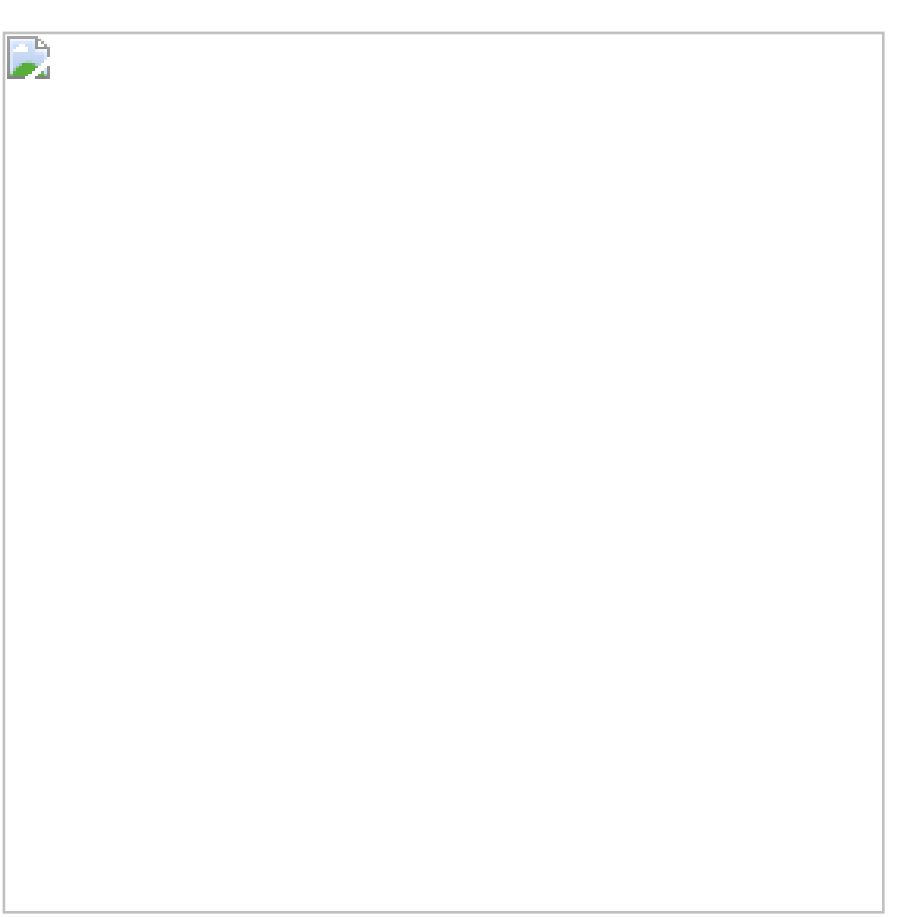

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A PROGRAM TO ERADICATE TWENTY-FOUR NONNATIVE INVASIVE PLANT SPECIES FROM SANTA CRUZ ISLAND

Coleen Cory[1] and John J. Knapp[2,3]

ABSTRACT.—Santa Cruz Island, California, has been free of nonnative vertebrates since 2007, but nonnative invasive plants remain one of the most significant threats to the recovery of the island's native ecosystems. Just over one-fourth of the island's flora is comprised of nonnative, naturalized plant species. In 2007, an island-wide invasive plant survey indicated that several species were candidates for eradication based on factors such as their distribution, abundance, invasiveness, and known or projected harmful impacts on the native biota. In 2008, The Nature Conservancy (TNC) and Native Range, Inc., initiated a program to eliminate 15 invasive plant species from TNC's portion (76%) of the 246-km^2 island. An additional 9 species were targeted in subsequent years. As of 2012, a total of 882 populations of 24 weed species have been mapped and treated, and 73% of these populations are considered inactive (dead), with no aboveground living biomass. The majority of the remaining active infestations are due to resurgence from the soil seed bank. Continued monitoring and annual follow-up treatments of invasive plants will be required. Utilization of a small helicopter provides surveyors and herbicide applicators with efficient access to remote infestations and a platform from which to treat populations and detect individual plants. Most important in achieving project success is consistent treatment from year to year, which prevents reproduction and recovery of infestations. Long-lived soil seed banks for some species will be a management issue for years to come. Continued commitment to eradicating these weeds and the ability to detect incipient infestations and respond rapidly to eliminate them will be key determinants of success of this program.

RESUMEN.—La Isla Santa Cruz, California, ha estado libre de vertebrados no-nativos desde el 2007, pero las plantas no nativas invasoras continúan siendo una de las amenazas más grandes para la recuperación de los ecosistemas nativos de la isla. Poco más de un cuarto de la flora de la isla comprende especies de plantas no nativas naturalizadas. En 2007, un monitoreo de plantas invasoras de la isla indicaba que varias especies eran candidatas para su erradicación, basándose en factores como su distribución, abundancia, diseminación e impactos dañinos conocidos o proyectados sobre la biota nativa. En 2008, The Nature Conservancy (TNC) y Native Range Inc. iniciaron un programa para eliminar 15 especies de plantas invasoras de la porción de TNC (76%) de la isla de 246 km^2. En los siguientes años se centraron en nueve especies adicionales. Para 2012, se han asignado y tratado un total de 882 poblaciones de 24 especies de herbáceas, y el 73% de estas poblaciones se consideran inactivas (muertas), sin biomasa viva por encima de la tierra. La mayoría de las infestaciones activas restantes son causa de la resurgencia del banco de semillas en el suelo. Se requerirá un monitoreo continuo y un seguimiento anual de los tratamientos de plantas invasoras. La utilización de un pequeño helicóptero proporciona a los topógrafos y a los que aplican los herbicidas un acceso eficiente a plagas remotas, como también una plataforma desde la cual tratar poblaciones e incluso detectar plantas individuales. Aún más importante que el éxito de este proyecto es el tratamiento continuo de año en año, el cual previene la reproducción y la recuperación de las plagas. Los bancos de semillas longevas de algunas especies será un tema de gestión para años venideros. El compromiso continuo por erradicar estas hierbas y la habilidad para detectar plagas incipientes y responder rápidamente para eliminarlas serán los determinantes clave del éxito de este programa.

The impact of invasive plants on wildlands around the world is enormous (D'Antonio and Vitousek 1992), and these invasives are a significant factor affecting the preservation of native biodiversity (D'Antonio and Meyerson 2002). Invasive weeds are plants that evolved in one region of the globe and then were introduced to another region, often without the predators and diseases that keep their numbers in check, thus providing these weeds with a competitive advantage over native plants in their new range (Cal-IPC website 2012). Many attempts to eradicate invasive plant species have been undertaken around the world (Rejmánek and Pitcairn 2002, Mack and Lonsdale 2002, Woldendorp and Bomford 2004, Simberloff 2009). Some efforts have been successful, but only when the total population size and number of populations was small. Additionally, many of these successful eradication projects targeted only one species, not a suite of weeds. Invasive species are

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considered the second greatest threat to biodiversity worldwide and are the leading cause of species extinctions in island ecosystems (IUCN 2011, SCBD 2013). While invasive species can be difficult to control or eradicate at continental scales, islands can provide an opportunity for managing invasive species in a contained and limited setting.

Santa Cruz Island (SCI) is the largest (246 km^2) of 8 Channel Islands, lying 35 km off the coast of southern California. The Nature Conservancy (TNC), a nonprofit conservation organization, assumed management of the western 90% of the island in 1978 and currently owns and manages 76% of the island as a nature preserve. The eastern 24% of the island is owned and managed by the National Park Service (NPS) as part of the Channel Islands National Park. The island is undeveloped and has no paved roads or commercial infrastructure. Two parallel mountain ranges create a major central valley and steep canyons that descend to the coastline off rugged peaks over 600 m high. The island, which lies within a Mediterranean biome, hosts several vegetation communities, including chaparral, coastal sage scrub, grasslands, oak woodlands, pine forests, and coastal strand (Junak et al. 1995, Cohen et al. 2009). The island is the most biologically diverse of the 8 southern California Channel Islands and is home to 12 endemic species, including the endemic Island Scrub-Jay (*Aphelocoma insularis*), 9 endangered or threatened plants, and the endangered Santa Cruz Island fox (*Urocyon littoralis santacruzae*) (Schoenherr et al. 1999).

When TNC began management of its portion of the island in 1978, the native landscape had been severely damaged by nearly 150 years of grazing and soil disturbance by nonnative ungulates, many of which were feral. Vegetation cover was minimal and erosion was widespread (Brumbaugh et al. 1982, Van Vuren and Coblentz 1987). Much of TNC and NPS's management attention over recent decades focused on removing those ungulates, the last of which were removed in 2007 (Morrison 2007). With those threats eliminated, more organizational attention is now focused on nonnative, habitat-modifying invasive plants—more commonly referred to as weeds. Many nonnative plants have been introduced to SCI since Europeans first occupied the island in the mid-1800s. By 1995, 170 nonnative plants (26% of the island's flora) were considered to be naturalized (Junak et al. 1995), though not all these nonnative plant species invade natural areas and disrupt native habitats.

Although limited weed control was conducted by TNC, the NPS, and volunteer organizations from the 1980s through 2006, no comprehensive weed map or management plan existed. In 2007, TNC and its contractor Native Range, Inc. (NRI), conducted an islandwide weed survey of 55 high-priority weeds that were selected based on expert opinion and statewide prioritization by the California Invasive Plant Council (Knapp et al. 2009). Weed locations were marked with a global positioning system (GPS) and entered into a geographic information system (GIS) program (ESRI ArcMap). The resulting map of weed distributions, along with input from weed experts and land managers, contributed to a TNC weed management strategy that initially targeted 15 weed species for total eradication from the island (Knapp et al. 2007). Information from the California Invasive Plant Council (Cal-IPC 2006) about invasiveness and detrimental ecological impacts of these weeds on native species, communities, and processes was also incorporated into decisions about which weeds to eliminate. An additional 9 weed species have been added to the list since then for a total of 24 species targeted for eradication (Table 1). A weed species will be declared "eradicated" when no aboveground living biomass has been observed for 5 years after its known soil seed bank viability.

In this paper, we describe weed eradication work conducted by The Nature Conservancy on TNC land on Santa Cruz Island from 2007 to 2012. We also discuss the elements that have led to successful eradication of the majority of targeted weed populations on SCI and the challenges that lie ahead.

METHODS

In 2008, TNC and NRI began treating populations of focal weeds on Santa Cruz Island based on the weed management strategy described in Knapp et al. (2007). At that time, there were over 360 populations of the 15 targeted weeds. A population can consist of 1 to over 100 individual plants, with an average population size of 9 m^2. A noncontiguous cluster of weeds separated by more than

TABLE 1. Weed species targeted for eradication on Santa Cruz Island. All species are found on TNC property; 11 are also found on NPS property. The Location column notes distinct characteristics of some populations. Population numbers represent TNC land only. Status is current as of June 2012.

Scientific name	Common name	Location	Year first treated by NRI[a]	Total pops.[b]	Inactive (dead) pops.	Active populations		
						Mapped 2008–2011, treated 2008–2012	Emergent (seed bank) pops.	Mapped 2012, treated 2012
Acacia decurrens	Green wattle	All on TNC land	2008	1	1	0	0	0
Acacia melanoxylon	Blackwood acacia	2 trees on NPS land at del Norte cabin	2008	86	51	0	25	10
Albizia lophantha	Plume acacia	NPS removing recruits on NPS land at Prisoners Harbor	2008	22	7	0	3	12
Carduus pycnocephalus ssp. *pycnocephalus*	Italian thistle	All on TNC land	2008	2	0	0	2	0
Centranthus ruber	Red valerian	All on TNC land	2012	5	4	1	0	0
Cortaderia selloana	Pampas grass	NPS and TNC removing on both properties	2008	121	84	0	33	4
Ehrharta erecta	Panic veldt grass	All on TNC land	2012	2	0	0	2	0
Eriogonum giganteum var. *giganteum* + hybrids	Saint Catherine's lace	All on TNC land	2008	36	28	2	5	1
Ficus carica	Fig tree	In landscaping at TNC Main Ranch & NPS Scorpion Ranch & Smugglers Ranch	2009	7	6	1	0	0
Genista monspessulana	French broom	All on TNC land	2008	67	15	4	48	0
Hedera canariensis	Canary Island ivy	In landscaping at NPS del Norte cabin	2011	15	8	3	3	1
Helichrysum petiolare	Licorice plant	All on TNC land	2008	13	0	13	0	0
Malva assurgentiflora	Catalina mallow	All on TNC land	2009	4	3	0	1	0
Oenothera xenogaura	Beeblossom	All on TNC land	2011	2	0	2	0	0
Olea europaea	European olive	NPS removing on NPS land, except in orchard at Smugglers Ranch	2008	10	9	0	0	1
Opuntia ficus-indica	Mission cactus	All on TNC land	2008	4	4	0	0	0
Pelargonium × *hortorum*	Garden geranium	In landscaping at TNC Main Ranch & NPS Scorpion Ranch	2009	5	2	2	1	0
Phalaris aquatica	Harding grass	Large populations on NPS land	2012	26	0	24	0	2
Pinus pinea	Italian stone pine	NPS removing on NPS land at Prisoners Harbor	2008	143	75	1	12	55
Rubus armeniacus	Himalayan blackberry	All on TNC land	2008	19	12	3	4	0
Schinus molle	Peruvian peppertree	In landscaping at NPS Scorpion Ranch & del Norte cabin; male trees in landscaping at TNC Main Ranch	2008	243	217	3	149	
Solanum elaeagnifolium	White horsenettle	All on TNC land	2009	3	1	0	2	0
Tamarix ramosissima	Tamarisk	NPS & TNC removing	2008	45	42	0	0	3
Washingtonia robusta	Mexican fan palm	1 tree at TNC Main Ranch	2008	1	1	0	0	0
TOTALS				882	570	59	155	98

[a]Native Range, Inc.
[b]Pops. = populations.

Fig. 1. Helicopter delivering technician to weed infestation in rugged terrain on Santa Cruz Island.

30 m (100 ft.) was designated a separate population (infestation).

Approximately 80% of these populations were located in remote, rugged, roadless areas of the island. For that reason, NRI utilized a small helicopter (Switzer 330 or Switzer 333) to deliver technicians to those weed infestations, where a variety of methods were used to kill weeds (Fig. 1). In some cases, weed technicians still needed stout ropes and determination to reach individual plants on sheer cliff faces (Fig. 2). These challenges prompted us to conduct an experimental trial to access and treat pampas grass (*Cortaderia selloana*) using herbicide ballistic technology (HBT; Leary 2012, Leary et al. 2012) from a helicopter platform. HBT involves encapsulating herbicide into paintball shells and using a pneumatic air gun (i.e., a paintball gun) to "shoot" isolated weeds. This high-concentration, low-volume herbicide application method delivers precise quantities of herbicide to targeted weeds and reduces off-target damage. When conducted from a helicopter, this method permits applicators to quickly treat small outlier populations and more safely treat weeds growing on steep vertical cliffs that might otherwise be unreachable.

Infestations nearer to established, unpaved roads were accessed by driving and then hiking to the weed sites. Most weeds were treated with herbicide applied as foliar spray or as part of a drill and fill, basal bark, or cut stump application. Glyphosate and triclopyr were the main herbicides used, along with aminopyralid for Italian thistle. As part of an integrated pest management approach, some smaller plants were hand removed when feasible.

Most weed populations were treated once per year. Weed treatments typically occurred over a 15–26-day period in spring of each year (2008–2012). An additional one-day visit was made in late winter to treat Italian thistle (*Carduus pycnocephalus* ssp. *pycnocephalus*). Occasionally, follow-up visits over the course of 3–4 days would occur in fall to treat pampas grass and other newly detected populations.

The weed team consisted of 2–8 weed technicians and a helicopter pilot. In addition to treating and monitoring weeds, all weed team members including the pilot were skilled at identifying weeds from the air and GPS mapping new weed locations on their way to and from known weed populations.

By the second year (2009), many of the original weed populations were dead. Encouraged by this early success, we added 4 weed species to the eradication list, and the number of targeted weed populations rose to just over 500. In subsequent years, as the number of

Fig. 2. Technician treating pampas grass on steep cliffs on Santa Cruz Island.

active weed populations decreased and the efficiency gained by using the helicopter increased, more populations of these weeds, along with more weed species (2 in 2011 and 3 in 2012), were added to the eradication list and treated. The number of treated (active) or monitored (dead) populations increased to 784 in 2011 and finally to 882 in 2012. Despite more than doubling the number of targeted weed populations, the annual cost decreased by approximately 50% over 6 years due to treatment efficacy and efficient implementation. We estimated that between 12 and 15 weed populations could be treated in a day by one weed technician. It generally took more time to relocate dead infestations which had either washed or withered away and to confirm that populations presumed to have been eradicated had not emerged from the seed bank than it did to relocate and treat active weed populations.

When grouped by habitat (USDA–NRCS 2013), targeted weeds consisted of trees, shrubs, herbs or forbs, and perennial grasses. Nine (37%) of the targeted weed species were trees: green wattle (*Acacia decurrens*), blackwood acacia (*Acacia melanoxylon*), plume acacia (*Albizia lophantha*), fig (*Ficus carica*), olive (*Olea europaea*), Italian stone pine (*Pinus pinea*), Peruvian peppertree (*Schinus molle*), tamarisk (*Tamarix ramosissima*), and Mexican fan palm (*Washingtonia robusta*). Seven (29%) were shrubs: French broom (*Genista monspessulana*), St. Catherine's lace (*Eriogonum giganteum* var. *giganteum*), Canary Island ivy (*Hedera canariensis*), licorice plant (*Helichrysum petiolare*), Catalina mallow (*Malva assurgentiflora*), mission cactus (*Opuntia ficus-indica*), and Himalayan blackberry (*Rubus armeniacus*). Five (21%) were herbs or forbs: Italian thistle, red valerian (*Centranthus ruber*), beeblossom (*Oenothera xenogaura*), garden geranium (*Pelargonium* × *hortorum*), and white horsenettle (*Solanum elaeagnifolium*). Three (13%) were perennial grasses: pampas grass, panic Veldt grass (*Ehrharta erecta*), and Harding grass (*Phalaris aquatica*). Thirteen of the targeted weeds were known to occur only on TNC property, whereas 11 were known to occur on both TNC and NPS properties (Table 1, Fig. 3). Most of these targeted weeds that occur on NPS property are being treated by NPS staff, with an aim of achieving island-wide eradication.

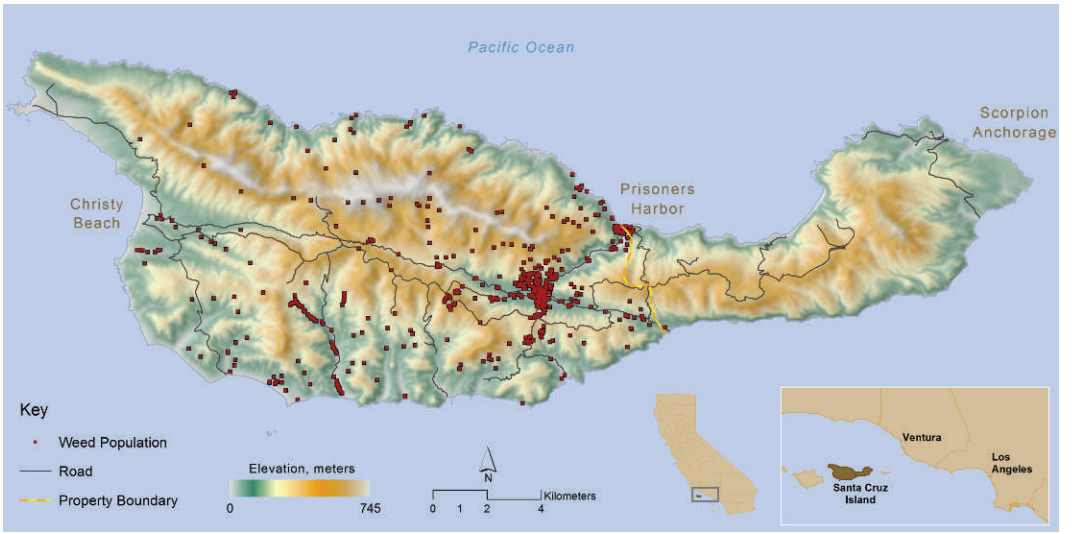

Fig. 3. Location of weed populations targeted for eradication on TNC property on Santa Cruz Island.

In some cases, the targeted weeds were escapees from landscape plantings around historic ranch buildings or areas of human activity (e.g., Peruvian peppertree, European olive). In these cases, special management actions have been implemented both by TNC and NPS to preserve the historic integrity of the cultural landscape. For example, in the case of Peruvian peppertrees (planted near the TNC Main Ranch compound in the central valley of the island and at Scorpion Ranch on the east end of the island), only female trees were removed and the non-seed-producing male trees were left in place. The sole Mexican fan palm at the Main Ranch was also left in place, because viable seeds from it have not been observed.

RESULTS

At the end of 2011, 784 weed populations comprising 21 weed species had been mapped and treated in one or more years from 2008 to 2011. The number of years each population was treated depended on the year it was first detected and whether any live aboveground parts were visible each year. By 2012, 570 (73%) of these populations were inactive, meaning no aboveground living biomass was present at that location. The other 214 (27%) populations were active, meaning portions of the original plant were still alive or seedlings had emerged from the seed bank (Fig. 4).

While conducting the 2012 remote-location weed work, an additional 98 populations of our 24 targeted weed species were mapped and treated for the first time, bringing the total number of mapped and treated weed populations to 882. Among these additional populations were 33 populations of 3 weed species first added to our eradication list in 2012 (Table 1). Despite being treated when first discovered in 2012, these 33 new populations must be considered active until they are revisited and reassessed during the 2013 season.

Of 784 populations mapped and treated between 2008 and 2011, 214 were still active in 2012. One hundred fifty-five (72%) were active due to resurgence from the seed bank around now-dead parent plants (Table 1). However, once a weed population was targeted for removal and treated, all seed production was stopped at that location.

Three weed species (mission cactus, green wattle, and Mexican fan palm) appear to have been eradicated from native habitats on TNC property. Live biomass from green wattle and fan palm has not been observed since 2009, and none has been observed from mission cactus since 2011. One fan palm remains in the landscaping at the TNC Main Ranch, another was eliminated on the west end of the island, and seedlings have not been observed near or far from the parent plant at either location since mapping occurred in 2007.

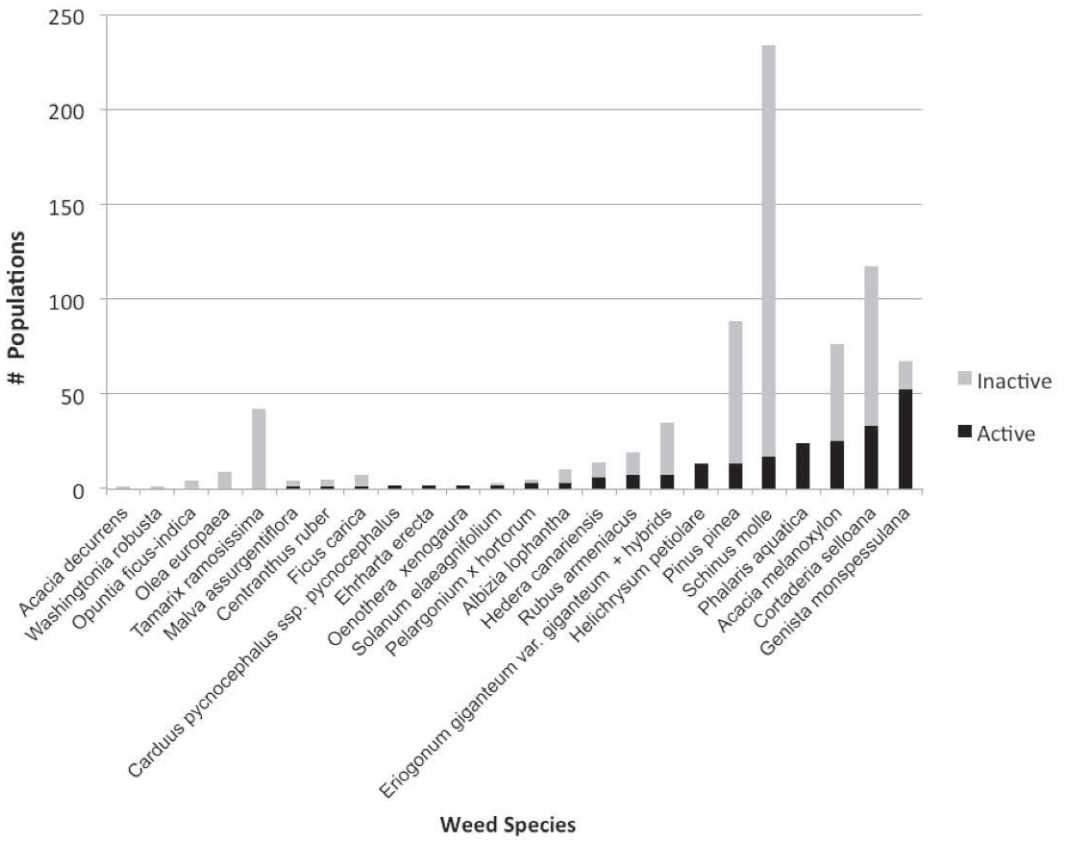

Fig. 4. Number of known active (alive) and inactive (dead) targeted weed populations as of June 2012 on TNC property on Santa Cruz Island. A weed population can consist of 1 to over 100 individual plants. A noncontiguous cluster of weeds separated by more than 30 m (100 ft.) is considered a separate population (infestation). Numbers do not include the 90 new weed populations found, mapped, and treated for the first time in 2012.

Based on past success and current weed population distributions and conditions, we anticipate that all wild populations of another 4 weed species will become inactive by 2014. St. Catherine's lace and its hybrids (Catalina mallow, fig trees, and olive trees) will likely be counted with mission cactus, green wattle, and Mexican fan palm as eradicated from the wild on Santa Cruz Island.

DISCUSSION

Several factors have contributed to the ongoing success of the TNC weed program on Santa Cruz Island. Foremost was an island-wide weed map and a weed plan that thoughtfully evaluated and ranked the highest priority weeds to target for eradication. Rather than base our actions on weeds that were most visible, accessible, or personally annoying, we assessed weed presence, distribution, density, tractability, and ability to disrupt native ecosystems as part of the process for selecting weeds to eradicate from the island. This is why we did not choose widespread weed species covering more than 100 ha.

Using a GIS database (ESRI ArcMap) to map and track locations and status of weed populations from year to year allows weed workers to return to precise locations to re-treat weeds and to monitor infestations that were previously treated, displayed no aboveground biomass, and would otherwise be difficult to relocate. The database also allows us to track efficacy and timing of treatments. The attention to detail and continuity in staffing allows individual weed technicians to recognize and remember idiosyncrasies of specific sites for

more efficient treatment and monitoring. A small helicopter is essential for detecting and accessing the many weed populations that are located away from roads, often in steep, rugged terrain. Without this tool, we estimate that the time needed to access and treat or monitor the over 800 populations would have required a much larger crew and nearly 10–12 months instead of 2–4 weeks (Knapp et al. 2011).

Long-term institutional commitment by SCI land managers to achieve weed eradication allowed consistent monitoring and treatment of weed populations with helicopter support prior to seed set. As a result, we were able to stop reproduction of all 24 targeted weeds on TNC property and eliminate nearly 98% of the original weed populations mapped between 2008 and 2011. A variety of individuals, agencies, and volunteer groups participate in weed control on the island, and it is essential to coordinate their activities so duplication of effort does not occur and all actions are tracked. Good communication among field technicians, staff, and partners through quarterly meetings, phone calls, emails, and shared databases facilitate the recording of new weed locations and weed treatment activities. The agreement between TNC and NPS to treat most of the shared targeted weeds on both sides of the jurisdictional property line puts island-wide eradication within our reach.

Several challenges face us at this juncture. Weed germination and flowering times vary from year to year depending on temperature and the timing and amount of rainfall. This variability complicates advanced planning and scheduling of weed treatments because staff and contractors may not always be available at the optimal time for weeds to be treated.

Invasive plants could still arrive and establish on the island by blowing in on winds from the mainland or from adjacent islands, floating in on ocean currents, or hitchhiking on visitors' boots or camping gear. Fortunately, NPS is actively managing invasive plants on neighboring islands within the Channel Islands National Park. Biosecurity measures have been enacted by TNC and NPS and continue to be strengthened for Santa Cruz Island (Boser et al. 2014). In order to detect possible new weed infestations, however, it would be wise to conduct periodic comprehensive island-wide weed surveys, which can then serve as the basis for revising and updating the weed management strategy.

We must continue to find and treat weeds before they reproduce to stop the cycle of growth and expansion. Detection is becoming more difficult as native vegetation recovers from decades of feral ungulate grazing, grows tall and dense, and obscures small weeds and seedlings. If we wait for the weeds to get larger, they may reproduce before they are seen and treated. Although weeds in flower are often easier to detect in the landscape, it is too late in that stage to stop their reproductive cycle. But the greater challenge to total elimination of a weed population for most of the targeted species is the presence of a persistent soil seed bank. Some of these weeds, especially those in the pea family (Fabaceae), have long-lived seeds that can lie dormant in the soil for many years until favorable conditions trigger their germination (Bossard et al. 2000, Coffey and Kirkman 2006, DiTomaso and Healy 2007, Kaeser and Kirkman 2012). Blackwood acacia, French broom, and plume acacia are fabaceous weeds that we are aiming to eradicate on SCI. Weed managers must diligently monitor these locations for many years to ensure no seed has sprouted. In the years ahead, we will continue to visit every population and treat any seedlings emerging from the latent seed bank before they have a chance to produce more seeds. Over time, the seed banks will dwindle and become exhausted.

Weed eradication is a multiyear undertaking. The GIS database that tracks weed locations and treatments and the written weed strategy were developed to help preserve institutional memory when staff turnover occurs. Continuity must also be maintained through adequate funding and institutional commitment. As the number of weeds decreases, support and funding can disappear because the weed is not as visible and is no longer perceived as a threat. Starting a project of any sort is often exciting and enticing. Successfully completing a project can be satisfying and laudable. But maintaining commitment and interest during the long hard work between project start and finish is difficult. Adequate attention, funding, and staffing is needed to eventually accomplish weed eradication.

Knowing that weed eradication programs are often long campaigns and that there are limited conservation dollars and competing priorities, we sought to achieve eradication success as quickly as possible. We evaluated the

strengths and shortcomings of many weed management programs and adopted strategies that worked consistently across programs. Santa Cruz is an island but so too are many mainland parks and preserves that are surrounded by development. The strategies utilized on SCI have been adopted and modified to eradicate invasive plants elsewhere in California (Knapp and Knapp 2010, Burger et al. 2012) and have shown similar results.

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