and subsequent changes only small. Three native species, zamia palm (*Macrozamia riedlei*), the shrub, *Lasiopetalum membranaceum*, and a small herb, red ink Sundew (*Drosera erythrorhiza*), disappeared from the study site altogether. These species were too infrequent to accurately assess whether this is related to the herbicide treatment. The weedy annual, Blowfly grass (*Briza* spp.) increased in cover from an average cover class of <1% cover in 2005 to 6–25% cover in 2010.

Case Study 2: Sedgelands in Holocene dune swales, a threatened ecological community, Point Becher

The sedgeland at Point Becher was relatively species poor and overall similarity between transects was high (Table 2). We found significant changes in species abundance across the four year study (ANOSIM Global R = 0.744, p = 0.001). Pairwise tests between years revealed significant differences between 2005 (before treatment) and 2006 (R = 0.776, $p <$ 0.008) and between 2007 and 2008,

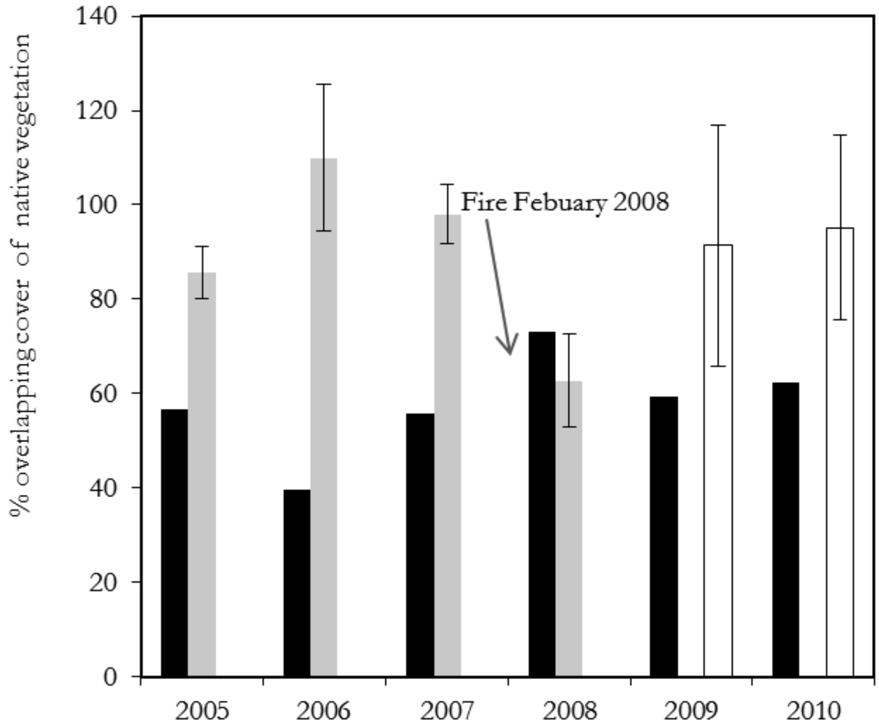

Figure 1. Change in total cover of native vegetation across sites over five years before and following treatment of Terracina spurge (*Euphorbia terracina*) with metsulfuron-methyl hand removal (Paganoni Swamp, black bars), and triasulfuron (Point Becher, gray bars, and Burns Beach, white bars). Paganoni data was estimated from midpoint Braun-Blanquet cover values, Point Becher and Burns Beach data was measured using point intercepts.

Table 2. Average percent overlapping cover of species that contributed to more than 90% of the changes in abundance of flora at Point Becher over the four year study. Average Bray-Curtis similarity was used to estimate homogeneity in species composition between plots within years. * denotes non-native species.

Species	Mean cover (%)			
	2005	2006	2007	2008
bare twig rush (*Baumea juncea*)	48.5	60.6	53.3	37.6
knotted club rush (*Ficinia nodosa*)	35.8	48.0	40.9	16.4
**rye grass* (*Lolium* sp.)	20.8	11.3	9.1	5.4
*hare's tail grass (*Lagurus ovatus*)	19.8	18.3	19.4	31.4
*Terracina spurge (*Euphorbia terracina*)	19.2	1.2	0	0
*Guilford grass (*Romulea rosea*)	10.0	3.6	2.2	6.3
native spear grass (*Austrostipa flavescens*)	0.3	1.3	1.9	4.2
heath Xanthosia (*Xanthosia huegelii*)	0	0	0	4.0
Average Similarity	**85.8**	**79.3**	**85.8**	**82.1**

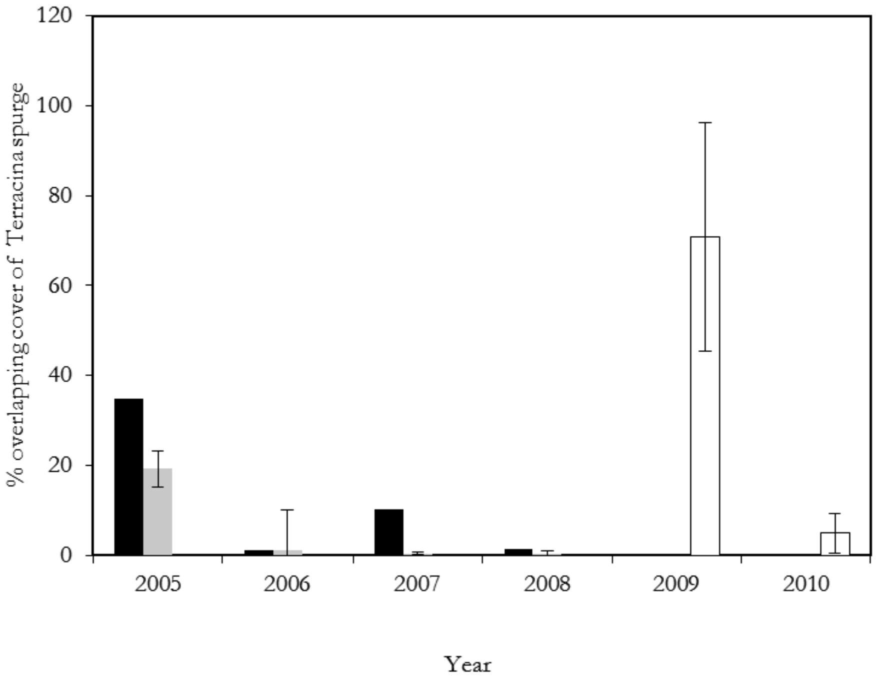

Figure 2. Cover of Terracina spurge (*Euphorbia terracina*) before and following treatment with metsulfuron-methyl hand removal (Paganoni Swamp, black bars), and triasulfuron (Point Becher, gray bars, and Burns Beach, white bars). Paganoni data estimated from midpoint Braun-Blanquet cover values, Point Becher and Burns Beach data measured by point intercepts.

Table 3. Average percent overlapping cover of species that contributed to more than 90% of the changes in abundance of flora at Burns Beach following one treatment of triasulfuron. Average Bray-Curtis similarity was used to estimate homogeneity in species composition between plots within years. *denotes non-native species.

Species	Mean cover (%)	
	2009	**2010**
*Terracina spurge (*Euphorbia terracina*)	71.6	4.8
coastal honey myrtle (*Melaleuca systena*)	40	35.6
old man's beard (*Clematis linearifolia*)	14.6	15.5
*annual grass	18.6	25.8
Lomandra maritima	11.8	15.3
Desmocladus flexuosus	10.1	11.2
Lepidosperma sp.	6.1	8.4
berry saltbush (*Rhagodia baccata*)	2.1	3.2
Average Similarity within years (controls)	**68.8**	**51.6**
Average Similarity within years (treatments)	**62.4**	**33.2**

following the February 2008 fire (R = 0.966, $p < 0.008$).

Terracina spurge decreased from 19.2% overlapping cover before treatment to 0.0% two years following the initial treatment (Table 2, Figure 2). Mean percentage overlapping cover of native species increased following the initial treatment from 85.1% in 2005, before treatment to 110.0% after the first year of treatment. Following the fire in 2007–8, mean percentage overlapping cover of native species dropped to 62.7% (Figure 1). We found an increase in the two dominant native sedges, knotted club-rush and bare twig rush in the three years before the fire (Table 2). Although not targeted for control, triasulfuron also appeared to reduce cover of the weeds rye grass (*Lolium* sp.) and Guilford grass (*Romulea rosea*).

Following the fire in February 2008, the significant change in abundance across the site was mainly attributable to a decrease in the two sedges and an increase in the cover of a native grass and the appearance of the native herb, *Xanthosia huegelii*. Invasive species that contributed to the change following fire include an increase in the annual hare's hail grass (*Lagurus ovatus*) and Guilford grass (Table 2).

Case Study 3: Coastal Shrublands, Burns Beach

BACI analyses showed a highly significant before-after and control-impact interaction (BACI; Pseudo $F_{(1,36)} = 5.13$, $p = 0.001$) revealing a significant change in species abundance between 2009 and 2010, related to the triasulfuron treatment. The greatest contribution to the change was a decrease in the cover of Terracina spurge from 71.6% in 2009 to 4.8% in 2010 (Table 3, Figure 2). Also contributing was the 10% decrease in the cover of the dominant shrub coastal honey myrtle and an increase in cover of berry saltbush, the woody climber old man's beard (*Clematis linearifolia*), the rush *Desmocladus flexuosus*, the sedge *Lepidosperma* sp. and the lily *Lomandra maritima*. Overall cover of native species however changed little following treatment, going from 91.4 in 2009 to 95.1% one year following treatment in 2010 (Figure 1). There was an increase in cover of introduced annual grasses (Table 3). Overall similarity between plots decreased between years but the decrease was much more apparent in the treatment plots (Table 3).

Discussion

The protection and restoration of natural systems is the primary objective of invasive species management. Controlling environmental weeds in species diverse natural areas can be challenging; the control methods often cause off target damage and impact the recovery of native vegetation. Across the three plant communities included in this study, the control methods trialled resulted in a significant decrease in the cover of Terracina spurge over the study period together with an increase in cover of some native flora. In the coastal sedgelands, apart from a reduction in cover of Terracina spurge, an increase in cover of two dominant native sedges was the main contributor to the significant change in species diversity and cover that occurred following the first year of treatment. In the coastal shrublands, the main contributor to the change in species abundance was a decrease in cover of Terracina spurge. Although overall cover of native vegetation changed little in the twelve months following treatment, five of the six native species that contributed to change in species abundance showed a small increase in cover.

Metsulfuron-methyl, combined with hand removal of adults, in Banksia/eucalypt woodlands (Case study 1) resulted in off target damage to one of the dominant shrubs in the community, berry saltbush. This species was reduced to less <1% cover after five years of treatment. Another dominant shrub, yellow buttercups, also decreased in number between 2008 and 2009. Although this may partly be attributable to the herbicide application, this species is the specific host to moth larvae that was observed in unusually high numbers in 2008–9. This resulted in defoliation and a highly visible reduction in cover of yellow buttercups across the Banksia/eucalypt woodlands of Paganoni Swamp.

Although in this study metsulfuron-methyl in combination with hand removal resulted in some off target damage to native flora, it was effective, after five annual applications, in controlling Terracina spurge and the indications are that the Banksia woodland plant community within the treated area is starting to recover (Figure 2). However due to the off target damage and the fact that it took five years of treatment to bring cover down to less than 1%, metsulfuron-methyl in combination with hand removal should not be a preferred control option.

The longevity of this control program may be partly attributed to the soil disturbance caused by hand removal. Soil disturbance facilitates seed germination resulting in continued recruitment and persistence of the populations. Terracina spurge seed persist in the soil for three to five years with a percentage of the soil stored seed germinating each year (Cheam and Lee 1996). Most of the seed that does germinate is within the top 1 cm of the soil, with seed buried deeper in the soil profile remaining dormant (Cheam and Lee 1996). Soil disturbance brings seed closer to the surface and promotes germination (Riordan et al. 2008, Dorsey et al. 2010).

In contrast, triasulfuron was very effective, reducing Terracina spurge populations significantly in the first one to two years of the control program in the sedgelands with no seedling recruitment following the February 2008 fire. There is little published information on the response of the Terracina spurge seedbank to fire but based on observations elsewhere it was expected that fire would stimulate germination of any soil stored seed. Triasulfuron, as well as controlling adult plants, may have a residual effect on soil stored seed of Terracina spurge. Triasulfuron did not impact the plant communities of the coastal shrublands and the trend was for increasing cover of native vegetation following treatment. The results indicate triasulfuron is an effective tool for the management of Terracina spurge in coastal plant communities potentially leading to the protection and restoration of significant areas of the conservation estate within the Swan Coastal Plain bioregion and beyond.

In all three plant communities there was an increase in introduced annual grasses over the study period. Species included blowfly grass in the Banksia/eucalypt woodland, hare's tail grass in the sedgeland and annual veldt grass (*Ehrharta longiflora*), wild oats (*Avena* sp.), and hare's tail grass in the coastal shrublands. The increase in hare's tail grass in the sedgeland followed the fire in February 2008. Fire is often implicated in annual grass invasion in fragmented landscapes (Hobbs and Atkins 1991, Milberg and Lamont 1995, Keeley 2006) and the February 2008 fire event may have facilitated further establishment of hare's tail grass in the sedgelands. Annual grass invasion is also facilitated by enhanced availability of light, water and nutrients, particularly nitrogen (Hobbs and Atkins 1988, Prober et al. 2002, Bidwell et al. 2006). Light and water availability would have increased following a reduction in cover of Terracina spurge and the senescing biomass of Terracina spurge may have contributed to increased nutrient availability.

While we have developed an effective tool for managing Terracina spurge, an ecosystem approach to restoration of invaded communities (Zavaleta et al. 2001) will be required. The removal of Terracina spurge has protected large undisturbed areas of the conservation estate from invasion and facilitated an increase in the cover of native vegetation in previously invaded areas, however the disturbance caused by its removal also appears to have increased cover of annual grasses. Importantly those annual grass species, unlike Terracina spurge, are not considered serious weeds in the region (Bettink and Keighery 2008). Any restoration strategy for native vegetation invaded by Terracina spurge should consider the implications of increased cover of these introduced annual grasses and investigate methods to address possible causes.

Conclusions

Our results demonstrate Terracina spurge can be effectively managed where it is invading native plant communities and extensive areas of high conservation value bushlands can be protected from invasion. However, further trials are required in Banksia woodland to investigate off target damage of triasulfuron to associated native flora. The herbicide metsulfuron-methyl resulted in greater off target damage than triasulfuron and soil disturbance caused by physical removal of adult plants not killed by metsulfuron-methyl appeared to facilitate continued germination of soil stored seed of Terracina spurge. Therefore application of metsulfuron-methyl and physical removal are not the recommended control options for Terracina spurge invading native plant communities.

This study has significant implications for the management of Terracina spurge and the restoration of native plant communities in south-west Western Australia and other Mediterranean ecosystems where the species is invasive. Our results suggest that the herbicide triasulfuron can reduce populations of Terracina spurge significantly in the first years of a control program with little off target damage to co-occurring native species. In the plant communities of the coastal sedgelands and shrublands of south-west Australia, control of Terracina spurge with triasulfuron can facilitate recovery of native plant communities over time.

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References

Anderson, M.J., R.N. Gorley and K.R. Clarke. 2008. PERMANOVA+ for PRIMER: Guide to software and statistical methods. Plymouth, UK. PRIMER-E Ltd.

Australia's Virtual Herbarium. 2012. The Council of Heads of Australasian Herbaria. avh.chah.org.au.

Bettink, K. 2009. Geraldton carnation weed *Euphorbia terracina*: Draft strategic plan for the Swan NRM region. www.dpaw.wa.gov.au/images/documents/conservation-management/off-road-conservation/urban-nature/reports/euphorbia_terr_strategic_ plan_draft_dec_2009.pdf.

Bettink, K and G.J Keighery 2008. Environmental weed census and prioritisation, Swan NRM Region. Perth:Swan Catchment Council and Department of Environment and Conservation. www.dpaw.wa.gov.au/images/documents/conservation-management/off-road-conservation/urban-nature/reports/swan_environmental_weed_assessment_2008_summary.pdf

Bidwell, S., P.M. Attiwill and M.A. Adams. 2006. Nitrogen availability and weed invasion in a remnant native woodland in urban Melbourne. *Austral Ecology* 31:262–270.

Bonham, C.D. 1989. *Measurements for Terrestrial Vegetation*. New York, NY: John Wiley and Sons.

Braun-Blanquet, J. 1965. *Plant sociology: The study of plant communities*. London: Hafner.

Brown, K. and K. Brooks. 2002. *Bushland Weeds: A Practical Guide to their Management.* Greenwood, Australia: Environmental Weeds Action Network.

Cheam, A.H. and S.I. Lee. 1996. Ecology of Geraldton Carnation Weed. Western Australian Department of Agriculture. (unpublished data).

Clarke, K.R. 1993. Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* 18:117–143.

Clarke, K.R. and R.N. Gorley. 2006. PRIMER v6: User Manual/Tutorial. Plymouth. PRIMER-E Ltd.

Department of Environment and Conservation. 2011. Interim Recovery Plan 2011–2016 for Sedgelands in Holocene dune swales. Interim Recovery Plan No. 314. Perth, Australia: Department of Environment and Conservation.

Dorsey, A., E. Avina and C. Brigham. 2010. Euphorbia terracina: Why worry? 2010 Cal-IPC Proceedings, Ventura, CA, California Invasive Plant Council. www.cal-ipc.org/symposia/archive/pdf/Cal-IPCProceedings2010Web.pdf.

Elzinga, C.L., D.W. Salzer, J.W. Willoughby and J.P.Gibbs. 2001. *Monitoring Plant and Animal Populations*. Malden Massachusetts: Blackwell Science, Inc.

Flory, S.L. and K. Clay. 2009. Invasive plant removal method determines native plant community responses. *Journal of Applied Ecology* 4:434–442.

Gibson, N., B.J. Keighery, G.J. Keighery, A.H. Burbidge and M.N. Lyons. 1994. A floristic survey of the southern Swan Coastal Plain. Report for the Australian Heritage Commission prepared by the Department of Conservation and Land Management and the Conservation Council of Western Australia (Inc).

Government of Western Australia. 2010. Perth Biodiversity Project 2010 Remnant vegetation by vegetation complex dataset for Perth and Peel. pbp.walga.asn.au/Portals/1/Templates/docs/2010%20Remnant%20Veg%20Extent%20Stats.

Hobb, R.J. and L. Atkins. 1988. Effect of disturbance and nutrient addition on native and introduced annuals in plant communities in the Western Australian wheatbelt. *Australian Journal of Ecology* 13(2):171–179.

Hobb, R.J. and L. Atkins. 1988. Interactions between annuals and woody perennials in a Western Australian nature reserve. *Journal of Vegetation Science* 2:643–654.

Hulme, P.E. 2006. Beyond control: Wider implications for the management of biological invasions. *Journal of Applied Ecology* 43:835–847.

Keeley, J.E. 2006. Fire management impacts on invasive plants in the western United States. *Conservation Biology* 20:375–384

Keighery, G.J. and B.J. Keighery. 2007. Biology and weed risk in Western Australia. Pages 1–6 in Proceedings of the Geraldton Carnation Weed (*Euphorbia terracina*) Workshop and Field Day. June 21st 2007 pp. 1–6, a Skills for Nature Conservation Workshop organised by the Urban Nature Program of the Department of Environment and Conservation, Perth, held at the Naragebup Rockingham Regional Environment Centre, Peron, Western Australia.

Keith, D.A., T.G. Martin, E. McDonald-Madden and C. Walters. 2011. Uncertainty and adaptive management for biodiversity conservation. *Biological Conservation* 144:1175–1178.

Lesica, P. and D. Hanna. 2009. Effect of biological control on leafy spurge (*Euphorbia esula*) and diversity of associated grasslands over 14 years. *Invasive Plant Science and Management* 2:151–157.

Lindenmayer, D.H. and M.A. Burgman. 2005. *Practical Conservation Biology*. Collingwood, Victoria: CSIRO Publishing.

Margolius, R. and N. Salafsky. 1998. *Measures of Success: Designing, Managing, and Monitoring Conservation and Development Projects*. Washington, DC: Island Press.

Milberg, P and B.B. Lamont.1995. Fire enhances invasion of roadside vegetation in southwestern Australia. *Biological Conservation* 73:45–49.

Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A.B. da Fonseca and J. Kent. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403:853–858.

Parsons, W.T. and E.G. Cuthbertson. 2001. *Noxious weeds of Australia*. 2nd ed. Melbourne: Inkata Press.

Prober, S.M., K.R Thiele and I. Lunt. 2002. Identifying ecological barriers to restoration in temperate grassy woodlands: Soil changes associated with different degradation states. *Australian Journal of Botany* 50:699–712.

Riordan, E.C., P.W. Rundel, C. Brigham and J. Tiszler. 2008. Morphological traits and invasive potential of the alien *Euphorbia terracina* (Euphorbiaceae) in coastal southern California. *Madroño* 55:52–59.

Shea, K., H.P. Possingham, W.W. Murdoch and R. Roush. 2002. Active Adaptive Management in Insect Pest and Weed Control: Intervention with a Plan for Learning. *Ecological Applications* 12:927–936.

Smith, A.R. and T.G. Tutin. 1968. *Euphorbia* L. Pages 213–226 in T.G. Tutin, V.H. Heywood, N.A. Burges, D.M. Moore, D.H. Valentine, S.M. Walters and D.A. Webb (eds), *Flora Europaea: Plantaginaceae to Compositae (and Rubiaceae)*. Vol 4. Cambridge: Cambridge University Press.

Underwood, A.J. 1992. Beyond BACI; The detection of environmental impacts on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* 4:145–178.

WCSP. 2012. World Checklist of Selected Plant Families. Facilitated by the Royal Botanic Gardens, Kew. apps.kew.org/wcsp/.

Western Australian Herbarium. 1998. FloraBase: the Western Australian Flora. Department of Parks and Wildlife. florabase.dec.wa.gov.au/.

Zavaleta, E.S, R.J. Hobbs and H.A. Mooney. 2001. Viewing invasive species removal in a whole-ecosystem context. *Trends in Ecology & Evolution* 16:454–459.

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