The Santa Margarita River *Arundo donax* Control Project: Development of Methods and Plant Community Response[1]

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Abstract

A large-scale effort to control the aggressively invasive exotic species *Arundo donax* in the Santa Margarita River watershed in California's south coast ecoregion was initiated in 1997. The project was prompted by the need for Marine Corps Base Camp Pendleton to address impacts to habitat for federally-listed endangered species and wetlands regulated by the Army Corps of Engineers. As of 2000, 27 km of the main stem of the Santa Margarita River had been treated. The methods employed were tested in preliminary trials before widespread implementation; additional techniques emerged during the course of the project. Although the primary target is *A. donax*, 14 other invasive exotic species that also threaten riparian ecosystem functions were treated when encountered. Vegetation-monitoring transects were established in *A. donax* removal areas to document the effectiveness of the different treatments and recovery of plant communities. *A. donax* was reduced by over 90 percent after the first treatment and accounted for less than 2 percent absolute cover after three follow-up annual treatments. An experiment testing low-cost methods for establishing woody species after *A. donax* control was also conducted. Cuttings were installed with no follow-up maintenance. Approximately 30 percent of *Baccharis salicifolia* and large (3-6 m) willow cuttings survived 2 years.

Key words: Arundo donax control, invasive species, riparian restoration, Santa Margarita River

Introduction

Arundo donax is an invasive, non-native plant seriously impacting much of the riparian habitat throughout coastal California including Marine Corps Base Camp Pendleton. It is estimated to have infested 68 percent of the riparian vegetation in the central portion of the Santa Ana River (Douthit 1993) and is thought to be the most serious exotic pest plant problem in southern California coastal rivers (Bell 1998). It grows up to 10 m tall and can be found in small clumps to monocultures of hundreds of hectares (Cummins and Zedler 1998, Dudley 2000). It is not known to produce viable seed in the western United States, and so it spreads only vegetatively through rhizomes or stem fragments (Dudley 2000). Establishment from vegetative parts requires either burial in deep, moist layers of soil or near-saturated conditions at the surface for prolonged periods. Therefore, establishment of new patches occurs primarily in conjunction with flooding. Between flood events, spread occurs outward from existing patches (Else 1996). Prior to initiation of control on the Santa

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Margarita River on Camp Pendleton, *A. donax* occupied approximately 26 percent of the riparian system, including 13 percent of the 2-year floodplain (bankfull channel geomorphic surface), 39 percent of the 2-10-year floodplain (active floodplain geomorphic surface) and 23 percent of the riparian system outside of the 10-year floodplain (terrace geomorphic surface) (Cummins and Zedler 1998, Smith and Lichvar 1999). The total area infested (greater than 80 percent *A. donax* cover) in the watershed prior to treatment was estimated at 300 ha (260 ha on Camp Pendleton and 40 ha upstream) on over 40 km of the main stem and tributaries (Giessow, unpubl. data).

Need for Control

Large stands of *A. donax* displace native vegetation and associated wildlife species and increase flood and fire hazard (Bell 1998, Dudley 2000). On the Santa Margarita River, three endangered species have suffered habitat loss resulting from invasion of *A. donax*: *Vireo bellii pusillus* (least Bell's vireo), *Empidonax traillii extimus* (southwestern willow flycatcher), and *Bufo californicus* (arroyo toad). On the Base, habitat loss resulting from *A. donax* invasion is considered to pose the greatest threat to arroyo toads (ACS/ES Camp Pendleton, 1994), which likely are unable to move through dense stands (Lovich and others 2001). In San Diego County, however, most riparian restoration has been done to mitigate impacts to the least Bell's vireo (Kus 1998).

Because riparian communities are adapted to high levels of natural disturbance, one strategy proposed for recovery of these systems is to remove *A. donax* and other invasive exotics and rely on natural flood dynamics for the recovery of native communities. Because of the high cost of restoration of woody riparian habitats, *A. donax* removal followed by natural re-colonization by native species achieves a cost savings that allows much larger areas to be restored (Bell 1998). On Camp Pendleton, *A. donax* control, with or without replanting of native vegetation, serves to mitigate temporary and permanent impacts to endangered riparian species. This is based on the premises that natural processes will result in the recovery of native habitats that support the listed species and that control will prevent future habitat losses from anticipated *A. donax* spread (ACS/ES Camp Pendleton 1994, Babbitt and others 1995).

Strategies for Control

Control efforts need to be coordinated and sustained due to the sheer size of the effort required to eradicate *A. donax* (Bell 1998). At the current cost of $49,000 per ha for eradication (initial control and 19 years of follow-up), the total cost to eradicate *A. donax* from the Santa Margarita River watershed is estimated at $15,000,000 (J. Giessow unpubl. data[4]). It is unlikely that such a sum is available from a single source, even in smaller amounts spread over time, and consequently, it is likely that there will be discontinuities in control efforts between the beginning and the end of eradication.

Throughout southern California, restoration of riparian habitat is compromised by *A. donax* invasions of restored sites (Stein 1998). Because *A. donax* establishes readily from vegetative fragments, but not from seed, it was evident that control at

[4] Unpublished data on file at Dendra Inc. 1003 Hygeia Ave. Encinitas, CA 92024

the Santa Margarita River should proceed from the upstream portions of the watershed downstream. Without this approach, removal in the lower reaches would be only temporary, because dispersal of vegetative parts downstream would reestablish populations. The lack of seed production means that once *A. donax* is removed from a drainage in this manner, it can remain free of *A. donax* indefinitely. Reintroduction by human activities (for example, illegal dumping of yard trimmings) can occur, but it is rare enough that periodic checks should be sufficient to prevent its reestablishment. The likelihood of discontinuities in the overall control effort heightens the need to begin upstream.

Site-specific control methods needed to be developed where *A. donax* was intermixed or adjacent to habitat for federally listed species, to avoid direct and indirect impacts to those species as required under the Federal Endangered Species Act. This was achieved through limits on control activities during the breeding season for southwestern willow flycatchers and least Bell's vireos (March 15 to August 31) and the use of methods that minimize damage to native woody species during control activities. To avoid damaging egg masses of arroyo toads, *A. donax* control is limited during the toad breeding season, generally from February 1 to July 15. In addition, activities are minimized near damp sandy areas during September to avoid impacts to juvenile arroyo toads.

The most effective time to begin control using foliar spray treatments is August, when the plant begins to move photosynthate into the rhizomes after flowering but before the onset of winter dormancy, when leaves turn yellow, usually beginning in November (Bell 1998). Because of the need to avoid impacts to endangered species, the actual time available for foliar herbicide application is approximately 8 to 10 weeks per year, from mid-September to the onset of winter dormancy. Mechanical control theoretically can occur at any time, but it is restricted during the spring breeding season. Occasional exceptions have been made in informal consultation with the U.S. Fish and Wildlife Service, allowing control during the breeding season in large, solid stands of *A. donax* and toward the end of the breeding season in August if it could be documented that all nesting endangered species had left the area.

In 1994, the U.S. Army Corps of Engineers issued permits for three actions under the Clean Water Act that required on-site *A. donax* control one to four times. In 1995, at the request of the Marine Corps, the Corps of Engineers modified the permits to consolidate the control efforts, move them upstream, and extend the length of control to 5 years. To accomplish this, the Marine Corps partnered with The Nature Conservancy, the Mission Resource Conservation District, and private land owners to move mitigation commitments as far as possible upstream in the watershed. This consolidated project was conducted as an experiment to test control methods for watershed-wide eradication. Our objectives were to document treatment effectiveness on *A. donax* removal, improve methods as we learned more, document and minimize costs of treatment, and monitor plant community recovery. Our expectation was that *A. donax* could be removed on a large scale and that within 5 years the cover would be at a maintenance level of less than 5 percent. Plant community recovery objectives were defined by numerical targets for areas of riparian habitat throughout the Base. When it became clear that watershed-wide eradication of *A. donax* was feasible and the recovery of woody species was proceeding slowly, we added a restoration component to evaluate inexpensive methods of woody-species establishment. Because least Bell's vireos are one of the primary target species intended to benefit from ecosystem recovery following *A. donax* control, we focused our attention on the recovery of native woody species. As of fall 2000, *A. donax* treatments had been initiated and were in various stages of completion on 43 km of the river. All of the control projects were initially funded for 5 years of treatment.

Methods

Treatment of A. donax

Based on our initial evaluation of methods, we selected foliar application of a 6 percent glyphosate solution as the primary method of control (Giessow and Giessow 1998). We used a second approach, the cut stem method, where there was a risk of overspray onto native species from foliar application. With the cut stem method, *A. donax* stalks are cut close to the ground and herbicide (100 percent solution) applied within two minutes of cutting. In solid stands of *A. donax* with only isolated small willows (less than 5-cm diameter stems), the willows were cut back to 1 m in height, and plastic bags were placed over them prior to foliar herbicide application in an effort to foster post-treatment site recovery. A concerted effort was made with both methods to preserve as much native woody vegetation as possible within and adjacent to treatment areas to enhance site recovery. These individuals provide seed and propagules for vegetative reproduction.

Approximately 8 km of river supporting 25 ha of *A. donax* was treated with foliar application of herbicide between September and November 1997. Crews used 4-wheeled all terrain vehicles (ATV) with a 190-liter (50-gallon) power sprayer and 30-50 m of hose to access sites. Typically, one ATV was used to haul the pesticide and spray equipment, with crew members following on foot. When sites were over about 1.5 km from the access point, filtered creek water was used to mix with the herbicide. Use of the filtered creek water led to increased maintenance costs for the sprayers, so the cost of travel was balanced against the maintenance costs. Because the *A. donax* clumps were too dense to penetrate, coverage of central stems within large clumps was obtained by spraying from a 7-m aluminum extension ladder. To ensure that all stems were sprayed, patches larger than 10-15 m across were accessed from 1-m wide trails cut through them.

Because of access and cost considerations, the foliar treatment was not followed by cutting and/or mowing of dead stems. Three primary concerns developed regarding leaving dead standing biomass: 1) the dead stems would be more likely than live *A. donax* to wash downstream and become lodged behind bridges, 2) dead standing material is a fire hazard, and 3) the addition of so much dead material to the river system would alter habitat for sensitive estuarine species such as tidewater gobies (*Eucyclogobius newberryi)*. The concern for bridges was high because of past problems at Camp Pendleton caused by vegetation, including *A. donax,* during flood events. We subsequently addressed the fire hazard in part by manually knocking down strips of dead *A. donax* (leaving the stalks on the ground) to act as fire breaks.

Removing and processing *A. donax* biomass can be difficult and costly. Huge volumes of material are generated (up to 45 kg m^{-2}) when the biomass is removed (A.H.B.M. Wijte pers. comm.). In addition, removal of biomass is not always possible in remote sections of the river with little access or in areas where damage to habitats supporting federally listed endangered species would result. These concerns led to the initiation in 1997 of experimentation with mechanical removal of the entire plant. Approximately 3 ha were treated in an initial mechanical control project in the fall of 1997. Both stems and rhizomes were removed with a clamshell bucket on a trackhoe or excavator and processed through a tub grinder to minimize potential for resprouting and make the material re-usable as mulch. To avoid impacts to native species, this method was used only in solid stands where access without damage to native woody species was feasible. Starting in 1999, we were required by Air Pollution Control District regulations to spray water for dust control as the biomass was being ground. After extraction of the stalks and rhizomes with the track hoe, laborers walked over the site and removed remaining pieces of rhizomes. Scattered resprouting from missed pieces of rhizome were either pulled by hand or treated with herbicide.

Resprouts from both the mechanical and cut stem methods were often retreated with foliar spraying the following spring. This was done to prevent the *A. donax* stalks from growing so tall that the less effective cut stem method was again required in the fall to avoid overspray onto native species. Native woody vegetation 3 m or taller can be avoided using mechanical removal, although *A. donax* left near those plants must be treated using cut stem or foliar herbicide application.

Vegetation Monitoring

Twenty-one transects were established in 1997 to monitor the effectiveness of the foliar *A. donax* treatment. The locations of all transects were recorded at sub-meter accuracy using a Trimble Pro XR GPS (global positioning system) unit. The transects varied in length from 12 m to 39 m and extended 2-5 m beyond the *A. donax* patch measured. Due to the small size of the mechanically treated area, only two transects were established, both 50 m in length.

Initial sampling was carried out from October to November 1997 after the first *A. donax* control treatments had been applied. Re-sampling was conducted in October 1998, 1999 and 2000. Fall, rather than spring, sampling was done to minimize activities in least Bell's vireo habitat during the breeding season.

Aerial vegetation and ground cover were recorded every meter along the transect line using the point intercept method (Bonham 1989). At each point, a height pole was held vertically and the composition of the canopy cover described by recording the species of every plant that intersected the pole. Height of each plant contacting the pole was recorded to the nearest 0.1 m. The number and type of *A. donax* resprouts (rhizome or branch) were recorded within a 1-m belt along the length of the transect. Surface soil texture was measured for all transects using a sedimentation test in which soil aggregates were dissolved; and the proportions of sand, silt and clay were determined based on the quantity of soil settling during specified time periods.

The percentage of absolute foliar cover was calculated by summing all of the interceptions for each species along a transect and dividing by the number of points on the transect. Species were grouped for analysis by life form (herb, tree, or shrub) and origin (native or exotic) into the categories *A. donax*, exotic herbs, native herbs, native shrubs, native trees, and no vegetation. The herbaceous categories included all non-woody species except *A. donax*. The dominant species within the exotic and native herb communities were determined from a tally of herb-species interceptions within each treatment. Native trees included *Salix lasiolepis*, *S. laevigata*, *S. gooddingii*, and *Populus fremontii*, while native shrubs included *Baccharis salicifolia*, *S. exigua*, *Vitis girdiana*, *Toxicodendron diversiloba*, *Malacothamnus fasciculatus*, and *Sambucus mexicana*. The "no vegetation" category included all points with no live aerial cover.

The initial vegetation composition (pre-treatment) at each site was estimated from the immediate post-treatment data with the aid of aerial photographs taken at a scale of 1:3000 in October 1997. Pre-treatment shrub and tree cover was assumed to be equal to post-treatment cover. Pre-treatment *A. donax* cover was based on the physical presence of stalks on the transect.

A linear regression model was used to evaluate the effects of treatment, floodplain position (active floodplain or terrace), and soil texture (expressed as percent sand) over time on absolute vegetation cover by life form. *A. donax* resprouting (resprout density) over 2 years following foliar herbicide treatment was analyzed using linear regression. Annual changes in percent absolute foliar cover within treatments were evaluated using Student's t-tests.

Site Restoration

A. donax was mechanically removed from a 25-ha site 11 km from the river mouth during fall 1999/winter 2000. A small-scale restoration experiment was carried out in January 2001 within 30 5x5-m plots to test the effect of mulching on survival of cuttings planted to revegetate the site. Fifteen plots were covered with a 25 cm thick layer of mulch consisting of chipped *A. donax* ranging from 1-15 cm in length. Because stem and root fragments of *A. donax* rarely sprout when spread at this depth (Lawson and Smead 2001), we chose it as the mulch material.

All 30 plots were planted with three pole cuttings and five whip cuttings. The pole cuttings were willows (*S. exigua*, *S. lasiolepis*, or *S. gooddingii*); whip cuttings consisted of two *B. salicifolia* and three willows. All plant material was collected locally. Pole cuttings 3-6 m in length were planted 2.5-3 m deep in holes that were drilled with a 3-m auger. Whip cuttings 50-125 cm long were planted 25-50 cm deep. The whip cuttings were scarified at the base to encourage root formation and planted using rooting hormone. Typically, the surface soils were moist from 20-30 cm but dry until the upper fringe of the groundwater was encountered 0.5-2 m deep. The bottom 30 cm of most holes was moist or saturated. A few locations were completely dry below the moist surface. Most holes were silty sand for the entire profile, although some were coarse sand. Poles were watered before and after cuttings were planted with approximately 20 liters of water.

Survival and canopy dimensions were measured after 2 years, in January 2003. Canopy volume was calculated from the canopy dimensions using volume formulas based on the shape of the plant (Ludwig and others 1975 in Bonham 1989). Surface soil texture was measured and expressed as percent sand for each plot using the sedimentation test described above.

The effect of treatment (mulch, no mulch) on survival and canopy volume of *B. salicifolia* and of willows after 2 years was analyzed using linear regression with percent sand and distance from the active river channel as covariates.

Results

Response of A. donax *to Treatment*

A wildfire burned 7 of the 21 foliar transects in September 1998 prior to the 1998 sampling. To control for the effect of fire on our results, the burned and unburned transects were analyzed separately in all years.

Live *A. donax* foliar cover was reduced by more than 90 percent after 1 year and by almost 100 percent after 3 years with both the foliar spray and mechanical removal (*table 1*). While it is difficult to provide an exact measure of kill because there is no practical way to measure the amount of live rhizomes underground, both methods effectively killed the plants, including rhizomes, with very little resprouting in subsequent years.

In 1998 and 1999, all live *A. donax* cover on the burned transects was the result of rhizome resprouting. In the unburned stands, *A. donax* stem density averaged 0.04 m^{-2} in 1998 and 0.02 m^{-2} in 1999, while in the burned stands it averaged 0.06 m^{-2} in 1998 and 0.19 m^{-2} in 1999. Rhizome sprouting appears to have been stimulated by the burns; however, the difference in resprouting between the burned and unburned stands was not statistically significant ($F = 1.56$, $df = 41$; $p = 0.21$).

Table 1—*Mean percent absolute cover by life form following foliar spray (n=14 transects), foliar spray/burn (n=7 transects), and mechanical removal (n=2 transects).*

	1997	1998	1999	2000
Foliar Treatment (*df*=3)				
A. donax	68.0[1] (20.0)[2] a	1.5 (4.1) b	0.0 (0.0) b	1.4 (4.3) b
Exotic Herb	22.5 (18.6)	30.4 (22.0)	47.6 (31.6)	52.4 (47.8)
Native Herb	28.1 (32.3)	44.3 (30.5)	27.7 (37.9)	26.9 (20.9)
Native Shrub	15.4 (23.1)	6.4 (9.3)	9.6 (14.4)	11.3 (20.4)
Native Tree	23.9 (20.7)	11.7 (11.1)	15.8 (20.1)	22.2 (24.4)
No Vegetation	8.3 (17.4)	37.1 (22.1)	29.3 (23.4)	25.4 (14.1)
Foliar Treatment-Burned (*df*=3)				
A. donax	92.2 (6.1) a	1.6 *[3] (2.8) b	1.4 (2.5) b	0.0 (0.0) b
Exotic Herb	9.3 (11.2)	1.8* (2.5)	63.1 (22.4)	88.0 (29.8)
Native Herb	5.7 (6.7)	3.3* (2.4)	35.4 (13.3)	33.5 (13.6)
Native Shrub	6.3 (14.9)	0.0* (0.0)	3.5 (7.5)	12.4 (23.5)
Native Tree	22.5 (23.5)	0.0* (0.0)	7.2 (6.9)	11.4 (9.9)
No vegetation	0.9 (2.3)	93.8* (6.1)	25.1 (15.9)	6.9 (6.0)
Mechanical Treatment (*df*=3)				
A. donax	100.0 (0.0) a	7.9 (11.1) b	0.0 (0.0) b	0.0 (0.0) b
Exotic Herb	0.0 (0.0) a	147.1 (22.1) b	100.0 (13.9) c	93.2 (15.2) c
Native Herb	0.0 (0.0)	52.9 (13.9)	23.5 (27.7)	53.0 (44.3)
Native Shrub	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	2.0 (2.8)
Native Tree	0.0 (0.0)	0.0 (0.0)	1.0 (1.4)	0.0 (0.0)
No Vegetation	0.0 (0.0)	3.0 (4.2)	2.0 (2.8)	3.9 (5.5)

[1] Mean separation using Student's t-tests. Means within a row followed by the same letter are not significantly different at p = 0.05.
[2] Values in parentheses are one standard deviation.
[3] Means followed by an * were from plots sampled 1 month after a wildfire.

If *A. donax* is not killed completely by the herbicide, sprouting may occur at the leaf and branch nodes on the stems. In an earlier study, plants that by their above-ground appearance were thought to be dead resprouted over a year after treatment (Giessow and Giessow 1998); we saw this occasionally during this study as well. These resprouts were easy to kill with one foliar herbicide application. Although we did not monitor individual plants, where leaf and branch node sprouts were detected on transects none were found the year following re-treatment. In 1998, eight sprouts were counted on two transects; they were treated, and none were detected in those transects in 1999. Likewise, five sprouts were detected on two different transects in 1999; by 2000 there were none.

Plant Community Development

The influence of floodplain position and soil texture on absolute vegetation cover by life form was analyzed separately for the burned and unburned foliar-treated sites using linear regression. In the unburned foliar-treated transects, the only significant response to treatment other than the decrease in *A. donax* was an increase in native herb cover. Native herbs increased in cover as a function of two two-way interactions between year and floodplain position ($F = 2.72$; $p = 0.06$) and floodplain position and percent sand, which ranged from 63 to 98 percent ($F=7.19$; $p=0.01$), revealing that floodplain position influenced native herb growth in certain soil types, but in a manner inconsistent across years. In 2000, but not in other years, the percent cover of native herbs decreased in coarser soils in the terrace but not in the active floodplain. No significant changes in vegetation cover occurred on the burned transects other than the decline in *A. donax* cover.

The post-treatment exotic herb community was dominated by *Hirschfeldia incana* in all years, followed by *Conium maculatum, Melilotus alba,* and *Chenopodium album*. *Artemisia douglasiana* was the most frequently encountered native herb in all years except 1998, when it was the second most frequent. *Phacelia cicutaria* was the next most frequently encountered native herb, followed by *Ambrosia acanthicarpa*. While absolute cover of herbs varied by treatment and year, the same species dominated.

Cover of native trees and shrubs was initially low on all treated areas, and none of the changes over the course of the study were significant. However, while not statistically significant, absolute cover of both trees and shrubs on the unburned transects showed the same pattern, dropping from 1997 to 1998 and then increasing each year thereafter (*table 1*). We also noted interesting though not statistically significant differences in cover on different geomorphic surfaces. In each year, the cover of native shrubs was higher (by 4-25 percent) on the active floodplain than on the terrace, while for native trees it was lower (by 6-15 percent) on the active floodplain than on the terrace.

With the mechanical treatment, in addition to the response by *A. donax* there was significant inter-annual variation in exotic herb cover but not in native herb cover (*table 1*). Exotic herbs increased rapidly in cover the first year after treatment, followed by a significant fluctuation between the second and third years. Native herb cover increased post-treatment, but the change was not statistically significant.

Site Restoration – Survival and Growth

Distance from the active river channel to the restoration plots ranged from 30 to 320 m. Percent sand on the plots ranged from 23 to 84 percent. Survival of willow pole cuttings averaged 31 percent per plot (n=28 plots, s.d.=36), while for willow whip cuttings survival averaged only 1 percent per plot (n=28 plots, s.d.=6). Per plot survival of the *B. salicifolia* whip cuttings averaged 28 percent (n=29 plots, s.d.=34).

Linear regression modeling of the effects of mulching and covariates distance to river and soil texture (percent sand) on survival significantly predicted willow pole survival (r^2=0.28; p=0.05). Survival was nearly twice as high (37 percent) on unmulched plots as it was on mulched plots (20 percent). Mulch treatment interacted with soil texture, such that within mulched plots willow survival decreased as percent sand increased, while in plots without mulch there was no pattern between survival and soil texture (F = 3.27; p = 0.08). A significant model was also produced describing *B. salicifolia* survival (r^2=0.50; p=0.05). *B. salicifolia* survival, however, was unrelated to mulching and was a function of an interaction between distance to river and percent sand (F=6.45; p=0.02). Survival was highest on finer textured soils farthest from the floodplain.

The average canopy volume on the restoration plots was 1.4 m^3 (s.d.=1.2) for *B. salicifolia* and 1.5 m^3 (s.d.=2.2) for the willows. Canopy volume was unrelated to mulch treatment, distance to river, and soil texture.

Costs

A. donax Treatment

The costs for *A. donax* control are highly variable depending primarily on accessibility of the site and density of the *A. donax*. The costs reported below exclude program management and reporting. For the foliar spray method supplemented with the cut stem method, our average annual costs per ha dropped by over 85 percent after the initial treatment and did not change significantly after that for retreatments (*table 2*). These costs did not include any manipulation or removal of the biomass. The cost to create several firebreaks by knocking down dead standing biomass was almost $5,000 per ha of firebreak. This work had to be done by hand because the sites could not be accessed by mechanized equipment without damaging riparian woodland habitat.

Because of the problems with biomass management, the mechanical treatment was never fully implemented as originally planned. The cost for mechanically removing and grinding about 14 ha of *A. donax* in 1998/1999 was approximately $19,800 per ha. This includes estimated costs of treating the *A. donax* with herbicide using cut stem and foliar application around native vegetation within and around the margins of the site and treating resprouts in the first spring, but does not include costs for biomass management. Treatment costs for the follow-up annual treatments are

Table 2—*Labor, herbicide and cost per ha for foliar treatment of* A. donax.

	Labor (man hours/ha)	Herbicide (liters/ha)	Total Treatment (cost/ha)
Year 1 (initial treatment)	150	130	$9,900
Year 2 (1st re-treatment)	15	7	$1,350
Year 3 (2nd re-treatment)	12	2	$1,100
Year 4 (3rd re-treatment)	15	2	$1,200

estimated to be the same as for the foliar spray method, because with so little live *A. donax* left, the primary costs are associated with getting to the site and searching for the few live stems present.

Site Restoration

The average labor cost per whip cutting was 0.32 hours and per pole planting was 1.07 hours. The mulching of the plots required 26 hours of labor plus the cost of the equipment. The planting of 180 whip cuttings required a total of 58.25 hours: 10 hours for collecting cuttings and 48.25 hours for planting the cuttings. The planting of 115 pole cuttings required 123.5 hours: 30 hours for collecting the pole cuttings and 93.5 hours for planting. The time required for mulching is not included in either the pole or whip cutting calculations. Planning, report writing, and monitoring are not included in these estimates.

Discussion

Efficacy of Control

While mid-November is often cited as the date of onset of winter dormancy in *A. donax* (Bell 1998), our experience, based on evaluation of plants in the field, is that it is often later, particularly near the coast. In addition, we have found that the plants are still susceptible to the herbicide after leaf yellowing begins when there is still green tissue present. A site-by-site evaluation of dormancy can extend the limited time available for foliar herbicide application.

Both foliar herbicide application and mechanical removal that includes removal of the rhizomes are effective methods of *A. donax* control and allowed us to meet our objective of less than 5 percent cover in 5 years. With both methods we were able to minimize damage to existing native trees and shrubs. We found that foliar treatment was less costly than mechanical and easier to accomplish in areas with poor access. On the other hand, mechanical treatment resulted in the use of less herbicide, consistent with general Navy policy directing the minimization of pesticide use (U.S. Department of the Navy 2002). Our initial conclusions were that both methods were useful in specific situations; however, difficulties and costs associated with grinding and using the biomass caused us to discontinue the mechanical removal method in 2001. Problems included spontaneous combustion of the piled, chipped biomass, presumably caused by increased decomposition of wetted material resulting from water sprayed to control dust. Insufficient need for the mulch for landscaping or other uses on the Base led to a lack of use and build-up of the stockpiles. While resprouting is low when the material is spread thin (Lawson and Smead 2001), it can be high in large stockpiles, creating a need for further treatment.

The two treatment methods affect *A. donax* plants differently. With foliar spray treatments, very high kill of the aboveground biomass is achieved with little subsequent resprouting. After the foliar spray treatment, the *A. donax* plant tissue dies gradually over several months. We hypothesize that this gradual death is not accompanied by rhizome resprouting because the hormones that suppress resprouting are still present in the stems and are only gradually declining. Based on elevated stem counts on transects where the stems were removed by wildfire compared to unburned transects, such an effect may last for a year. However, some resprouting can occur on foliar-sprayed plants with intact stems that have had no live aboveground biomass for over a year, so follow-up surveys and treatment are needed.

The low degree of resprouting following foliar spray contrasts with the rapid resprouting response to other methods where the stems or rhizomes are cut. There are also differences between the cut stem and mechanical treatments with respect to resprouting. When plants are pulled out of the ground during mechanical removal, many of the rhizome fragments resprout quickly. These resprouts are easily killed with herbicide application, as evidenced by the reduction in cover from 7.9 percent to 0 percent between 1998 and 1999 (*table 1*). Resprouting from entire rhizome masses left after the cut stem method requires repeated treatments over several years to kill. In an earlier study, after 2 years of annual treatment over 1.3 stems m^{-2} of live *A. donax* remained (Giessow and Giessow 1998). At that time, the stand was foliar sprayed to meet regulatory requirements.

Regardless of the method used in the initial treatment of *A. donax,* retreatments require approximately 12-15 hours of labor per ha of initially treated material. This effort includes both searching for resprouts and treatment time. It is important to note that the area searched during retreatments may be an order of magnitude larger than the initially treated area because retreatments cover all suitable habitat within the reach of the river in which the initial treatment occurred. Although this is a coarse estimate, it is sufficient for developing cost estimates for the entire treatment cycle and making management decisions. Once the first 4 consecutive years of retreatment have occurred, it is advisable to revisit the site less frequently to allow *A. donax* to grow to a noticeable size and optimize retreatment expenditures.

The importance of understanding riparian zone physical and ecological processes to produce consistent, successful riparian restoration has been noted (Goodwin and others 1997). This is also true of exotic plant eradication. To achieve watershed scale eradication of *A. donax,* all sites with the target exotic must be treated, not just the sites most likely to support a desired plant community within a specified time frame. Otherwise, *A. donax* will reinvade downstream sites after flooding, compromising natural and restored habitats (Stein 1998). The beneficial effects of *A. donax* removal on a site with low flood return interval may be indirect and take the form of removing the potential for reinfestation at another site.

Plant Community Recovery

While not statistically significant, we detected trends in the response of native shrubs and trees to removal of *A. donax*. We believe that the decline from 1997 to 1998 was a result of flooding. Rainfall at the Lake O'Neill weather station (approximately 2 km from the study site) in the winter of 1997/1998 measured 802 mm, more than double the 125-year average of 351 mm (Office of Water Resources, Camp Pendleton unpubl.[5] data). Flood damage to native trees and shrubs was seen on a number of plots (J. Giessow pers. obs), and similar floods in the local vicinity had been reported to destroy up to 40 percent of standing vegetation (Hawkins and others 1997). After the initial decline, rainfall measured 218 mm in 1998/1999 and 225 mm in 1999/2000 (Office of Water Resources, Camp Pendleton unpubl. data), and native trees and shrubs showed a steady increase in cover, although the time frame was insufficient

[5] Unpublished data on file at the Office of Water Resources, Marine Corps Base, Camp Pendleton, CA 92055

for cover to equal or exceed the initial cover. The decline and subsequent increase in shrub and tree cover probably reflect an interaction of flood damage and increased moisture availability for plant growth resulting from the *A. donax* control (Dudley 2000) and flooding (Kus 1998). As would be expected, previously existing trees and shrubs often showed an increase in canopy cover in areas that had supported dense *A. donax* stands. Plants adjacent to sites, notably *Vitis girdiana* (wild grape), spread into treated areas and can produce significant amounts of cover (Giessow and Giessow 1998).

New herbaceous cover developed much more rapidly on the mechanically cleared sites than on the foliar sprayed sites, and exotic herbs generally accounted for much of the difference in cover between the treatments. After mechanical removal, the sites were characterized by bare, loose soil—good conditions for weedy species establishment (Hoshovsky and Randall 2000). The foliar-treated *A. donax* stands developed cover much more slowly. The *A. donax* litter cover provided few sites where seedlings could germinate and survive. However, the herbs that did establish tended to be large individuals, presumably because they had less competition from neighboring plants.

Understanding site potential is key to predicting and evaluating recovery. While woody species occur on all three geomorphic surfaces, their presence and ability to establish is controlled by the potential for flood damage as flood return interval becomes shorter and by lack of establishment events as flood return interval gets longer (Harris 1987, Hawkins and others 1997). As a result, not all sites occupied by *A. donax* have the same potential natural community. Soil and hydrologic variation in riparian areas results in mosaics of plant communities (Platts and others 1987). Expectations for system recovery after *A. donax* eradication must take into account that events that provide bare saturated soil suitable for willow recruitment are uncommon on the terraces, and even on the active floodplain they may occur with a frequency of only once in 10 years. While the active floodplain is the most suitable place for woody riparian species recruitment (Else 1996), the terraces support both riparian woodland and riparian scrub habitats (Smith and Lichvar 1999). If woody habitats are desired in the terraces after *A. donax* control, active restoration may be needed to achieve this goal within a short time frame.

Active Restoration

Our experiments evaluating methods to improve the survival of cuttings showed that mulching was counterproductive for establishing willows, whose survival was nearly twice as high on plots with no mulch. Mulching had no apparent effect on the survival of *B. salicifolia* or on the ultimate canopy volume of either this species or willows. Soil texture influenced survival of both willows and *B. salicifolia*. For willows, the effect was a simple one of lower survival on coarser soils. For *B. salicifolia*, however, survival was highest on finer textured soils farthest from the floodplain. Finer textured soils have higher available soil moisture (Brady 1974), which could explain higher survival in these soils. It is possible that unrecorded variation in other factors, such as microtopography at the study site, had an effect on factors important for survival, such as water availability.

Where natural processes are not expected to lead to a desired plant community within a specified time frame, our results show the use of cuttings to be an option to speed recovery, without the expense of planting and irrigating container stock.

Planning the installation of cuttings when high rainfall is predicted may be a feasible way of increasing survival and thereby decreasing unit costs. Because the plant material takes relatively little time to collect and is done at the time of planting, less advance planning is necessary, providing more flexibility in scheduling this activity. Considering the episodic nature of establishment and growth of woody riparian species and its link to flooding (Else 1996, Kus 1998), such a strategy may result in more canopy development over a specified time frame.

Identifying and Tracking New Invasions

The most neglected part of managing new invasions is the identification of new problem species at the earliest possible time. Identifying, tracking, and treating new invasions so that one problem exotic species is not replaced by another is extremely important (Hoshovsky and Randall 2000). While this study focused on *A. donax* control, Camp Pendleton's program has, in fact, identified 14 species to be controlled. Ecosystem managers need to know when new invasive species appear and then quickly develop and implement strategies to treat them. Watershed-wide coordination is critical. Having a large-scale program in operation makes it much faster and easier to tackle new exotic species that threaten sites where *A. donax* has been removed. This was demonstrated with two new invasive exotic species found on the Santa Margarita River: German ivy (*Delairea odorata*) was identified on approximately 1.5 ha of land on a tributary to the Santa Margarita River, and perennial pepperweed (*Lepidium latifolium*) was found over a larger area in the watershed in 2000. Because of existing funding and close coordination between the Marine Corps, Mission Resource Conservation District, and private landowners, treatment of both species was initiated within a month of discovery.

In the midst of a complicated large-scale task such as the *A. donax* program, the subsidiary task of looking for new species can be overlooked. In addition, the resources used to survey can be hard to justify when no new infestations are found, even though the increase in control costs from delayed detection can be substantial and exceed the cost of surveys (Hoshovsky and Randall 2000). While detection of new exotic species should draw on existing monitoring work, it needs to be an independent task with multiple visits every year initially and every few years in the long term. It should include vouchering and review of status. The review could be as simple as comparison with the California Exotic Pest Plant list (CalEPPC 1999). Exotic species that are not on the list should be evaluated to determine if they are recent escapes and a decision made as to whether to carry out localized control, no treatment, or full eradication.

The potential for new exotic species to invade and the detection and control of all upstream occurrences of *A. donax* must be addressed. A watershed-based organization that encompasses both public and private landowners is needed to coordinate watershed-based control over the long term and develop a program to detect new invasions before they spread. A Weed Management Area has been established for the Santa Margarita River watershed that addresses these issues (California Department of Food and Agriculture, Santa Margarita Watershed WMA: http://smslrwma.org).

Conclusions

The impetus for *A. donax* eradication in the Santa Margarita River is based on the premise that its removal will result in an increase in riparian cover and functional values for endangered species, as well as an avoidance of future habitat losses if *A. donax* were to spread throughout drainages (ACS/ES, Camp Pendleton 1994, Babbitt and others 1995). *A. donax* eradication is feasible, and although much has been accomplished, substantial funding is needed to complete the job. Strategically timed and placed restoration and long term exotic species management, including detection and control, can insure that the ecosystem-recovery benefits of *A. donax* eradication efforts are realized in a cost-effective manner.

The temporal and spatial scales selected to evaluate recovery and to plan and execute post control restoration will determine to a large extent whether *A. donax* control is judged successful in improving riparian habitat for endangered species. Short-term expectations for succession at *A. donax* control sites must be balanced with the restoration of the natural functioning of the entire system.

Recovery objectives should be defined for specific management units. To effectively allocate resources, feasible objectives, including a time frame and measurable criteria, must be stated as clearly as possible from the beginning (Briggs 1996).

Management units should be based on geomorphic surfaces. Sites within units should be prioritized according to their potential for unassisted recovery. Sites with high potential may be a lower priority for scarce restoration funds than sites with lower potential. A site on a terrace that has the hydrology to support woody riparian species but a low occurrence of suitable natural establishment events could be a target for planting of cuttings.

The time frame to judge success should be tied to flood events of specific magnitudes. The criteria to evaluate restoration success should take patch size into consideration and reflect the natural mosaics of plant communities in the management unit.

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