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Prioritizing the Management of Arundo Donax: Recommendations for Removal and Revegetation in California Riparian Habitats

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This Master's Project

Prioritizing the Management of Giant Reed (*Arundo donax):* Recommendations for Removal and Revegetation in California Riparian Habitats

By

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List of Acronyms and Abbreviations

A. *Donax*- Arundo Donax

Cal-IPC- California Invasive Plant Council

IERCD- Inland Empire Resources Conservation District

EPA- Environmental Protection Agency

SEC- Sonoma Ecology Center

SPAD- Soil-Plant Analysis Development

USDA- United States Department of Agriculture

Abstract

The highly invasive grass species, giant reed (*Arundo donax),* has been a major contributor to riparian habitat degradation in California for over 50 years. Several modes of vegetative reproduction have allowed this alien species to take advantage of fluvial processes and rapidly spread within California watersheds. *A. donax* dramatically alters hydrologic regimes, displaces native vegetation, and removes food and habitat for native wildlife. It is widely accepted that removal of this invasive on a watershed scale is critical to restore natural riparian processes and facilitate the reestablishment of native flora and fauna. The following study analyzed the efficacy of past eradication projects and the subsequent recovery of native vegetation through either passive or active means. Through this analysis, recommendations were made for prioritizing removal sites, determining the most effective removal methods, and employing passive or active revegetation. This study determined the the three highest priority removal sites applicable to a wide variety of California watersheds are: upper watershed, largest *A. donax* infestations, and infestations in close proximity to fire prone areas. The most cost-effective removal method for large *A. donax* clumps is foliar spray with a 3-6% glyphosate solution. To minimize the use of herbicide and remain within the legal limit of 7qt/acre, mechanical removal should be used for large infestations whenever access allows for the use of heavy machinery, especially near urban areas. For moderate to small clumps, the most effective control methods are "bend and spray/hook" (3-6% glyphosate) and "cut-stem," (100% glyphosate). Cut-stem is recommended near urban areas to avoid overspray or when *A. donax* is mixed in with native vegetation. If active revegetation is required, all *A. donax* should be removed prior to revegetation to eliminate the threat of reinvasion; the only exceptions to this are when it is necessary to immediately restore habitat for sensitive species or when erosion is a major concern. Due to the high costs of active revegetation and the lower ecological value of artificially plant riparian forests, passive revegetation should be used whenever possible. *A. donax* eradication on a watershed scale is feasible with proper planning, but the process may take 20 years or more depending on the size of the infestation.

Section 1: Introduction and Objectives

Introduction

Riparian Habitats

Riparian habitats host a diverse array of plant and animal communities and provide crucial environmental services from water purification to nutrient cycling. Riparian vegetation communities are able to thrive under the dynamic conditions associated with fluvial systems, and can withstand stressors such as stem breakage, sediment deposition, and flooding (Howe, 2014). The unique ability of this vegetation to grow under stressful conditions results in plant communities that are very distinct from those found in terrestrial ecosystems, both in the habitat they create for fauna and in the ecosystem services they provide (Richardson et al., 2007). The habitat that this vegetation provides allows riparian systems to host a higher diversity of wildlife than most other types of ecosystems (Griggs, 2009.)

The delicate balance between natural fluvial processes and the subsequent response of native plant communities is extremely important, so any disturbances to these processes can have devastating effects. (Richardson et al., 2007). Some of these disturbances include damming, channelization, agricultural activities, and introduction of exotic species, all of which can alter hydraulic regimes and interfere with the natural recruitment of native species (Zaimes, et al., 2010). Bell, (1997) states that as much as 90% of the historic riparian habitat in Southern California has been lost as a result of anthropogenic interference.

Introduction of exotic species, specifically the large-statured invasive grass *Arundo donax* (Giant Reed), is thought to be one of the greatest contributors to riparian habitat degradation in California (Ambrose and Rundel, 2007). *A. donax* is particularly problematic in California because of its ability to outcompete native species and grow in extensive monocultures that provide little nesting habitat or food for native wildlife (Bell, 1997 and Lambert et al., 2010). The life history traits of *A. donax* including: vegetative reproduction, drought tolerance, rapid growth rate, and tolerance of a variety of soil conditions allow it to quickly invade riparian habitats and alter their structure and functionality (Coffman, 2007). Understanding these invasive characteristics is crucial in order to design management strategies that are cost-effective and ensure the long-term control of this species.

Historical Invasion and Current Distribution of *A. donax* in California

A. donax is a perennial hydrophyte that is widely considered to be native to Southeastern Asia, though more recent data suggests that it may have originated in the Mediterranean basin (Dudley et al., 2008). This species has been able to successfully invade riparian areas in Mediterranean, subtropical, and semiarid climates across the world and is now on the World's Most Invasive Alien Species List on the Global Invasive Species Database (Howe, 2014). Although *A. donax* has been cultivated in Europe, North Africa, and the Middle East for thousands of years, it is suspected that is was not brought to the Americas until the early 19th century (Lambert et al., 2010). *A. donax* was brought specifically to Los Angeles, California in 1820 to be used for erosion control along drainages and for basket construction, roof thatching, and in the creation of flutes and other instruments (Bell, 1997). Most of the *A. donax* plantations in California have since been closed, but there is current research being conducted in North America to determine if this species can be used as an adequate producer of biofuels (Mack, 2008).

Although *A. donax* has successfully colonized riparian systems across the United States (Figure 1), it has had the greatest impact in Southern California and along the Rio Grande River in Texas and Mexico at altitudes of 350 meters and below (Lambert et al., 2010). According to the California Invasive Plant Council (Cal-IPC), A*. donax* has also invaded river valleys in San Luis Obispo and Monterey counties, the San Francisco Bay Area, and in the San Joaquin and Sacramento River Valleys; recent data also suggests *A. donax* is increasing in the North Coast region. The rapid spread of *A. donax* in the Southwest United States has been attributed to the highly variable hydraulic regimes characteristic of these riparian systems (Bell, 1997; Lambert et al., 2010). In this region of the country, heavy rains and flash floods are common in the winter, which carry rhizome fragments downstream. Once established, *A. donax* can survive summer droughts and occupy the upper portions of the flood plain where other native plants may not be able to survive due to a lack of soil moisture (Lambert et al., 2010). The largest *A. donax* populations tend to occur in riparian areas of medium to large-sized streams with a less than 2% grade (Cal-IPC, 2011).

Analysis of historical aerial photographs has demonstrated that *A. donax* began spreading at a large scale in California in the 1960s (Cal-IPC, 2011). Through field investigations, Cal-IPC (2011) found that larger watersheds with wide floodplains have approximately 13% *A. donax* cover, but in certain portions of these watersheds greater than 44% cover was observed. The historic aerial photographs were also used to determine the patterns of growth and spread within California watersheds. Cal-IPC (2011) observed similar patterns in all watersheds in that between 1930-1960, only small, scattered populations of *A. donax* existed in low acreage. The aerial photographs revealed major changes in the distribution of *A. donax* starting in the 1960's, when land use changes and construction of levees altered the hydraulic regime of many California watersheds (Figures 2 and 3).

At this time, systems began experiencing continuous flow while others showed significantly elevated water tables. These conditions are very different than they were prior to the 1960s when watersheds were broader and much drier (Cal-IPC, 2011). *A. donax* aggressively expanded into dense stands during the 1970s-1980s as a result of watershed alteration, and by the 1990s, the plant appeared to be close to its current distribution (Cal-IPC, 2011). It is worth noting that lateral spread of *A. donax* is generally slow at approximately 1 to 2 feet per year. Aerial photographs during times of rapid expansion were linked to disturbance events such as floods and fires, supporting the idea that *A. donax* relied on disturbances for lateral spread rather than natural rhizome growth. Positive response to disturbances appears to be one of the main reasons why *A. donax* has spread so rapidly in Southern California where watersheds are characterized by episodic, large-scale floods every 25 to 100 years (Cal-IPC, 2011).

It is well documented that *A. donax* is widely distributed across Southern California and is spreading into other regions of the state (Cal-IPC, 2011; USDA, 2015; Bell, 1997). Calflora took on the task of mapping *A. donax* distribution from the Tijuana River in the south to Humboldt County in the north through user submitted observations (Figure 4). Using aerial photography and field surveys, Cal-IPC concluded that the gross area of *A. donax* infestation is 8,907 acres, and the net area (adjusted for *A. donax* cover) is 7,864 acres; It was also concluded that the gross area where *A. donax* treatments occurred was 3,000 acres, 34% of the peak *A. donax* acreage (Table 1). Visual inspection of Figure 4 shows that the majority of gross *A. donax* acreage occurs between Tijuana to the south and Santa Barbara to the north. However, aerial mapping also reveals that *A. donax* is spreading north up to Humboldt County, with the Salinas River having the highest gross acreage in Central California at 2,006.1 (Cal-IPC, 2011). The gross treatment area of the Salinas River was only 8% compared to the 34% average of the total study area, suggesting that *A. donax* invasion into Central California is more recent and control projects in this region are not as widespread as in Southern California. More expansive treatments in Central and Northern California are needed to prevent the further spread of *A. donax.*

The following section describes the ways in which *A. donax* degrades riparian ecosystems. As well as altering the physical structure and hydrology of streams and rivers, *A. donax* also reduces food and habitat for wildlife by displacing native vegetation. The negative impacts described in this section can be felt within entire watersheds due to do the ability of *A. donax* to reproduce vegetatively. Understanding the destruction that *A. donax* causes will hopefully inspire people to take action to eradicate this highly invasive species in California watersheds.

Ecological Impacts

Once established, *A. donax* can have devastating impacts on riparian ecosystems by altering natural fluvial processes and outcompeting the native vegetation that serves as critical habitat and food for local wildlife (Cal-IPC, 2011). *A. donax* is able to spread so quickly in riparian systems because of its ability to reproduce via plant fragments that get broken off during floods and carried downstream, forming new plant clones (Lambert et al., 2010). Along with this ability to spread downstream during winter floods, *A. donax* can also tolerate low soil moisture and survive summer droughts (Coffman, 2007). The ability of *A. donax* to grow well in these dynamic, often stressful conditions make California watersheds ideal habitat for this species to invade.

Alterations to Hydrology and Geomorphology

The capability of *A. donax* to dramatically alter the hydrology and geomorphology of streams and rivers is related to its dense above- and belowground growth and heavy water consumption (Bell, 1997; Lambert et al., 2010). Once established, *A. donax* grows into dense, monotypic stands that retain excess sediment and eventually constrict river channels, altering flow regimes (Bell, 1997) (Figure 5). Historically, California watersheds were dry in the summer and fall with multiple broad, shallow channels braided around larger sand and gravel bars (Cal-IPC, 2011). Sediment accretion around *A. donax* near stream banks eventually leads to the narrowing of channels into a single, deep channel with confined flows, increasing water velocity in the main channel and choking off smaller channels from receiving water; this velocity increase in the main channel results in excess channel incision and bed scour (Cal-IPC, 2011). Channel incision is often coupled with vertical accretion of the floodplain where *A. donax* is present, up to 0.8 ft./yr., which deepens channels and results in steeper stream banks (Cal-IPC, 2011).

A. donax root systems are extremely dense with up to 40% greater tensile strength compared to native species such as the Red Willow (Brinke, 2010). The increase in stream bank stability alters the natural bank erosion rates and further exacerbates the problem of channel narrowing and increased flow during low and mid-flow periods (Cal-IPC, 2011). Despite the root density, major flood events can still uproot large sections of *A. donax* and carry them downstream, where they can pile up and cause flooding, structural damage, and/or re-establish as new populations (Cal-IPC, 2011) (Figure 6).

The excessive water consumption of *A. donax* is another ecological concern as the rates of transpiration are much higher than that of California native plants (Table 2), creating unnaturally low groundwater tables (Watts and Moore, 2011).

Mature *A. donax* leaves have a large surface area, which results in average transpiration rates of up to 40mm/day per stand during the growing season (Cal-IPC, 2011). This rate is extremely high in comparison to native plants such as the Red Willow, which has an average transpiration rate of 2.1 mm/day (Johns, 1989). The rate of water consumption represents one stand of *A. donax*, so riparian systems that are heavily invaded can experience massive water losses as a direct result. As previously stated, *A. donax* is very drought tolerant despite its heavy water consumption; this tolerance, coupled with intense water use, allows *A. donax* to outcompete native vegetation once the groundwater table is too low for native plants to access water (Cal-IPC, 2011 and Lambert et al., 2010). The reduction in groundwater is not only detrimental to native vegetation communities by reducing soil moisture, but it also results in the removal of excess water from streams and rivers to replace the groundwater that was lost (USGS, 2015).

Wildfire/ Post-Fire Monopolization

The capability of *A. donax* to increase the risk of wildfires is perhaps one of the most damaging aspects of its invasion as the impacts can be widespread. Riparian habitats typically serve as natural barriers to wildfire, but when *A. donax* is present the fuel load greatly increases (Coffman, 2010). This species contains a much higher average dry biomass (mass excluding water)(155 tons/hectare) compared to native woody plants such as willows (36.8 tons/hectare). The dry biomass in mature stands also contains much more energy to produce fires (2,790 GJ/hectare) compared to native willows (16.8 GJ/hectare) (Cal-IPC, 2011 and Williams et al., 2008).

The growth pattern typical of *A. donax* results in dead biomass within mature stands being focused at the top of the plant, where dead secondary branches and senescing leaves are concentrated (Cal-IPC, 2011). Dead leaves also fall and accumulate at the base of *A. donax* stands, creating even more fuel to promote wildfire year-round (Spencer et al., 2006). The highly volatile, dead biomass associated with *A. donax* stands, coupled with the height of growth (up to 10m) creates the potential for intense fire to occur high in the canopy of riparian vegetation at any time of year, even during rain (Cal-IPC, 2011 and Coffman, et al., 2010). Even when natural wildfires occur without the influence of *A. donax*, once these fires reach mature stands they quickly increase in intensity, burning hotter and more completely than wildfire not occurring within *A. donax* (Cal-IPC, 2011 and Spencer et al., 2006) (Figure 7).

In addition to its capacity to increase the frequency and intensity of wildfires, *A. donax* reacts positively to post-fire conditions, often resprouting 1-2 weeks after fire while native vegetation remain dormant for several months (Cal-IPC, 2011 and Coffman et al., 2010) (Figure 8a). Coffman (2007) found that one year after a fire on the Santa Clara River, *A. donax* dominated the area and compromised roughly 99% relative cover, a 24% increase compared to pre-fire conditions. Post-fire monopolization of *A. donax* results in a vegetative community structure that is unsuitable for local wildlife for up to five years, depending on the intensity of fire (Cal-IPC, 2011) (Figure 8b). Sensitive species, such as the least Bell's vireo, that rely on a very specific riparian vegetation structure are especially affected and can show a significant decline for many years after a fire (Coffman et al., 2010). The shear intensity and amount of vegetation burned during *A. donax* fires also results in direct loss of native fauna that are unable to escape the area (Cal-IPC, 2011).

Impacts on Native Vegetation and Wildlife

As previously stated, *A. donax* easily outcompetes native flora and fauna for space and resources and changes the physical structure of their environment, resulting in a decline of native riparian species. As *A. donax* becomes established, it grows in such dense stands that recruitment of native vegetation is significantly lowered (Bell, 1997). Excess water consumption leading to a lowered groundwater table also negatively effects plant recruitment and can even result in the loss of established native plants that require soil moisture to survive (Lawson et al., 2010). Post-flood and fire monopolization by *A. donax* is also a major factor in the reduction of native vegetation, which take significantly longer to re-establish compared to *A. donax* (Coffman, 2007).

This displacement of native vegetation results in the decline of native fauna, which several studies (Lawson et. al., 2005; Cal-IPC, 2011; Herrera and Dudley, 2003) have quantified in areas experiencing *A. donax* invasion. Cal-IPC (2011) assigned *A. donax* impact scores rated from 0 to 10 (Table 3) for federally endangered or threatened riparian species and totaled them for various *A. donax* infested watersheds in California (Figure 9). Impact scores for each species were based on the following criteria: general ecological and habitat needs, reproduction, movement, range, and other potential impacts or threats (Cal-IPC, 2011). High impacts scores suggest that *A.donax* modifications to the biotic and abiotic environment have a significant negative impact on that particular species.

No evidence has shown that *A. donax* serves as suitable habitat or food for native wildlife, and studies have even found that the leaves of this plant contain several chemicals that are toxic to wildlife, including silica, hydroxamic acid, and cardiac glycosides (Bell, 1997 and Cal-IPC, 2011). Systems that are overrun by *A. donax* see a significant decline in terrestrial and aerial arthropods because the plants structure is unsuitable for species in this trophic level (Herrera and Dudley, 2003). Riparian systems dominated by *A. donax* also experience an increase in water temperature as a result of reduced in-stream shading that native plants normally provide; this temperature increase leads to lower oxygen levels, higher pH in shallow water, and formulation of toxic ammonia (Bell, 1997). The lowering of water quality has been shown to reduce the abundance of aquatic arthropods, fishes, and amphibians (Cal-IPC 2011 and Herrera and Dudley, 2003).

Many riparian birds exclusively rely on these ecosystems for food and habitat, so a reduction in terrestrial, aerial, and aquatic arthropods from *A. donax* invasion results in a significant decline in these species. Cal-IPC (2011) found that of 22 federally listed riparian species, 11 are severely impacted by *A. donax*, most notably: least Bell's vireo, arroyo toad, southwestern willow flycatcher, steelhead trout, and tidewater goby (Figure 9). From the studies mentioned above, it is clear that *A. donax* negatively impacts the health of riparian species; this demonstrates the importance of timely removal in order to prevent the further decline of native flora and fauna.

Purpose and Objectives

The negative impacts that *A. donax* has on the on riparian ecosystems make removal of the plant a top priority in many California riparian restoration projects.

Successfully eradicating *A. donax* is very difficult and requires a strategic management plan that takes into account all factors that may affect the efficacy of treatments. Some of these factors include: location of the watershed, position within the watershed, vegetation community structure, density/size of *A. donax* stands, site accessibility, budget, presence of threatened or endangered species, and numerous other factors. An understanding of the complex interactions between these site-specific factors is crucial to prioritize removal efforts, choose the most effective control methods, and determine when active revegetation is necessary. It is challenging and time-consuming to create effective eradication plans that take into account all of these factors. It would be beneficial for managers to have a resource pulling together all of these factors to provide recommendations that are applicable to a variety of *A donax* infested areas in California.

In an effort to stop the further spread of *A. donax* in California, this study will provide the necessary information to allow managers to more easily draft eradication plans with the highest potential for success. The following are the main objectives of this study: provide an understanding of how to best prioritize *A. donax* removal sites, determine the most effective removal methods based on all possible site-specific factors, and decide if active revegetation is necessary. These recommendations are especially useful for sites in central and northern California because the invasion of *A. donax* into this region is more recent and less widespread. Implementing more effective management plans for infested watersheds in the northern half of the state will hopefully prevent an *A. donax* problem as severe as in southern California.

To make recommendations for eradicating *A. donax,* I will investigate the methods *A. donax* uses to rapidly spread within watersheds and discuss case studies in California that evaluate the effective control of *A. donax* and the subsequent plant community response. I will also analyze additional efficacy studies that provide a more in depth comparison of specific treatment methods, herbicide formulations and concentrations, and timing of herbicide applications. During this analysis, I will be taking into account all factors that potentially played a role in the success of treatments, such as the size of the *A. donax* invasion, presence of non-target vegetation and sensitive wildlife, and accessibility to the removal areas. The case studies will be the main focus for my recommendations, but the *A. donax* invasive ecology studies previously discussed will be a crucial component to support my conclusions. My recommendations will applicable to a wide variety of watersheds, but managers will need to fine tune their own eradication plans as there are countless combinations of factors that may affect the success of *A. donax* control efforts.

Section 2: Invasive Ecology of *A. donax*

Introduction

A. donax has several life history traits that have allowed it to successfully invade California watersheds and spread throughout the state. *A. donax* is a hydrophyte (adapted to growing in wet conditions) that often grows in dense monotypic stands and favors the Mediterranean-like climates of its native habitat (Coffman, 2007). *A. donax* is the largest of the 6 species in its genus, growing up to 10 meters in height and as much as 5 cm per pay (Bell, 1997 and Coffman, 2007).

Rhizomes and Fragmentation

The lateral spread of *A. donax* via normal rhizome growth is fairly slow at 1 to 2 feet per year, suggesting that other ecological traits are the main contributors to the vast expansion of this species (Cal-IPC, 2011). Boland (2006) attributes the rapid spread of *A. donax* within watersheds to its asexual reproductive techniques. *A. donax* does not produce viable seed in California and therefore must rely on rhizome growth and fragmentation to expand within watersheds (Boland, 2006). The ability of *A. donax* to reproduce asexually via fragmentation appears to be an advantage in California watersheds given the episodic flood events characteristic of the state. In addition to the natural flood events in California, anthropogenic alterations to watersheds after the 1960s appear to have exacerbated the spread of *A. donax* by increasing the frequency and intensity of flows (Cal-IPC, 2011). During periods of flooding, stems and rhizomes of *A. donax* can break off and get dispersed downstream where new clones can root and become established (Coffman, 2007 and Bell, 1997). Although this is one of the main methods by which *A. donax* spreads within watersheds, some studies suggest layering is another important asexual method *A. donax* relies for reproduction (Boland, 2006; Cal-IPC, 2011; Dudley, 2000).

Layering

Layering is defined as the advantageous production of roots and shoots from normal plant stems that bend and come into contact with soil (Boland, 2006) (Figure 10). Boland (2006) conducted a study in Southern California to examine the lateral growth of *A. donax* via layering, and compared that to the growth rates achieved from fragmentation and normal rhizome growth. The results showed that the rate of expansion via layering was 7.4 times faster than the annual expansion rate from rhizomes. Layering also produced 25 times more new recruits compared to fragmentation (Boland, 2006). Although some studies slightly disagree on the rates of expansion through rhizomes, fragmentation, and layering (Bell, 1997; Else, 1996; Dudley, 2000; Boland 2006) it is clear that a combination of these reproductive methods allows *A. donax* to easily spread and overtake riparian systems. In addition to understanding the reproductive methods of *A. donax*, it is also important to understand the abiotic factors that can facilitate its rapid growth and expansion.

Resource Exploitation: Santa Clara River Study

Coffman (2007) conducted a study in the Santa Clara River and found that nutrient input, soil moisture, and light all contribute to the invasion of *A. donax* in regions with Mediterranean-type climates. The experimental design employed full factorial randomized plots, each containing a two-species or one-species competition grouping (Coffman, 2007). Cuttings were taken from two species of native riparian trees and one shrub species, while rhizomes were taken from *A. donax* plants, all to be grown in experimental plots. The native trees selected for the experiment included: *Salix laevigata* (red willow), *Populus balsamifera* (black cottonwood), and *Baccharis salicifolia* (mulefat). Before planting, each plot was randomly treated with different levels soil moisture (high and low), nutrient additions (high and none), and light (high and low) (Coffman, 2007).

In addition to these resource treatments, each plot was either planted as a monoculture of four plants (one-species grouping) or as a combination of two *A. donax* plants and two plants of a single native species (two-species grouping). The purpose of this experimental design was to examine the role of competition between *A. donax* and native species in riparian systems under different conditions of resource availability (Coffman, 2007). Competition was considered to exist when the mean biomass of a species in the mixed groupings was lower than that of a species grown in monoculture; this reaction was considered to be positive when mean biomass was higher in mixed groupings compared to monocultures (Coffman, 2007).

After the second growing season, it was concluded that *A. donax* biomass was higher than that of the native species for nearly every combination of soil moisture, light, and nutrient conditions. The mean biomass of *A. donax* in monoculture under high nutrient, soil moisture, and light conditions was 2-34 times higher than the biomass of native species under all conditions (Coffman, 2007). At the completion of the study, a comparison of mean aboveground biomass by species in mixed groupings versus monocultures did not reveal a clear pattern. Resource competition between *A. donax* and native plants varied significantly by species and treatment levels, and contrary to what was expected, *A. donax* outcompeted a native plant species only under the most stressful conditions (Coffman, 2007). Coffman suggests that the short duration of the study may be the reason for these mixed results and proposes that future long-term studies of resource competition should be carried out.

Although the study revealed an absence of resource competition, the results did demonstrate that *A. donax* obtains a higher biomass than native plants under most environmental conditions (Coffman, 2007). This is an important conclusion that supports her hypothesis and suggests that *A. donax* has the potential to eventually outcompete native plants given enough time. This is especially concerning for California watersheds that are regularly exposed to similar high resource conditions as a result of both natural fluvial events and human activity, such as agriculture (Coffman, 2007 and Cal-IPC, 2011). Coffman's experiment demonstrates the need for aggressive management of *A. donax* in California to prevent it from forming extensive monotypic stands and outcompeting native species.

Resource Exploitation: UC Berkley Study

Some of the major conclusions of the Coffman study were also supported by a subsequent study conducted by Lambert et al. (2013), which measured the effects of nutrient enrichment, soil conditions, and light on the above- and belowground productivity of *A. donax*. Lambert et al. (2013) support Coffman's claim that hydrologic alterations to California watersheds, along with excessive nutrient loading from agricultural activity and urbanization, may be major factors contributing to the invasion of *A. donax* into these systems. This study is different than that of Coffman (2007) because the abiotic factors were evaluated in a controlled environment. By measuring *A. donax* growth in a greenhouse with consistent temperature and humidity, researchers hoped to eliminate undesired environmental variables and employ more precise treatments levels (Lambert et al., 2013).

A. donax rhizomes were collected from the Russian River in Healdsburg, California and cut into similar sized pieces with the same number of culm (stem) buds. These rhizomes were brought to a greenhouse at the University of California, Berkeley and planted in containers with following three riparian soil types: sand treatment consisting of coarse plaster sand, a silt treatment composed of a 50:50 mixture of mineral clay and fine sand with low organic content, and a 2:1:1 riparian mixture consisting of clay, sand, and humus-based potting soil (Lambert et al., 2013). Nitrogen treatments were used to represent three levels of nutrient availability: high N, low N, and no N. Treatments were applied to the low N containers every three weeks at a rate of 10 g m $^{-2}$ N, using equal parts ammonium nitrate and potassium nitrate; the same nutrient mixture was also used for the high N containers but on a weekly basis. These inputs are similar to what would naturally occur in California riparian systems in close proximity to agricultural lands (Lambert et al., 2013).

To evaluate the effects of moisture on *A. donax* productivity, three moisture levels were selected that simulate levels naturally occurring in riparian habitats prone to *A. donax* invasion (Lambert et al., 2013). The moisture levels include: a saturated treatment representing near-stream conditions, a moist treatment similar to what would be found in soils at a further distance from streams, and a dry treatment representing soils found higher up in the floodplain or in channels that experience seasonal droughts (Lambert et al., 2013). Light treatments were applied by positioning containers to receive either full sun exposure or 20-30% sun exposure (shade treatment), which was verified using a hand-held light meter. These light treatments were chosen to represent natural exposure of *A. donax* to solar radiation in recently scoured channels free of vegetation or under a fully established riparian canopy (Lambert et al., 2013). After completing one full year of treatments, plants were extracted from the soil and dissected into their aboveground (root and rhizome) and belowground (culm and leaf) components; the plants were then air-dried for two weeks before the biomass was measured using a spring scale (Lambert et al., 2013).

The results of this study indicate that all treatments had statistically significant effects on the aboveground and belowground biomass of *A. donax*, but these effects varied greatly between treatments (Lambert et al., 2013). The nitrogen treatments appeared to have the most significant effect on the growth of *A. donax,* as these treatments accounted for over 45% of the total biomass variation. Soil types also had a significant impact on *A. donax* biomass production and accounted for 40% of the variation (Lambert et al., 2013). It was reported that soil moisture and light also affected the plant growth, but these effects were minor in comparison to nitrogen treatments and soil types.

In addition to comparing variation in biomass across the different treatments, Lambert et al. (2013) also examined each of the treatments individually to determine how the different levels affected biomass production. Nitrogen treatments had a significant effect on *A. donax* growth; total biomass in plants treated with high nitrogen was 32% higher in comparison to plants treated with low nitrogen or no nitrogen. Lambert et al. (2013) also found that nitrogen treatments increased biomass production of both belowground and aboveground structures, but the production was greater in belowground structures. The difference in biomass production between soil types appeared to have a strong effect on the growth of *A. donax* as well, with plants grown in riparian soils producing 65% more biomass compared to plants grown in silt or sand (Lambert et al., 2013). Soil moisture also played a role in biomass production, with plants that were watered periodically (moist soil) producing more biomass than plants grown in saturated soils. The dry soil treatments had a significant negative impact on plant growth with a 68% lower total biomass than plants grown in moist soils. Light treatments also appeared have a significant effect on *A. donax* growth, although this effect was much less than what was observed in all other treatments. Lambert et al. (2013) also reported that biomass in plants exposed to full sunlight was 24% greater than that of plants grown in shade. It was also observed that plants grown in full sun had a 34% increase in rhizome production over the course of the study (Figure 11).

The results of this study support the findings of Coffman (2007), in that nutrients, soil type, moisture, and light all play a role in the invasion of *A. donax* into riparian systems. This experiment demonstrates that nitrogen is a major driver of *A. donax* growth, as was supported by Coffman's study. This is an important conclusion as many riparian systems in California receive nutrient inputs from urbanization and agricultural practices. Nutrient inputs are likely to increase as the population grows so it would be beneficial to place high priority on managing *A. donax* in watersheds that are exposed to excessively high nutrient levels. As discussed by Coffman (2007), early management of *A. donax* in high nutrient systems can prevent the plant from forming monotypic stands and allow native plants to successfully compete for space and resources.

Section 3: Case Studies

Introduction of Case Studies

Recommendations for managing *A. donax* are strongest when they are based off past studies that evaluate the success in removing *A. donax* and reestablishing native species. During this analysis, it is necessary to understand all aspects of the project sites, removal methods, size/density of clumps, project costs, restoration efforts, and other factors that will aid in making recommendations for future removal projects. The following section examines two studies detailing the effectiveness of *A. donax* removal and native plant revegetation in California, one occurring in the San Timoteo Canyon and the other in the Santa Margarita River.

These studies were chosen because they collectively provide sufficient data on the post-treatment responses of *A. donax* and native plant communities in the short and long-term in southern California. The San Timoteo Canyon study is especially useful in determining the long-term effectiveness of *A. donax* removal because the data was collected 13-14 years after the completion of the project. This is the only known study that provides post-treatment data more than a decade after the completion of the project. This study is also a useful indication of how the control of *A. donax* might be different for inland watersheds as opposed to coastal watersheds, such as the Santa Margarita River. However, this study lacks some data on the specific locations where certain removal methods were used, making it difficult to directly compare the efficacy of the methods used in this project.

The Santa Margarita River *A. donax* control project provides percent cover data for *A. donax* and native vegetation for the first five years after the initial treatments. This data is useful in determining how *A. donax* and native vegetation may respond to treatments and revegetation in the short-term. This study also provides data related to the costs and labor hours associated with removal efforts, which has proven to be difficult to access from other removal projects. Since the study was published five years after the initial treatments, it is difficult to conclude how successful this project will be in the long-term. However, the amount of data provided within these first five years is extremely useful in determining the more immediate response of *A. donax* and other native/non-native vegetation to treatments. The project locations for both of these studies serve as good representations of typical southern California watersheds that have become degraded as a result of *A, donax* infestation.

Study 1: A Review of the Removal of *Arundo Donax* from a Riparian Area in Within San Timoteo Canyon

Introduction

Howe (2014) conducted a study to determine the effectiveness of multiple *A. donax* removal projects that occurred between the years 2000 and 2001 within the San Timoteo Canyon in Redlands, CA. Howe (2014) used the following guidelines to determine the effectiveness of the removals: re-invasion of *A. donax* within the study area, establishment of other non-native species, and growth of native species in place of removed *A. donax*. To measure the efficacy of treatments, Howe (2014) obtained pre-treatment data from the Inland Empire Resource Conservation District (IERCD) and established randomized plots across the study area to obtain new data. Additional sites were visited to measure the effects of leaving *A. donax* in place, the short-term effects of *A. donax* removal, and the ability of riparian areas to recover naturally without active restoration. In addition to collecting field data, Howe (2014) analyzed IERCD aerial photographs of an untreated, ecologically similar area and a site undergoing natural recovery following treatments. After completing the study, Howe (2014) concluded that the removal efforts were effective in controlling *A. donax* and promoted natural recovery of native vegetation.

Project Site

This study took place within a 42-acre portion of the San Timoteo Creek, a tributary of the Santa Ana River (Howe, 2014) (Figure 12). Since the 1830s, the land within San Timoteo Canyon has been dramatically altered as a result of human activities such as agriculture, illegal dumping, off-highway vehicle use, and introduction of non-native species (Howe, 2014). These activities have been especially damaging to San Timoteo Creek and have altered its natural hydraulic regime (Howe, 2014). Howe (2014) cites the introduction of *A. donax,* as the major contributor to habitat degradation and the decline of native species in this area.

Prior to any treatments, *A. donax* had dense growth in many portions of the creek, displacing native vegetation such as arroyo willow (*Salix lasiolepis*) and cottonwood (*Populus fremontii*). The replacement of these species with *A. donax* led to a decline in native animal populations, most notably the least Bell's vireo (*Vireo bellii pusillus*) and southwestern willow flycatcher (*Empidonax traillii extimus*), both of which are federally listed endangered species (Howe 2014). The IERCD started implementing removal projects in 2000 after noticing the damage *A. donax* was causing in San Timoteo Creek. The projects spanned 110 acres of the creek and removed a total of 30 acres of *A. donax* in less than two years (Howe, 2014) (Figure 13).

Methods

To quantify the efficacy of the removals, Howe (2014) used data from past removal projects within San Timoteo Creek and visited a portion of the site to measure vegetation cover. By comparing the new percent cover with the acreage of *A. donax* previously removed, Howe (2014) determined how effective the treatments were in controlling *A. donax* and facilitating natural establishment of native vegetation. Plots were established by randomly selecting 8 points in unknown locations using ArcGIS software (Howe, 2014). Data was collected from each plot on two occasions, once in February 2013 and again in May 2013. After measuring the new percent cover of *A. donax* within each plot, Howe (2014) compared this data to the total acreage of *A. donax* previously treated within the entire removal site.

The most common method the IERCD used for *A. donax* removal was grinding large patches using heavy equipment, followed with a glyphosate foliar spray (directly on leaves) of respouts once they reach I to 2 meters in height (Howe, 2014). In addition to this method, the IERCD applied glyphosate foliar spray to uncut plants and a direct spray to hand cut stems (cut stem method); all of these methods required annual re-treatments for two to five years to maintain complete control (Howe, 2014). This study did not provide the glyphosate concentrations used, but it is common practice to use 3-6% for foliar spray and 100% for the cut stem method (Cal-IPC, 2011; Lawson et al., 2005; Spencer et al., 2008).

Howe (2014) also established a non-random site to examine the ability of habitats in this region to recover via natural fluvial processes, following a disturbance. This was named the "Washout Area" because it had experienced a small landslide following a flood in 2010 and was an area of interest for the IERCD (Figure 14). Howe (2014) compared 2011 post-flood photographs to new photographs and data collected in February 2013. The same procedure as in the other eight plots was used to estimate the percent vegetation cover for all species in the area. Comparing the 2011 photos with the new photos and data allowed Howe to make general conclusions on the ability of native vegetation in the area to recolonize following a disturbance. This site was also useful in measuring the competition between native and non-native species in a recently cleared area. Although it is unclear if *A. donax* occupied the area prior to the flood, it still provides insight on how riparian vegetation communities may respond when growing space suddenly becomes available, as what often occurs after treating *A. donax,* especially following mechanical removal.

An additional non-random site, named plot 16, was established to study the short-term effects of *A. donax* removal (Figure 15). This area was treated for *A. donax* in October 2012 by the IERCD. Howe (2014) visited this site and carried out the same monitoring procedure that was used for all other plots. Once again, IERCED photographs and data were compared to new photographs and data obtained from this study. The purpose of studying this area was to compare the more immediate effects of *A. donax* removal to the long-term effects, as determined by the 8 randomized plots (Howe, 2014).

Results

At the conclusion of the study, Howe (2014) determined that the removal of *A. donax* in San Timoteo Creek study area was effective both in the short and long-term. *A. donax* was only observed in plot 17 at 11%, while the remaining seven random plots did not contain any *A. donax*. Averaging the percent cover across all eight plots resulted in a 0.64% *A. donax* cover; this represents only 0.27 acres of the total 42.3 acre study area (Howe, 2014). An IERCD field ecologist attributed the higher percent cover in plot 17 to the fact that the area was treated for *A donax* one year prior to the study in October, 2012, while the other plots were in areas that were treated between 2000 and 2001. Howe was not aware that this area was treated more recently prior to speaking with the IERCD ecologist. If this percent cover trend is applied to the entire original removal area, *A. donax* occupies only 0.70 acres of the 110 acre removal site (Howe, 2014). *A. donax* was not observed in the washout area, and in plot 16 only dead *A. donax* rhizomes were present at 25% cover (Howe, 2014). There were two additional invasive species found in two of the eight random plots, summer mustard (*Hirshfeldia incana)* and poison hemlock (*conium maculatum)*, but these only accounted for less than 1% of the species in these plots. The washout area contained three invasive species: *Hirshfeldia incana*, salt cedar (*tamarix ramosissima)*, and *conium maculatum*, but these only accounted for 4% of the species cover. In Plot 16, four of the five species found were non-native (Howe, 2014).

Discussion

The results from this study indicate that mechanical grinding and glyphosate foliar spray, foliar spray only, and cut stem were all effective control methods because *A. donax* was reduced to a small percentage of its original area, with native species comprising the majority of the vegetation cover. Because none of the plots in the areas that were treated in 2001-2002 contained any *A. donax,* it can be concluded that all three of the removal methods were effective in the long-term. The presence of *A. donax* in the recently treated area of plot 17 demonstrates the need for continued retreatments to prevent *A. donax* from reestablishing. The fact that *A. donax* was only observed this plot supports the findings of other studies (Lawson et al., 2005; Cal-IPC, 2011; Bell, 1998) in that resprouts are common for up to five years after initial treatments, depending on the control methods used.

The tendency of *A. donax* to produce resprouts means that annual monitoring is almost always necessary for up to five years to control further invasion (Cal-IPC, 2011; Coffman, 2011, Lawson et al., 2005). The IERCD followed this protocol and conducted annual retreatments for at least two years, as required, before it was concluded that *A. donax* was sufficiently controlled in the area (Howe, 2014). The control of *A. donax* in the San Timoteo Creek within this time frame follows the general trend seen in other removal projects (Lambert et al., 2005; Cal-IPC, 1998). However, it is recommended that monitoring of the entire project site should be conducted at least on a bi-annual basis for up to 20 years to ensure complete eradication (Lawson et al., 2005; Bell, 1997). The San Timoteo Canyon would benefit from such monitoring, especially because some areas (Plots 16 and 17) were treated only one year prior to this study and resprouts are likely to occur.

Reestablishment of native plant species in the washout area without active restoration demonstrates that natural flood dynamics alone may be sufficient to restore native plant communities. Although it is unknown whether *A. donax* previously occupied the washout, the area is just west of the original removal site, making it possible for *A. donax* to invade (Howe, 2014). The fact that this area remained free of *A. donax* indicates that the 2000-2001 removals prevented further invasion downstream. It appears that native vegetation in this region can reestablish within a few years with adequate natural resources and exposure to flooding. The low percentage of other non-natives in the washout area may be related to native vegetation reestablishing quickly enough to outcompete exotic species for space and resources. The low percentage may also indicate that areas directly within the waters path are unsuitable for the establishment of non-natives because they are not adapted to cope with riparian disturbances. In the absence of exotic species, active restoration may not be necessary as native plants have adequate space and resources to reestablish naturally. This supports conclusions of other studies (Bell, 1997; Cal-IPC, 2011) in that active restoration may not be necessary in areas close in proximity to the flood plain; non-native vegetation often struggles to remain intact in these areas and native vegetation respond positively to disturbance dynamics.

As other studies have indicated (Bell, 1997; Lawson et al., 2005; Cal-IPC, 2011) natural reestablishment is often dependent on position within the watershed and should be evaluated on a project-by-project basis. Native plants that have adequate soil moisture and more exposure to natural disturbances (e.g. floods) are more likely to establish themselves quickly enough to compete with exotics (Bell, 1997; Richardson et al., 2007). Based on the data provided in this study, it cannot be determined exactly what aspect of *A. donax* removal allowed native vegetation to recover more quickly than exotic species. It is reasonable to conclude that a combination of adequate growing space, soil conditions, and restoration of natural fluvial processes all played a role in the successful revegetation of native species. It is likely that the recovery of native vegetation will continue in San Timoteo Canyon as long as *A. donax* is not reintroduced. A healthy vegetation structure may also promote a rebound in the animal community that had previously suffered from habitat degradation. Future studies in San Timoteo Canyon would be beneficial to measure the response of wildlife to *A. donax* removal and reestablishment of native vegetation.

Study 2: The Santa Margarita River *Arundo donax* Control Project: Development of Methods and Plant Community Response

Introduction

Lawson et al. (2005) evaluated the success of an *A. donax* control project that took place within a portion of the Santa Margarita River running through the Marine Corpse Base Camp Pendleton in Southern California. The project was initiated in 1997 after Camp Pendleton was required to evaluate impacts on federally listed endangered species regulated by the Army Corps of Engineers (Lawson et al., 2005). This project involved an initial treatment in 1997 followed by three annual re-treatments until the year 2000. In addition to removing *A. donax*, Lawson et al. (2005) took cuttings from native shrubs and trees and planted them in experimental plots to determine if *A. donax* fragments can be used as mulch. It is important to note that one year after the initial treatment, a wildfire burned a portion of the monitoring area. The burned and unburned areas were analyzed separately to eliminate fire as a potential variable. The main objectives of program were to reduce *A. donax* cover to 5% by the fifth year of treatments and to determine feasible methods to restore native woody plants as habitat for endangered species (Lawson et al., 2005). At the conclusion of the project, it appeared that the treatments were effective in eradicating *A. donax*, but using it as mulch for active restoration of native species was counterproductive (Lawson et al., 2005).

Project Site

The Santa Margarita River is approximately 50 km long and runs southwest from Riverside County, eventually draining into the Gulf of Santa Catalina in

Oceanside, San Diego (Friends of the river, 2014). The lower 16 km of the river runs through the Camp Pendleton Marine Corpse Base and is a major portion of the project area (Figure 16). Prior to starting treatments in 1997, *A. donax* had invaded 26% of the study area at greater than 80% cover (Lawson et al., 2005). The total infested area of the entire watershed was estimated at 300 hectares (ha), 260 ha on Camp Pendleton and 40 ha upstream of the base; this represents over 40 km of the Santa Margarita River's main stem and tributaries (Lawson et al, 2005). Three endangered species have suffered habitat loss on the Santa Margarita River as a result of *A. donax* invasion: least Bell's vireo, southwestern willow flycatcher, and arroyo toad. On Camp Pendleton, the arroyo toad was identified as the most vulnerable to habitat loss because the species is unlikely to move through dense patches of *A. donax* (Lawson et al., 2005). The project initially received five years of funding and obtained permits from the Army Corps of Engineers to apply treatments further upstream outside of the base (Lawson et al., 2005).

Methods

It was determined that to ensure the eradication of *A. donax*, initial treatment plus 19 years of follow-up treatments and monitoring was necessary, at a cost of $15,000,000 (Lawson et al., 2005). Most of the costs and labor hours during this 19-year period are associated with vegetation monitoring rather than follow-up treatments, as *A. donax* will likely be at a very low percentage. The project managers knew it was unlikely to obtain this amount of funding and accepted that there would likely be discontinuities in the control efforts (Lawson et al, 2005). Treatments began at the top of portion of the river to prevent further spread of *A. donax* downstream via fragmentation. Glyphosate herbicide (6% concentration for foliar and 100% for cut-stem) was applied to 8 km of river supporting 25 ha of *A. donax* during the initial treatment from September to November 1997. These treatments occurred during the *A. donax* growing season, just before the onset of winter dormancy, to maximize uptake of the herbicide from leaf to rhizome. The applications were further limited to 8-10 weeks because the ideal season for treatments overlaps with the breeding season of sensitive species in the area (Lawson et al., 2005).

The cut stem method was in replacement of foliar spray when there was a risk of overspray onto non-target species (Lawson et al., 2005). Due to budget and access limitations, dead biomass that accumulated following herbicide treatments was not removed. Leaving behind the dead biomass raised some concerns regarding the increased potential for wildfire, damage to bridges downstream, and habitat alteration for estuarine species (Lawson et al., 2005). These concerns prompted the experimental mechanical removal of 3 ha of *A. donax* using a clamshell bucket on a trackhoe, which removes the entire plant including rhizomes (Lawson et al., 2005). The fragments were then fed through a tub grinder to minimize the potential for resprouts and allow the material to be used as mulch. Any remaining rhizomes were collected immediately after grinding was complete and resprouts were often retreated with foliar spray the following spring. Mechanical removal was also limited during the breeding season, but exceptions were made for large stands of *A. donax* when nesting endangered species had already left the area (Lawson et al., 2005).

Lawson et al. (2005) carried out an additional small-scale experiment within a 25 ha area that was treated via mechanical removal during fall 1999/winter 2000 to evaluate the use of *A. donax* mulch. The experiment involved planting cuttings from three species of willow and *B. salicifolia* (mule fat) planted in 30 plots, and spreading a 25cm thick layer of mulch consisting of *A. donax* stem and root fragments. Survival, canopy dimensions, and soil texture (as percent sand) were measured after two years in January 2003 (Lawson et al., 2005).

<u>Post-Treatment Plant Community Response</u>

Lawson et al. (2005) noticed a general trend for each plot of a rapid increase in non-native plants (excluding *A. donax*) in the year following initial treatments with a fluctuation each year after. An obvious increase in native herbs was observed within the unburned foliar-treated area as a function of year and floodplain position, and as a function of floodplain position and percent sand in the soil (Lawson et al., 2005). The native herb community decreased in the year 2000 but increased in all other years. The vegetation cover did not significantly increase in the burned area throughout the entire duration of the study (Lawson et al., 2005).

There was also a clear variation in exotic herb cover for the areas exposed to mechanical treatments, but a general trend of non-natives rapidly increasing after the first year of treatment then fluctuating each year after. Native herb cover did increase after the first year of treatment but this change was not statistically significant (Lawson et al., 2005) (Table 4). As previously stated, mulching the native willows was counterproductive with survival being almost twice as high in the unmulched plots (37%) as in the mulched plots (20%) (Lawson et al., 2005). There was an obvious pattern observed in the mulched plots with willow survival decreasing as percent sand in the soil increased; there was no such pattern within the unmulched plots (Lawson et al., 2005).

Although post-treatment growth of native and non-*A. donax* exotic species was not statistically significant, general trends in plant community recovery were apparent (Lawson et al., 2005). All trees and shrubs showed a decline from 1997-1998, most likely from a flood that occurred that was more than double the 125 year average (Lawson et al., 2005). There was flood damage in a number of plots and nearby areas reported a 40% decline in standing vegetation during the same time. A steady increase in native trees and shrubs occurred each year following the 1997 flood, most likely from an interaction between flood damage and increased soil moisture following *A. donax* removal (Lawson et al., 2005). Trees and shrubs that remained intact during the flood showed an increase in canopy cover in areas that had previously supported dense stands of *A. donax* (Lawson et al., 2005). This is also likely related to an increase in moisture availability following the removal of *A. donax.*

This study indicates that position within the watershed plays a role in the survival of native woody species, so the potential for trees and shrubs to recover after removing *A. donax* will vary depending on the soil and hydrologic conditions (Lawson et al., 2005). Flood events that provide the bare saturated soil necessary for the development of healthy tree and shrub communities may only occur once in 10 years (Lawson et al., 2005). To establish woody species on upper terraces after *A. donax* is removed, active restoration may be necessary as moisture availability is often too low to support natural recruitment (Lawson et al., 2005 and Cal-IPC, 2011). Experimentation with tree and shrub cuttings showed that this type of restoration can speed up the development of native plant communities in areas where natural processes are unlikely to promote this process (Lawson et al. 2005). It is beneficial to time the installation of cuttings with periods of high rainfall to increase survival and decrease the costs by reducing the number of installations required (Lawson et al., 2005).

Mechanical treatments resulted in a more rapid increase of both native and exotic herbaceous plants compared to the foliar treatments, although exotic species accounted for much of the difference (Lawson et al., 2005). Mechanically treated sites were characterized by bare, loose, soil which are ideal conditions for the establishment of non-native species. Sites treated with herbicide showed much slower reestablishment of herbaceous plants, but the plants that did establish were larger than those found in the mechanically controlled sites. Lawson et al. (2005) attributed this to less competition with neighboring plants in the herbicide-treated sites compared to the mechanically treated sites. More aggressive removal of exotic herbaceous species following *A. donax* treatments, especially after mechanical removal, may be required to reduce competition and facilitate the establishment of native species.

Costs

After performing a cost analysis, Lawson et al. (2005) found that the costs for controlling *A. donax* varied greatly depending on the site accessibility and the density of *A. donax*. The cost per ha of initial foliar treatments alone was $9,900 and dropped to $1,350 for the 1st retreatment, then remained relatively constant thereafter. The costs per ha of the foliar spray method combined with the cut stem method dropped by over 85% after the initial treatment and remained constant for the remaining treatments (Lawson et al., 2005) (Table 5). The costs associated with the follow up treatments dropped because fewer labor hours were required and less herbicide was used as *A. donax* cover decreased.

Mechanical treatments were never fully implemented as originally planned due to problems with biomass management. The costs associated with mechanically removing and grinding 14 ha of *A. donax* in 1998/1999 were approximately $19,800 per ha, first retreatment included (Lawson et al., 2005). Included in this estimate is the use of cut stem and foliar herbicide treatments within the mechanically treated area where non-target species were present; biomass management is not included in this estimate. The costs for each follow-up treatment were estimated to be the same for mechanical removal and the foliar spray methods. The majority of these are associated with the time spent traveling to the site and searching for resprouts (Lawson et al., 2005).

Approximately 12-15 hours of labor per ha were required for the initial treatments with all removal methods. Lawson et al. (2005) noted that retreatments often require laborers to search a much larger area than the original treatment area because all adjacent habitats that are suitable for *A. donax* must be investigated. It is appropriate conduct less frequent site visits after four consecutive treatments once the resprouts grow to a more noticeable size, to optimize retreatment expenditures (Lawson et al., 2005). To eradicate *A. donax* from the entire watershed, all sites hosting the exotic plant must be treated, not just sites that are more likely to have a desired native plant community. If the whole watershed is not treated, especially at the top, reinvasion of *A. donax* downstream after floods is likely (Lawson et al., 2005).

Efficacy of Treatments

The results of this study indicate that *A. donax* eradication in the Santa Margarita River is feasible and has been successful thus far, but substantial funding is necessary in order to complete the 19-year project (Lawson et al., 2005). Since *A. donax* does not produce viable seed in California, treating it from the top of the watershed down can ensure that it will not reestablish as long as the system remains free of human reintroduction (Cal-IPC, 2011; Lawson et al., 2005). Lawson et al. (2005) also found that despite November being cited as the onset of winter dormancy for *A. donax* in California (Bell, 1998), dormancy near coastal areas usually occurs later. With proper pre-treatment investigations of *A. donax* dormancy, the time available to apply foliar herbicide treatments can potentially be extended (Lawson et al., 2005).

One year after treatments, live *A. donax* foliar cover was reduced by over 90%, and almost 100% after three years (Lawson et al., 2005). Very little resprouting was observed in subsequent years, with slightly more resprouting occurring within the area exposed to the 1998 wildfire, although statistically insignificant. The herbicide applications and mechanical removal of the entire plant were both effective in controlling *A. donax* and allowed the project to meet its goal of decreasing *A. donax* cover to 5% within the 5-year timeframe (Lawson et al., 2005). The decision to use herbicide applications or mechanical removal was mainly dependent on site accessibility and density of *A. donax* stands. Lawson et al. (2005) found that herbicide treatments were less costly than mechanical treatments and easier to accomplish in areas where accessibility was an issue. However, the Navy policy of minimizing the use of pesticides may serve as a potential barrier in using this method for the entire treatment area (Lawson et al., 2005).

Difficulties and costs associated with managing biomass prompted the project managers to discontinue mechanical removal in 2001, so it is difficult to fully conclude the efficacy of this method (Lawson et al., 2005). The issues that came about related to the accumulation of biomass following mechanical removal include: spontaneous combustion of dead biomass as a result of increased temperatures from decomposition, insufficient need for mulch near the project area leading to the buildup of biomass piles, and high rates of resprouting from large stockpiles (Lawson et al., 2005).

The foliar spray method resulted in high kill rates of aboveground biomass within several months and little resprouting after the initial treatment (Lawson et al., 2005). These results are similar to those found by Spencer et al. (2008) in that 5% glyphosate solution is an effective herbicide to kill *A. donax* stands with low rates of resprouting. Despite the low resprout rate, follow-up treatments are necessary in order to kill new growth before it grows tall enough to require the less efficient cut stem method (Lambert et al., 2005). Resprouting was much higher in the cut stem and mechanical removal methods, which supports (Cal-IPC, 2011; Spencer et al., 2008) in that cutting the stems of *A. donax* can stimulate new growth.

There are further differences in resprouting between these two methods in that mechanically removing the entire plant, including rhizomes, results in quicker resprouting compared to the cut stem method. Although resprouting is higher for mechanical removal, the new growth is easily killed with re-treatment the following year. The cut stem method produced less new growth, but these resprouts are more difficult to kill and require treatments over several years (Lawson et al., 2005). Giessow and Giessow (1998) showed similar results from the cut stem method and observed that after two years of annual treatment, over 1.3 stems $^{m-2}$ of live *A. donax* remained (Lawson et al., 2005). This need for multiple retreatments shows that the cut stem method may not be advisable in areas where accessibility is an issue or when funding limits the ability to perform retreatments.

Section 3: Treatment Method Comparison Studies

Introduction

Although there are numerous *A. donax* control projects taking place throughout California, very few provide post-treatment data and even fewer provide a direct comparison of the efficacy of different treatment methods. This information is critical to recommend *A. donax* removal methods with the highest potential for success. Projects that do provide data on the efficacy of treatments usually incorporate three or less removal methods, making it difficult to conclude the effectiveness of other existing treatments. It is important to study all existing treatment types, as some of the more commonly used methods (foliar spray, mechanical removal, etc.) may not be feasible in certain locations. The following section includes three studies that directly compare the efficacy of multiple treatment types, including some that are less commonly used. The studies also provide information on different herbicide concentrations, herbicide formulations, and timing of herbicide applications. The recommendations made in this paper are predominantly based off of these three studies and the two case studies above.

Study 1: Sonoma Ecology Center Arundo Eradication and Control Program, Phase 2 Final Report

Introduction

The Sonoma Ecology Center (SEC) implemented a program in 2001 to survey, control, and monitor *A. donax* in central California in an effort to streamline the process of watershed restoration. Phase 1 of this program began in 2001 and was completed in 2006; this phase involved five partners working in different watersheds regulated by the California Bay Delta Authority (SEC, 2010). All partners performed pre-treatment *A. donax* surveys followed by three years of monitoring. The SEC provided a template for a surveying, control, and monitoring protocol from which the partners modified to fit the needs of their individual projects. Phase 2 began in 2006 and was completed in 2008; this phase incorporated five additional partners for a total of ten (Table 6) and was intended to extend the monitoring period to a total of five years for phase 1 and 2 partners (SEC, 2010).

The main goals of this program were: survey the extent of *A. donax* infestation in central California watersheds, determine the most effective herbicide treatments to control *A. donax*, and monitor the post-treatment plant community response (SEC, 2010). Included in the program report are three studies conducted by ecologist and *A. donax* specialist David Spencer, which analyze the following: influence of different glyphosate concentrations on killing *A. donax*, efficacy of imazapyr treatments, and influence of timing on efficacy of glyphosate treatments. These studies together provide the most comprehensive analysis of the efficacy of different herbicide treatments to date.

Project Sites

The ten sites chosen for the SEC *A. donax* Eradication Program were based on the need for *A. donax* eradication and post-treatment restoration. The SEC determined that *A. donax* removal is essential for habitat restoration at these locations. The following is a list of each location included in this program: Lower American River and Sacramento Region watersheds (with locations in the Dry Creek Watershed, Arcade Creek Watershed, Morrison Creek Watershed, Laguna Creek Watershed, Elder Creek Watershed, Minnesota Creek Watershed, Humbug Creek

Watershed, North Fork and South Fork American River watersheds); Lindo Channel/Big Chico Creek Watershed; San Joaquin River Parkway; Napa River Watershed; Sonoma Creek Watershed; and San Francisquito Creek Watershed (Figures 17a-17f). The sites are composed primarily of riparian woodland, but some include stream islands and gravel bars that have become infested with *A. donax* (SEC, 2010). All of these sites are located in within the region controlled by the California Bay Delta Authority.

Methods

The ten partners participating in the SEC (2010) program all developed their own specific treatment methods based on their own needs. However, they were required to follow a template provided by the SEC to ensure that an appropriate comparison of the results can be made. Due to the fact that the treatment procedures varied for each partner, these results should be taken as qualitative information (SEC, 2010). The monitoring protocol was the same for all partners in terms of number of site revisits, timing of monitoring, required data, and methods for collecting data.

The following treatment methods were used during this study: foliar spray (glyphosate only and glyphosate + imazapyr), bend and spray (glyphosate only and glyphosate + imazapyr), cut stem or "cut stump" (glyphosate only and glyphosate + imazapyr), cut, resprout, spray (glyphosate only and glyphosate + imazapyr) foliar spray (imazapyr only), spray, cut, spray (glyphosate only), and cut only (no herbicides). The foliar spray, cut stump, and cut, resprout, spray methods were carried out the same as in other previously mentioned studies (Lawson et al., 2005; Cal-IPC, 2011; Howe, 2014), the only difference being some of the partners also used a 1.5% imazapyr solution. All treatment methods are listed in table 7.

The bend and spray method involves bending *A. donax* stems away from native vegetation without breaking them off, which keeps the vascular system intact allowing for the translocation of herbicide to the rhizomes (SEC, 2010). The spray, cut, spray method involves an initial foliar spray (glyphosate in this study) followed by cutting the stems to approximately 0.5 to 1 meter from the ground 4-6 months later, then spraying the resprouts the following spring (SEC, 2010). The cut only method (no herbicide) involves cutting the *A. donax* to the ground using mowing equipment with no follow up herbicide applications. Much of the information regarding equipment and herbicide concentrations used was not included in this phase 2 report. However, USDA researchers that participated in this program did report using 1.5%, 3%, and 5% glyphosate in their own projects. All partners applied treatments in the fall, sometimes continuing through spring if required (SEC, 2010).

Results

The majority of partners found that foliar application using glyphosate alone or a combination of glyphosate and imazapyr is the most effective method to kill *A. donax.* This method resulted in a high rate of *A. donax* kill with little to no resprouting, requiring minimal follow-up treatments (SEC, 2010). This study did not provide the glyphosate concentrations used by some of the partners, but the USDA reported that 3% and 5% glyphosate solutions were more effective than the 1.5% solution when applied as foliar spray (SEC, 2010). Applications of the 1.5% glyphosate resulted in resprouts the following spring. Table 7 provides further data on the percentage of partners reporting the efficacy of each treatment method. As previously stated, due to the lack of data from some partners these results should be taken as qualitative rather than quantitative; additional studies would be beneficial to back up the results of this study.

Discussion

The results of this study demonstrate that foliar applications (3-5% glyphosate) are effective in controlling *A. donax* and ensure that efforts to treat resprouts are minimal. Foliar applications using 3-6% glyphosate have also been shown to be effective in other studies (Lawson et al., 2005 and Cal-IPC, 2011). This study also shows that the bend and spray method is very effective, but is more time consuming than foliar applications and only recommended when non-target species are present (SEC, 2010). The cut stump method, which is also commonly used when non-target species are present, appears to be less effective then the bend and spray method but is less time consuming. The efficacy of the bend and spray method may be due to the fact that the vascular system remains intact which allows the herbicide to more readily enter the rhizome system, effectively killing the entire plant (SEC, 2010). The cut stem method does not leave this vascular system intact, likely making it more difficult for the herbicide to enter the rhizome system. This idea is supported by Lawson et al. (2005), who observed high rates of resprouting after the cut stem method was employed. The cut, resprout, spray method did not appear effective as it required multiple retreatments for up to four years, but other studies (Cal-IPC, 2011 and Lawson et al., 2005) found that the resprouts were easily killed within two years after using this method. It would be beneficial for future studies to measure the efficacy of these three treatments, especially because they are commonly used in areas in close proximity to non-target species.

Two methods had low success rates: 1) spray, cut, spray and 2) cut only (no herbicide); based on these results, it is not advisable to use them to treat *A. donax*. Both of these methods trigger resprouts, especially the cut only method, as observed by (Lawson et al., 2005; Cal-IPC, 2011; Bell, 1997). These and many other projects consistently report quick resprouting after cutting *A. donax* stems, which has made the application of herbicide following any form of mechanical removal common practice. Based on the lack of data on the use of imazapyr in this study, it cannot be determined if it is more effective than glyphosate when used in any treatment method. However, Spencer et al. (2009) found that 1.5% imazapyr is not as effective as 1.5% glyphosate. Additional research into the use of these two herbicides may provide more evidence to support the findings of Spencer et al. (2009). Overall, this study shows that foliar applications using 3-5% glyphosate are the most effective form of herbicide treatment to kill *A. donax* in areas where overspray onto non-target species is not an issue. In more sensitive habitats, the bend and spray method is very effective but this time consuming process may be more appropriate for smaller patches of *A. donax.* The cut stem method may be appropriate in sensitive habitats that are easy to access for retreatments, and when labor hours are limited on a day-to-day basis.

Studies 2-4: David Spencer Herbicide Studies

Introduction

David Spencer conducted three studies to analyze the efficacy of herbicides used for *A. donax* control based on application timing, herbicide concentrations, and type of herbicide used. Nearly all *A. donax* removal methods use herbicides in some form, so these studies are very useful as they aid managers in maximizing the efficacy of herbicide treatments. Two of the studies focus on glyphosate because this herbicide is the most widely used for *A. donax* removal projects. The third study compares the efficacy of glyphosate and another herbicide, imazapyr, which is used less commonly because its effectiveness in killing *A. donax* is less understood. These studies are incorporated into the SEC *A. donax* Eradication and Control program to provide further support to the analysis of different herbicide control methods.

Project Sites

The study conducted by Spencer et al. (2008) (glyphosate concentration) took place in Sonoma Creek and at the Sycamore Island Ranch Preserve in Fresno, CA. The Spencer et al. (2009) study (imazapyr efficacy) was carried out within an area previously treated by one of the SEC partners at the Gray Lodge Wildlife Area near Gridley, CA (figure 17b). The third study, Spencer et al. (2011) (treatment timing) was conducted in a controlled outdoor setting in Davis, CA and within a naturally occurring *A. donax* stand in Fresno, CA.

Methods

Glyphosate Concentrations/Imazapyr Efficacy

To test the efficacy of herbicide doses, Spencer et al. (2008) applied 1.5%, 3%, and 5% glyphosate herbicide as foliar spray to *A. donax* stands. In addition to the foliar spray, the cut stem method was also tested using a 5% glyphosate solution applied directly to the stem within 2 minutes of breakage. The cut stem method was included because it was previously reported to be effective in areas where sensitive species are present (SEC, 2010; spencer et al., 2008). All treatments were applied using a hand-operated backpack sprayer. Post-treatment leaf chlorophyll content and the number of living and dead tissue was measured within randomly placed quadrats. The following spring, Spencer et al. (2008) returned to count the number of *A. donax* resprouts, measure the width of each plant, and perform biomass calculations. To compare the efficacy of different herbicide formulations, Spencer et al. (2009) also monitored a site that had been treated with a 1.5% solution of imazapyr applied as foliar spray (SEC, 2010). These treatments were applied in the summer less than 30 days before the study began, and the monitoring procedure was the same as in Spencer et al. (2008) (SEC, 2010).

Timing of Glyphosate Treatments

To determine whether timing was a factor in the efficacy of *A. donax* glyphosate treatments, Spencer et al. (2008) gathered rhizomes to grow plants in a controlled outdoor setting in Davis, CA. Treatments were applied to four plants using a foliar spray of 1.5% glyphosate solution. Plants were randomly assigned a treatment month on each of the following dates: 15 September 2006, 16 October 2006, 16 November 2006, 15 April 2007, 15 June 2007, and 15 August 2007. Untreated pants were also included as a control. At monthly intervals, each plant was measured for leaf chlorophyll content, proportion of living to dead stems, and beginning in spring 2007, the number of newly emerging stems (Spencer et al., 2008; SEC, 2010). The same procedure was carried out within a naturally occurring *A. donax* in Fresno, CA except three plants were treated on the following dates: 27-28 September 2006, 18 October 2006, 7 June 2007, and 14 August 2007. The monitoring procedure at the Fresno field site incorporated randomly placed 20x30 cm plots, five of which were selected to collect data (Spencer et al., 2008).

Results

Timing of Glyphosate Treatments

The month following treatments, all plants from showed significantly lowered chlorophyll regardless of the application date; one year after treatments, no plants had any living stems (Table 8) (Spencer et al., 2008). Plants in Fresno also showed a decline in Chlorophyll levels the month after treatment, but these values recovered to near control levels by 2008 on leaves from new shoots (Spencer et al., 2008). However, chlorophyll levels in plants treated in September remained low through 2007. The proportion of living stems was significantly different due to the timing of the treatments, with plants treated in September having the lowest proportion of living stems m^{-2} (Spencer et al., 2008). Treated plants did produce new shoots in the post-treatment growing season, indicating that some rhizomes survived the treatments. However, timing of treatments appeared to influence the number of new shoots with plants treated in September or October having the lowest mean number of new stems (Spencer et al., 2008). Combining the number of living stems with the number of new stems indicates that September and October treatments with 1.5% glyphosate were more effective in killing *A. donax* than the June or August treatments (Spencer et al., 2008)

Imazapyr Efficacy

Imazapyr (1.5%) treatments resulted in decreased leaf chlorophyll content in *A.donax* within one month after treatment. Chlorophyll content continued to decrease though November, but increased again the following spring (Spencer et al., 2009). The proportion of living stems was unaffected by imazapyr treatments, and number of new stems produced the following spring was indistinguishable from the control plants. Spencer et al. (2009) states that these results differ from those found by Brenton (2002) in that 3-5% imazapyr treatments were effective in killing *A. donax,* though this study lacks sufficient data. The results of this study also differ from Spencer's own experience using imazapyr, which was successful in controlling *A. donax* later in the year. The difference in results could be attributed to differences in the timing of application and the concentration of imazapyr used (Spencer et al., 2009).

Glyphosate Concentration

Glyphosate treatments of 1.5% or greater resulted in a significant decline in leaf Chlorophyll concentrations in plants grown at Sycamore Island (Spencer et al., 2008). After measuring the proportion of living stems post-treatment, there was an obvious difference in plant response to the 1.5%, 3%, and 5% glyphosate treatments (Table 9). The proportion of living stems decreased more significantly beginning in May, 2007 in plants treated with 3% or 5% glyphosate than in plants treated with 1.5% glyphosate. The fact that the 3% and 5% glyphosate plants did not produce any new stems the year after treatments indicates that the rhizomes were killed (Spencer et al., 2008). A similar pattern was observed at Sonoma Creek with leaf

Chlorophyll content significantly declining after glyphosate treatments of 1.5% or greater. The plants treated with 5% glyphosate showed the greatest decline in leaf chlorophyll content (Spencer et al., 2008). A similar pattern to Sycamore Island was also observed at Sonoma Creek in that the proportion of living stems showed a greater decline in July, 2007 in pants treated with the 5% glyphosate, and no new stems were produced in 2007. Plants treated with 1.5% glyphosate did produce new stems in 2007 (Spencer et al., 2008). The cut stem method (5% glyphosate) did not result in a difference in the leaf chlorophyll concentration or proportion of living stems compared to plants that received foliar treatments with 5% glyphosate.

Discussion

Timing of Glyphosate Treatments

Spencer et al. (2011) attributes the differences in the Davis and Fresno experiments to the plant size. The pot-grown Davis plants (average height 0.91 m) were about one-fourth of the size of the naturally growing Fresno plants (average height 3.9 m). Smaller plants are potentially more susceptible to glyphosate because they have a reduced rhizome mass available to produce new growth (Spencer et al., 2008). The results from the naturally growing Fresno *A. donax* indicate that glyphosate treatments are most effective in late summer or early fall (September-October). This is likely the ideal time because as plants prepare for winter dormancy, they move storage products to the rhizomes (Odero and Gilbert, 2010; spencer et al., 2008). As indicated by Lawson et al. (2005), controlling *A. donax* through the use of herbicides is most effective when the solution enters the rhizome system; this is more likely to kill the entire plant and lessen the number of resprouts the following growing season.

Imazapyr Efficacy

The data obtained by Spencer et al. (2009) suggests that 1.5% imazapyr is not as effective as 1.5% glyphosate in killing *A. donax.* This conclusion is based on a comparison of this study to the results Spencer et al. (2008), which showed that 1.5% glyphosate did result in the killing of *A. donax.* A similar result was observed by SEC (2010) in that only one out of the two participating partners reported imazapyr as an effective foliar herbicide. The partner that did report imazapyr as an effective herbicide also stated that this solution is more effective when used in combination with glyphosate. More research into the use of imazapyr to treat *A. donax* would be beneficial, but the successes of glyphosate treatments observed in other studies (Lawson et al., 2005; Cal-IPC, 2011; Howe, 2014) indicate that this is the most effective herbicide currently in use.

Glyphosate Concentration

The results of this study indicate 3% and 5% glyphosate foliar applications were the most effective treatments for killing *A. donax* with a single, late season application (Spencer et al., 2008). The data also suggests that 1.5% glyphosate treatments are less effective in killing *A. donax* stems and do not inhibit the production of new stems. Similar results were observed by (Lawson et al., 2005) in southern California in that 6% glyphosate treatments were effective in killing 90% of *A. donax* one year after treatments, and almost 100% after three years. Although Lawson et al. (2005) did observe resprouts the following spring, these were easily killed with one follow up treatment. The cut stem method did not appear to be more effective in killing *A. donax* compared to the foliar spray, which was also the case for SEC (2010) and Lawson et al (2005). The similar results obtained from these three studies indicate that the cut stem method is not advisable unless close proximity to sensitive species or native vegetation is an issue. This process is more time consuming than foliar applications and often produces more resprouts the following year (Cal-IPC, 2011; Giessow and Giessow, 1998; Lawson et al., 2005). Based on the results of this study and of similar studies (Cal-IPC, 2011 and Lawson et al., 2005), 4-6% glyphosate solution is the most effective concentration to control *A. donax* in situations where foliar spray is the most appropriate application method

Discussion

After analyzing all of these studies, several common themes come about that indicate the most effective ways to eradicate *A. donax*. It appears that 3-6% glyphosate foliar spray is the most consistently effective method to treat larger patches of *A. donax* when there is little threat to overspray onto non-target species. Imazapyr does not appear to be as effective in killing *A. donax* as glyphosate, as demonstrated by the SEC partners and Spencer et al. (2009), though further study of the efficacy of this herbicide would be beneficial. Glyphosate foliar spray is also the most effective method when site accessibility prevents the use of heavy machinery. This process is easier to carry out within dense vegetation and causes less damage to the substrate than mechanical removal. The low rate of resprouting resulting from foliar treatments was consistent across all studies, minimizing the necessity for retreatments as long as the herbicide is applied during the growing season, before the onset of winter dormancy. The low resprout rate after foliar treatments is especially beneficial for sites that are hard to access for retreatments. Since the hours of labor are the same for foliar spray and mechanical removal but the equipment costs are much lower, foliar spray appears to be the most cost-effective method for larger patches.

Based on these studies, mechanical removal may be appropriate for large *A. donax* stands that are too dense to make foliar treatments a feasible option and when the site is accessible for heavy machinery. It appears that the chief advantage of mechanical removal is that the process uses less herbicides and larger patches of *A. donax* can be removed much quicker than with foliar treatments. The removal of the entire plant, including rhizomes, lessens the chance of regrowth in the future as long as resprouts are promptly treated. As indicated by Lawson et al. (2005), mechanical removal should always be followed by grinding of *A. donax* and spreading it as a thin layer to minimize resprouting and eliminate the threat of flooding or fire. The accumulation of loose, dead *A. donax* biomass seems to be the main problem with this method and removal is very expensive, making this a less ideal option than foliar treatments unless herbicide use is restricted. Another issue with this mechanical removal is that the soil disturbance associated with this method may increase exotic herbaceous species. The increase in non-natives may require retreatments for several years following initial treatments, adding to the initial costs.

Section 5: Recommendations and Conclusion

Introduction

The following section provides recommendations for prioritizing *A. donax* removal sites, determining the most effective removal methods, and carrying out passive or active revegetation, based on site-specific factors. Numerous factors play a role in determining where to focus removal efforts and what removal methods will ensure long-term control of *A. donax* for a given site. It is also difficult to determine whether it is appropriate to actively restore native plant communities or allow natural riparian processes to revegetate the area. Time, budget, equipment, and labor are often limiting factors during riparian restoration projects, so it is critical to understand what methods are likely to have the highest potential for success under these limitations. A lack of understanding of the invasive ecology of *A. donax* and the efficacy of treatment options has often led to management decisions being made without sufficient scientific information (Coffman et al., 2011).

The goal of this section is to provide managers with general guidelines to assist them in creating effective *A. donax* eradication plans. These recommendations are based off of an analysis of past removal projects, as well as studies evaluating the invasive ecology of *A. donax*. It is important to note that I cannot legally advise the use of herbicides, so these are not to be taken as recommendations. The differences between California watersheds such as geographic location, topography, proximity to urban areas, and many other characteristics allow for some fine-tuning of these recommendations to align with the needs of a particular site.

Prioritization of Removal Sites

Careful planning of where to focus removal efforts is critical because removing *A. donax* from certain areas will result in greater ecological benefits than removal from other areas. Limitations such as time, budget, and labor may prevent the removal of all *A. donax* from a given area, making careful prioritization essential to the success of the project. Most of these recommendations are described in the Santa Clara River Riparian Revegetation and Monitoring Handbook (2011) but are rearranged slightly to better align with a broader range of California watersheds. These removal priorities are listed from the highest priority down, but all of these are still very important considerations that cannot be ignored for any project.

Priority 1: Upper Watershed

Reproduction via fragmentation is a major factor in *A. donax* overtaking watersheds in a relatively short period of time. The episodic flood events characteristic of California serve as an ideal vehicle to drive the establishment of *A. donax* through entire watersheds. Implementing removal efforts on a watershed-wide scale is critical because all interconnected bodies of water are susceptible to *A. donax* infestation from upstream sources. As long as *A. donax* occupies the upper watershed, there is a constant source of new *A. donax* propagules to spread downstream. Since *A. donax* does not produce viable seed in California, removal of the plant in a top-down manner means that the system can remain free of further reestablishment indefinitely (Lawson et al., 2005). This, of course, is based on the assumption that the system will remain free of *A. donax* reintroduction from outside sources. Identifying potential outside sources of propagules is recommended so that measures can be taken to prevent further *A. donax* invasion.

It may not always be feasible to remove all *A. donax* from the upper watershed, especially when an infested area is inaccessible. When this is the case, all that can be done is to treat *A. donax* as far upstream as possible and continue to monitor and treat new growth. If project limitations prevent complete removal from the upper watershed, resources should be allocated to treat the accessible largest clumps of *A. donax* in the upper reaches. Treating larger upstream clumps will minimize further recolonization in downstream locations; this will ensure a more efficient use of resources by allowing more *A. donax* removal from new areas, rather than retreating the same areas each year.

Priority 2: Largest *A. donax* Infestations

The largest patches of *A. donax* are the greatest sources of *A. donax* propagules, and therefore should be removed before smaller clumps. These larger patches also remove more significant portions of riparian habitat and cause more degradation to the structure and functionality of watersheds. The ecological benefit of removing large clumps is therefore much greater than the benefit of removing smaller clumps in most circumstances. Examples of some situations when removing the largest clumps first may not be as ecologically beneficial are: when they are found in the lower watershed, when they occur in higher terraces and are unlikely to release fragments into the water, and when another clump is posing a significant fire threat to riparian forests.

Larger patches also pose a greater risk of flooding, as large *A. donax* rafts can uproot during major floods and cause flooding and structural damage downstream (figure 6). Larger *A. donax* patches also act as greater sources of fuel for wildfires, which usually cause significantly greater damage than wildfires not burning within *A donax* infested areas (Coffman et al., 2010). Accessibility is of course an issue, so treating the largest patches as far upstream as possible is likely to have the greatest ecological benefit for most sites. It is ultimately up to the managers to weigh the benefits of removing the largest propagule sources first over other areas. This decision can be difficult because removing larger infested areas is more costly and time-consuming than treating smaller clumps. Despite the effort involved, the chance of reinvasion is dramatically lowered when the largest upstream clumps of *A. donax* are treated. When recolonization is eliminated as a threat, native vegetation has a much greater chance of naturally recovering following *A. donax* removal.

Priority 3: Infestations Adjacent to Fire-Prone Areas

Wildfires burning through *A. donax* infested watersheds are extremely damaging to riparian habitats and pose a great risk to other surrounding habitats. Wildfires in *A. donax* infested areas burn much hotter than non-*A. donax* fires and can completely scorch all vegetation, leaving only charred, bare ground. Native vegetation may take three or more years to regrow, while *A. donax* thrives in these conditions and can monopolize the area within one year (Coffman et al., 2010) (figure 8b). The near complete loss of native vegetation can result in a significant decline of wildlife, and the fires themselves can cause direct loss of animals that cannot escape the burning area (Cal-IPC, 2011).

A. donax that grows high under riparian canopies is especially damaging because when the plant catches fire, entire riparian forests can be lost. Fires that burn through riparian habitats not infested with *A. donax* generally burn closer to the ground, scorching more herbaceous plants and small shrubs rather than trees. Riparian trees take a much longer time to recover compared to herbaceous plants and small shrubs, so *A. donax* poses a serious threat to riparian habitats near fire-prone areas. Riparian habitats naturally serve as firebreaks, but *A. donax* invasion reduces the ability of these habitats to hinder fires from burning through to other areas.

The damage that fires cause to native vegetation and wildlife in *A. donax* infested watersheds is a serious issue, leading managers to place this as a top priority in many cases. The Santa Clara River Riparian Revegetation and Monitoring Handbook places removal in fire prone areas at the top of the priority list, which is appropriate given the dry climate and proximity to fire prone shrublands at that site**.** It is recommended that whenever there is a serious threat of wildfire burning *A. donax* infested watersheds, removal should be a high priority because of the potential for major losses to native vegetation and wildlife. Removal near fire prone areas is also important when the site is located in close proximity to urbanized areas. However, because these recommendations are meant to be applicable to across a wide range of California watersheds, removal near fire prone areas has been given third priority in this list.

Not all riparian habitats in California have an equal chance being exposed to wildfire, so removal priority should depend on the fire regime of the project site. For example, southern California riparian habitats adjacent to chaparral have a high chance of burning, especially during Santa Ana winds; removal of *A. donax* within riparian forests in these habitats would likely have the greatest ecological benefit. Since the threat of wildfire in a watershed located in a northern coastal forest is much lower, removing the largest infestations from the upper watershed would likely have the greatest ecological benefit. As with every aspect of *A. donax* eradication, all site factors should be considered so that efforts are focused on practices that will ultimately make the greatest contribution to restoration to watershed-wide restoration.

Priority 4: Habitat for Threatened or Endangered Species

Since *A. donax* invasion can affect entire watersheds, there is potential for negative impacts to any wildlife that rely on the watershed. However, it is important to pinpoint habitats where threatened or endangered species are known to nest and treat *A. donax* in those areas promptly. Some species in California, such as least Bell's vireo and arroyo toad, exclusively rely on riparian habitats. *A. donax* invasion is a serious threat for these species because it can displace the native vegetation that serves as habitat for terrestrial species and lower the quality of habitat for aquatic species. Treating *A. donax* in areas where threatened or endangered wildlife have been confirmed is critical to prevent further losses and support a rebound of their populations. *A. donax* removal in these habitats must be coordinated so it does not occur during the breeding season (Cal-IPC, 2011). This limits the available time for treatments, especially foliar herbicide applications, which are already limited to the growing season of *A. donax.* The short timeframe for treatments within nesting habitat for special status species make prioritization complicated, but efforts should be made to treat these areas first whenever possible.

Removing *A. donax* from nesting areas for sensitive species such as southwestern willow flycatcher and arroyo toad will clear up space and resources to facilitate a healthier riparian vegetation community, which is critical for successful breeding. If the habitat has already been heavily degraded and active revegetation is necessary, removing *A donax* will allow restoration efforts to be carried out in a timely manner. It is important to carry out active revegetation promptly after removing *A. donax* because planted vegetation, especially trees, may take at least five years to grow into suitable habitat (Coffman et al., 2011). As is the case for prioritizing removal in fire-prone areas, not all project sites will have *A. donax* growing in habitat for threatened or endangered species. Although restoring habitat for sensitive species may be a top priority for some locations, it is not applicable to all riparian habitats and is therefore a slightly lower priority on this list.

Priority 5: After Floods or Fires

Since it is difficult and costly to remove large patches of *A. donax*, the ideal time to remove the plant from heavily invaded watersheds is immediately after floods or fires (Coffman et al., 2011). After these disturbances, much of the vegetation is removed so access to *A. donax* is much easier and the amount of intact *A. donax* is much less. Figure 7 shows a riparian habitat that was recently burned where access for heavy machinery would be relatively easy. Digging out the entire plant, including rhizomes, is also made much easier for the first couple of weeks after floods. Impacts to special status species during this time is low because much of the damage has already been done, making it easier to work without worrying about impacts to the habitat (Coffman et al., 2011). It is important to note that one year after wildfire, *A. donax* density can increase following herbicide treatments, so retreatments for up to five years may be necessary if herbicide treatments are performed. If access allows for the use of heavy machinery, mechanical removal is recommended after floods or fires because less resprouting will occur and issues with damaging native vegetation may not apply. This priority is based off of the savings in time, cost, and effort and not necessarily the direct ecological benefit. However, there is always some degree of benefit of removing *A. donax,* so taking advantage of natural disturbances is advantageous to habitat recovery on a watershed scale.

Priority 6: Areas Least Susceptible to Reinvasion

Treating *A. donax* in areas that are least likely to be reinvaded is extremely cost-effective because less money, time, and effort are needed to perform retreatments. Minimizing the necessity for retreatments will allow managers to allocate more resources to the initial treatments and can therefore remove *A. donax* from a much larger area. Treating areas that are unlikely to be reinvaded increases the ecological value of the initial treatments because native vegetation can begin to recover without the threat of competition from *A. donax*. The structure and functionality of rivers or streams can also recover faster when *A. donax* is eliminated as a source of degradation.

The area outside of the flood zone is less likely to be reinvaded because natural deposition of *A. donax* is highly unlikely without exposure to flooding (Coffman et al., 2011). Areas with low soil moisture and nutrient availability are also less likely to be reinvaded because these conditions are less suitable for rapid growth. This priority supports the idea that removal of large *A. donax* infestations from the upper watershed is still a top priority in most situations because this will decrease the number of areas that are likely to be reinvaded.

Control Methods

The following section provides recommendations for the most effective control measures that can be used under specific situations. Due to a lack of studies analyzing biological control efficacy, this treatment method its not included. It should also be noted that no *A. donax* biological control agents have yet been approved by the USDA (Dudley, 2009). Prescribed burning is another method that is not included in this study as the risks associated with fires, such as potential damage to non-target vegetation, can be difficult to manage (Dudley, 2009). Burning live *A. donax* also does not kill the rhizomes and may actually result in rapid regeneration of the plant, as supported by Coffman et al. (2010). It would be beneficial to carry out future studies analyzing the efficacy of these treatments, especially because they may lead to less frequent use of herbicides.

When using herbicides, marker dye should be mixed in to make the solution more visible to the applicator (SEC, 2010). Mixing in dye with the herbicide will eliminate confusion and potentially lessen the amount of herbicide used. Extreme care should also be taken to remain within the legal limit for glyphosate application at 7 qt./acre (EPA, 2015). The two most commonly used glyphosate herbicide brands are Round-Up and AquaMaster; AquaMaster is approved by the EPA for direct use on aquatic plants, but Round-Up should only be used in areas with no potential for leaching intro streams or rivers (Dudley, 2009). Although there has been some evidence showing that imazapyr can be an effective herbicide (SEC, 2010), few studies have analyzed the efficacy of this particular herbicide. Spencer et al. (2009) found that 1.5% glyphosate is more effective at killing *A. donax* than 1.5% imazapyr. Based on this study and the existing evidence that shows glyphosate is very effective, I would recommend this herbicide over imazapyr until additional studies support imazapyr as an effective for *A. donax* eradication. Very few other herbicide alternatives exist that are as effective in killing *A. donax* as glyphosate. Two herbicides that have been tested to kill *A. donax* are paraquat and triclopyr compounds, but these are no more effective than glyphosate and are not permitted for use near water (Dudley, 2009).

The use of herbicides has been a topic of controversy because of the potential health effects for humans and animals. In September, 2015, the EPA classified glyphosate as “Carcinogenic to Humans” following studies that show a potential link between glyphosate exposure and cancer. An article released by the San Francisco Chronicle on October 30, 2015 addresses the concerns of San Francisco residents that glyphosate may be carcinogenic. One woman interviewed for the article stated that she lost her dog to mouth cancer, most likely related to glyphosate contamination on tennis balls from areas treated with the herbicide. The article also points out that the San Francisco Department of the environment classified glyphosate as “Most Hazardous” in July, 2015. Despite the concerns of glyphosate toxicity to humans and animals, this article ends with the following statement by UC Davis veterinary toxicologist Robert Popenga: “There is no peer-reviewed literature right now suggesting that there is a correlation (of glyphosate exposure to cancer in animals)…as far as herbicides go, as long as they’re being used according to direction, your pet should be OK.”

Two additional long-term studies (Forest Pest Management Institute, 1989 and Newton et al., 1984) also concluded that glyphosate has no negative impacts on mammals, beneficial insects, birds, soil organisms, and aquatic organisms if used at the directed concentrations. Although these studies were conducted over 30 years ago, they have yet to be refuted by further studies of glyphosate toxicity. A study conducted by Puertolas et al. (2010) found that in the first three days following *A. donax* glyphosate treatments, glyphosate levels were fairly high in river water at 20-60 microg/l, but after twelve days these levels subsided. Puertolas et al. (2010) also determined that there were no toxic effects on macro-invertebrate communities in rivers exposed to glyphosate. However, the fact that glyphosate levels were high in river water immediately following applications demonstrates the importance of limiting herbicide treatments during the breeding season for sensitive wildlife, especially for aquatic organisms such as the arroyo toad.

The proposed health and environmental risks of glyphosate have led to many people not supporting the use of this herbicide, especially near urban areas. Although these concerns are important and worth investigating, the lack of current scientific evidence definitely proving that glyphosate is carcinogenic is insufficient to eliminate its use to treat *A. donax,* especially because it has been shown to be the most consistently effective removal method in numerous studies (SEC, 2010; Lawson et al., 2005; Coffman et al., 2011; Dudley, 2009). Since the goal of this study is to determine the most effective methods to control *A. donax,* it is still recommended to use glyphosate until further conclusive evidence proves the herbicide as being carcinogenic to humans and toxic to wildlife. The recent changes in labeling glyphosate as carcinogenic warrants investigation into alternative herbicides, such as imazapyr, or alternative removal methods that are both effective and safe for humans and wildlife. It is important to have at least one team member certified to apply herbicides so that workers can be properly trained to minimize the amount of herbicide used. If care is taken to apply the minimal amount of glyphosate needed for effective control of *A. donax*, avoid spraying during breeding season, and minimize overspray onto non-target species and into urban areas, glyphosate can be a safe and effective removal method.

Mechanical Removal

Mechanical removal using an excavator backhoe with a clamshell bucket and attached grinder is an effective way to remove large, dense stands of *A. donax* in easily accessible sites. Heavy machinery has the ability to dig out the entire plant, including rhizomes, which is crucial in order to kill *A. donax* completely. This method is most effectively used in more open areas, not necessarily within riparian forests or in areas with uneven ground or steep terrain. This method is also not recommended when sensitive wildlife is found within the removal area. All *A. donax* removed must be grinded and distributed on the ground as a thin layer to minimize resprouting, eliminate the potential for spontaneous combustion, and lower the risk of flooding. Any resprouts should be treated with either 4-6% glyphosate foliar spray or cut stem (100% glyphosate) once they reach 1-2 meters in height. Past projects have reported that resprouts are easily killed the following spring and further retreatments may not be required (Lawson et al., 2005; Coffman et al., 2011). An advantage with this mechanical removal is that it can be used year round, as opposed to herbicide treatments, but should be limited during the breeding season in areas where threatened or endangered species are known to exist. This method also uses less herbicide than foliar treatments depending on the amount of resprouts that need to be treated.

Mechanical removal is only feasible for easily accessible areas and for projects with an appropriate budget to operate the equipment and manage the biomass. The initial costs of mechanically treating 24 ha for the Santa Margarita *A. donax* control project was $19,800 per ha; this was twice the cost of initial foliar treatments in the Santa Margarita River. Mechanical removal is also advantageous for large *A. donax* clumps located in urbanized areas because the initial process uses no herbicide. Whenever retreatments are required near urban areas, the cut stem method is recommended over foliar spray (Sec, 2010). This is also an effective method when there is an insufficient labor force to deal with large infestations because only one worker is needed to operate the equipment; grinding and spreading the biomass does require additional workers. Biomass accumulation is a major issue associated with mechanical removal, and dealing with it can be expensive and time-consuming (Lawson et al., 2005). Another issue that can arise from mechanical removal is that it results in bare, loose soil, which may support rapid growth of exotic herbaceous species, as observed by Lawson et al. (2005). These soil conditions are also ideal for the recolonization of *A. donax* that could not be removed upstream, so adequate vegetation monitoring of mechanically treated sites is crucial. Due to the issues of accessibility, cost, biomass accumulation, and manipulation of the substrate, this method would only be recommended for large clumps in easily accessed, open areas when foliar treatments are not feasible.

Foliar Spray with 3-6% glyphosate

Research has shown that using a 3-6% glyphosate foliar spray is the most effective and economical way to treat *A donax* in situations that allow for its use (Lawson et al., 2005; Coffman et al., 2011; SEC, 2010). For large *A donax* patches, this method is generally more appropriate than mechanical removal because accessibility is not a factor, initial costs are much lower, and loose biomass does not accumulate. Loose biomass results whenever *A. donax* stems are cut or when the root system is no longer attached to the substrate. This biomass presents a much greater risk of flooding than intact *A. donax* and has a higher chance of producing resprouts (Lawson et a., 2005; Cal-IPC, 2011). Foliar treatments also result in little to no damage to the substrate, lessening the chance of immediate invasion by exotic herbaceous species. Leaving *A. donax* attached to the ground has two advantages: herbicide reaches the rhizomes more effectively when stems remain uncut, resulting in a higher kill rate and less resprouting; attached biomass presents less of a flood risk and does not need to be immediately broken down.

For pure stands of *A. donax* (80% canopy cover or greater), aerial spray via helicopter or airplane is the quickest and most efficient way to apply foliar spray when possible (Bell, 1997). Aerial applications can cover approximately 50 ha per day, using a concentrated glyphosate solution sprayed in very fine droplets (400 microns), which actually reduces the amount of herbicide used (Bell, 1997). The use of a helicopter is not recommended near urban areas, when there is a risk of overspray onto non-target species, and when navigation by air is not possible.

When *A donax* clumps are too small to make helicopters financially efficient and when *A. donax* makes up the understory mixed with native plants (less than 80% cover), herbicides should be applied by hand (Bell, 1997). When there is road access, street vehicles with 400 -liter spray tanks are a good alternative. Quad runners equipped with 60-liter sprayers are useful when there is no road access but the terrain allows for the use of off-road vehicles. As a last resort, 20 -liter backpack sprayers can be used when terrain does not allow for the use of off-road vehicles or when vegetation is too dense (Bell, 1997). If there are some non-target species in the area but *A. donax* makes up the majority of vegetation cover, plastic bags or another non-porous material can be used to cover the leaves of native plants during application. If there are enough natives around that would make this method too time-consuming, it would be more effective to choose a treatment method that can be applied to *A. donax* more accurately. Prior to starting applications, adequate training should be provided to minimize the risk of applying too much herbicide.

Foliar applications should be applied during the growing season just before the onset of winter dormancy to maximize uptake of the herbicide to the rhizomes (Bell, 1997; Lawson et al., 2005). Foliar applications should also be timed correctly so they are not applied during the breeding season for sensitive species, unless it has been determined that there are no nesting species near the treatment area (Cal-IPC, 2011). The growing season may vary between different geographic locations; for example, in the warmer climates of southern California it has been reported that applications can still be made into December (Giessow, 2001). In central and northern California, applications should be made earlier as the colder climate result in an earlier onset of winter dormancy. One partner of the SEC *A. donax* eradication program reported that applications were effectively made through October in Chico, but most evidence shows that August through September is the ideal timeframe for applications in central and northern California (Newhouser, 2008; SEC, 2010). Cold temperatures, especially in the evening, have been shown to stop translocation of the herbicide, rendering it ineffective (SEC, 2010). It is advisable to spray herbicides earlier in the day before temperatures cool and before temperatures begin to drop closer to winter. Herbicides should also not be applied if temperatures are expected to reach 90°F or higher as they can become volatile, potentially exposing both the applicator and non-target species in the area (USDA, 2015). Lastly, if standing *A. donax* presents a risk of wildfire but large infestations occur, stems should be promptly cut once the plant is dead. Any section of the infested area that is situated under a riparian forest canopy should be treated using the cut-stem method.

Bend and Spray/Hook Methods

The removal methods that have shown the next highest degree of success under glyphosate foliar applications are the bend and spray and "hook" methods (3-6% glyphosate). These are the preferred methods when overspray onto non-target species is an issue or when patches are too small to make foliar applications or mechanical removal financially efficient. To avoid confusion between these two methods and general foliar applications, it should be noted that the same 3-6% glyphosate solution is applied as a spray after the stems are bent. These two methods are also recommended for sites located within or near urbanized areas to minimize potential human exposure to the herbicide (SEC, 2010). Foliar applications use more herbicide (excluding aerial applications), so it is best to use the bend and spray or hook methods for smaller *A. donax* clumps when time is less of a factor. As with foliar applications, these methods do not involve cutting the stems, leaving the vascular system intact and allowing for translocation of the herbicide to the rhizomes, resulting in greater kill. This method also leaves dead *A. donax* in place attached to the roots, eliminating the issues related to loose biomass, such as flood risks.

For the bend and spray method, the *A. donax* is bent away from native vegetation, generally over open ground, so leaving the plant in place should have little to no effect on the growth of native species. If *A. donax* must be broken down, workers can grind the dead biomass and spread it as a thin layer approximately two months after the initial treatment. This method requires at least two workers to bend the stems and one herbicide applicator. Teams can easily rotate between three or four *A. donax* clumps at a time with careful coordination (Coffman et al., 2011). Leaving *A. donax* stems intact also minimizes resprouting, which is triggered when stems are cut (Bell, 1997; Lawson et al., 2005). Leaving stems intact eliminates the need for multiple retreatments, which is especially important when access to the site is difficult. This process is more time consuming than mechanical or foliar applications, but equipment and herbicide costs are lower than these two methods making it more practical for smaller clumps. This process is also more time consuming than the next preferred method, cut and spray, but the low resprout rate gives this method an advantage by minimizing retreatments.

The hook method is very similar to bend and spray, except only one worker is needed for the process. With this method, a worker inserts a PVC hook attached to an 8-foot pole, with an additional side hook attached next to the main hook. The worker inserts the hook into the center of the *A. donax* patch, grabbing about 10 stems and slowly walking backwards while spraying herbicide up the entire length of all ten stems (Coffman et al., 2011). This process uses the least amount of herbicide next to the bend and spray method, so it is also more appropriate for smaller patches. As with the bend and spray method, little to no resprouting occurs so multiple retreatments are often not required; at least one follow up visit is advised to ensure that resprouts are treated if they occur. The hook method is also effective when labor is limited because only one individual is needed to treat smaller patches. If there are only one or two workers available to treat small, isolated clumps, the hook method would be more efficient than the bend and spray method. Although there is no data on the efficacy of this specific method, the amount of herbicide used and the general application process is the same as the bend and spray method. Other than the amount of clumps that can be treated at one time, the efficacy of these two methods can be assumed to be the same.

Cut Stem (cut stump)

When mechanical removal and foliar applications are not feasible, the cut-stem method can be an effective way to treat small to moderate-sized patches of *A. donax*. This is not advised over the bend and spray or hook methods unless there is inadequate space to bend *A. donax* stems or when applications are made very close to non-target vegetation, wildlife, or near urban areas (Coffman et al., 2011). This method can also be beneficial for tall *A. donax* because it is difficult to apply foliar treatments or the bend and spray/hook methods to tall plants. The cut stem method is more efficient for clumps that cannot be treated mechanically or with foliar spray, but are too big for the more time-consuming bend and spray/hook methods to be feasible. It may also be more appropriate to use the cut stem method over the bend and spray/ hook methods near urban areas where human exposure to herbicides (no spraying involved with cut stem) is a factor or when standing *A. donax* is aesthetically unacceptable. Since standing *A. donax* may prevent a fire hazard, the cut stem method is also appropriate in areas adjacent to fire-prone shrublands, especially when situated under riparian forest canopies.

Since this method involves cutting the *A. donax* stems*,* resprouting usually occurs and up to four years of retreatments may be required (Lawson et al., 2005). The costs for this method associated with retreatments generally negate the initial equipment and herbicide savings compared to foliar and mechanical treatments. Site accessibility should also be taken into account because the labor costs for retreatments may be high in areas that take a long time to access. It is very important to apply the herbicide within two minutes of cutting the stem to allow translocation to the rhizomes, making careful planning essential. It is also necessary to make sure the cuts are clean and are not clogged with dirt or other debris that would interfere with herbicide uptake. To avoid this issue, initial cuts should be made and biomass immediately cleared from the area. After biomass is cleared, a second clean cut should be made on each stump and concentrated (100%) glyphosate applied within 2 minutes (Bell, 1997). This can also be an effective follow up treatment for small amounts of resprouts occurring after the use of other methods, such as mechanical removal.

Cut and Spray (Cut, Resprout, Spray)

The cut and spray or "cut, resprout, spray" method is another alternative to mechanical or foliar treatments for small to moderate-sized patches when non-target species are present or vegetation is too dense. For this method, *A. donax* stems are cut and debris is removed, then resprouts are sprayed 3-6 weeks later or when plants reach approximately three feet in height (SEC, 2010). Few studies have explored the efficacy of this method in depth, but the SEC *A. donax* Eradication Program partners found this method to be less effective than the cut stem method. Due to a lack of data on the efficacy of this method, I cannot confidently recommend cut and spray over the bend and spray/hook or cut stem methods.

One potential advantage of this method over the cut stem method is that it may be possible to cover a larger infested area within a single working day, since herbicides are not applied immediately after the cut is made. This method may also require less care and coordination compared to the cut stem because it is not necessary to apply herbicide within two minutes of cutting the stem, which can complicate the process. Although it is always recommended to adequately train workers, situations that result in less training and coordination may lead to this as the preferred method over the cut stem. As with the cut stem method, retreatments may be required for up to four years, so this should only be used in sites with relatively easy access and when adequate resources are available to perform multiple retreatments. Whenever possible, biomass should be ground up and spread out, as is the case for any method that involves cutting the stems.

<u>Biomass Removal</u>

Removal of dead biomass is the most expensive component of *A. donax* eradication, so it is recommended that biomass is left in place whenever possible

(Bell, 1997). The problem of managing biomass can most easily be avoided by using removal methods that do not involve cutting *A. donax* stems, chiefly foliar applications and bend and spray/hook methods. However, even these methods may require removal of biomass for one of the following reasons: biomass presents a fire or flooding hazard, is aesthetically unacceptable, or interferes with native plant restoration (Bell, 1997; Coffman et al., 2011). The Department of Fish and Game allows dead biomass to remain in the channel as long as the plant is uncut and the roots are intact; foliar applications and the bend and spray methods meet this criteria (SEC, 2010). Taking into account the issues of biomass accumulation, it is recommended that the material is ground up after the plant is dead, whenever possible. If poor access prevents the use of mechanical grinders or mowers, it is beneficial to cut stems into smaller pieces and spread out once the plant has died. Cutting stems into smaller pieces presents less of a flood risk and provides more open ground for native plants to grow.

Larger patches of dead *A. donax* biomass may especially have to be removed to mitigate hazards and allow for the reestablishment of native vegetation. An effective way to deal with biomass in a timely manner is to use mowing tractors or other heavy equipment with attached grinders to reduce the biomass to mulch and evenly spread it around the area. As previously stated, *A. donax* that is ground into chips does not generally resprout and poses little threat for flood or fire. As demonstrated by Lawson et al. (2005), *A. donax* mulch does not increase the growth rate of native vegetation, but it was also not found to hinder growth; the ecological benefits of grinding and spreading biomass outweigh the extra costs and time it takes to perform this type of work.

The fastest and most cost-effective way to deal with biomass removal is prescribed fire (Bell, 1997). This does not require grinding or spreading of dead material, rather entire piles of *A. donax* are burned. This process should be monitored extremely closely and should not be carried out when it can potentially affect native vegetation, sensitive wildlife, or other resources. This is also not recommended in close proximity to fire-prone shrublands or in urbanized areas. Due to the risks associated with prescribed fire, this is not recommended over grinding biomass unless situations occur where grinding is not possible and when dead biomass must be removed.

Hauling of dead biomass by vehicle is only recommended as a last resort when removal is required and no other options are feasible. This process is very expensive and time consuming, and also poses a threat of fragments falling off of the vehicle during transportation, potentially causing infestation to new areas. Most landfills also do not accept dead *A. donax* and those that do require it to be cut into short lengths and placed in plastic bags, further adding to the labor costs (Bell, 1997).

Post-Removal Revegetation

Although reestablishment of native vegetation is a major component of riparian habitat restoration, removal of *A. donax* alone may be sufficient to bring back native plant communities. Riparian forest revegetation is extremely expensive at tens of thousands of dollars per ha, limiting the size of the area to be restored and therefore the biological value of the restoration (Bell, 1997). For most restoration projects, it is recommended to rely on passive revegetation in areas that are on the floodplain or within channels. These areas are regularly exposed to flooding, especially in low flow channels, which facilitate natural reestablishment of riparian vegetation (Coffman et al., 2011; Bell, 1997). In general, active restoration is only recommended on higher terraces that are not frequently flooded and where adequate moisture and nutrients are available. The decision to use passive or active revegetation is specific to each project, but general guidelines are useful for managers to determine what portion of the budget should be used for revegetation (Table 10).

Passive Revegetation

Due to the high costs of riparian forest revegetation, it is generally more effective to allocate the majority of the project budget to removing as much *A. donax* from the watershed as possible (Bell, 1997; Racelis, 2012). Removing *A. donax* from the system has a much higher ecological value than planting artificial riparian forests, which often lack the complexity and stem density of natural forests (Bell, 1997). The removal of *A. donax* can be accomplished for a fraction of the cost of revegetation and opens up areas for natural reestablishment of native species. Watersheds that are mostly free of *A. donax* will begin to return to conditions more suitable for the establishment of native plants, with processes such as sediment accretion and channel constriction slowly reversed over time. Although anthropogenic changes make it unlikely for California watersheds to return to pre-European settlement conditions, removing *A. donax* will eliminate a major barrier in the restoration of healthy vegetation communities (Coffman et al., 2011).

Passive revegetation is appropriate when *A. donax* is removed from the floodplain or within river channels because flooding will facilitate reestablishment of native vegetation as long as there are diverse, healthy riparian forests upstream that can provide seeds or propagules (Bell, 1997). It is also critical to remove any *A. donax* upstream because fragmentation can lead to new *A. donax* growth at a much faster rate than any native vegetation is capable of achieving, especially trees and shrubs. Passive revegetation is also more appropriate for smaller *A. donax* removal areas, especially when they are adjacent to diverse riparian forests. Smaller areas exposed to flooding at least once a year are likely to return to healthy riparian forests within a reasonable timeframe than larger removal areas.

A. donax removal may result in disturbed, open ground that is ideal for exotic herbaceous species to colonize, as observed by Lawson et al. (2005) following mechanical removal in the Santa Margarita River. Larger areas may need to be actively revegetated to provide a barrier to reinvasion of exotic plants. When soils are stable within a recently treated area and there is little risk of erosion, it may not be necessary to plant natives as long as the area is exposed to flooding at least once a year (Coffman et al., 2011). Although it may take several years for native plants to recolonize naturally, the savings in cost and effort, as well as the high ecological value of a naturally colonized plant community make passive revegetation ideal in areas that allow for it.

Active Revegetation

Although passive revegetation is generally very effective, there are situations when active revegetation is necessary. When *A. donax* is removed from higher terraces that are not flooded at least once a year, installing pole cuttings or container grown plants is often necessary as natural recolonization is unlikely to occur (Coffman, 2011). As with passive revegetation, all *A. donax* should be removed from the watershed, or at least close to 100% under control. Removal of *A. donax* from the system is critical to prevent the reestablishment of *A. donax* located upstream of the restoration site, which would likely outcompete recently planted vegetation. *A. donax* retreatments also pose a threat to native vegetation, and the presence of native vegetation make retreatments more complicated and time-consuming (Coffman et al., 2011).

Areas that are targeted for active revegetation should also have adequate soil moisture and nutrients to ensure an appropriate survival rate of native plants. Installing irrigation systems is necessary in revegetated areas that have adequate soil nutrients but low moisture (Coffman et al., 2011). In situations where not all *A. donax* can be removed upstream or adjacent to a proposed restoration site, active revegetation may prevent further invasion into the area. Active revegetation may also be necessary to stabilize soils when there is a risk of soil or streambank erosion in recently cleared areas. When *A. donax* has heavily degraded confirmed habitat for threatened or endangered species, timely revegetation is often required to restore habitat faster than what can be achieved through passive revegetation. Lastly, native plants in degraded habitats may eventually be restricted to common species such as willows; in these cases, active revegetation would be beneficial to create a more diverse native plant community (Bell, 1997; Coffman et al. 2011).

As previously stated, active revegetation is extremely costly and time consuming, taking away from the time allocated to removing *A. donax* from the system. This type of restoration should be reserved for situations when passive restoration is not possible or when timely restoration of crucial habitat for special-status species is required. The dynamic nature of riparian ecosystems also makes recently planted vegetation vulnerable to flooding, making it a high-risk investment (Bell, 1997). This is another reason why active revegetation on the flood plain or within channels is inappropriate. Lawson et al. (2005) reported significant losses or damage to native plantings as part of the Santa Margarita *A. donax* Control Project from a major flood in 1993. Native scrub communities eventually recovered following this disturbance, after a few years, further supporting the idea that passive restoration is often sufficient in areas exposed to flooding. Although active revegetation can be beneficial in many circumstances, the quality of artificially planted forests is usually lower than that of natural forests. The ecological benefit of *A. donax* removal alone usually outweighs the value of artificially planted forests, so *A. donax* eradication should always be a top priority over revegetation.

Conclusion

California riparian habitats are extremely important as they host a diverse array of plant and animal communities and provide numerous ecosystem functions from water purification to nutrient cycling. Urbanization and agriculture have dramatically altered riparian habitats in California through the construction of levees, introduction of exotic plant species, and many other issues related to a rising population. Of all the drivers of riparian habitat degradation, the highly invasive grass *A. donax* has had one of the greatest negative impacts on the physical structure and ecological health of California watersheds since its introduction to Los Angeles in the early 19th century. Since the 1960's, *A. donax* has rapidly spread throughout California from the Mexico border up to Humboldt County; this invasion has heavily degraded riparian habitat by altering hydrologic regimes, increasing the frequency and intensity of fires, displacing native vegetation that serves as habitat for riparian wildlife, and numerous other issues. The ability of *A. donax* to spread via fragmentation and layering has allowed it to easily overtake entire watersheds, creating a major obstacle for riparian restoration projects.

The damage that *A. donax* has caused led to the removal of this invasive as being a top priority for many California riparian restoration projects. However, determining how to prioritize removal sites and choosing the most effective control methods requires an understanding of the invasive ecology of *A. donax* and a thorough analysis of past removal projects. A lack of studies analyzing the efficacy of removal methods had led to many eradication plans being drafted without the proper scientific data. This lack of sufficient scientific information makes it difficult for managers to be confident that their *A. donax* eradication plans will be successful and has resulted in a "trial and error" strategy being adopted for many removal projects. The goal of this study was to provide managers with the necessary resources to create eradication plans with the greatest potential for long-term *A. donax* control. These recommendations are applicable to a wide variety of California watersheds and take into account many of the factors that often complicate the implementation of successful eradication plans.

Through an investigation into the few existing studies analyzing the efficacy of *A. donax* treatments, this study has found that *A. donax* eradication is feasible but requires careful planning and up to 20 years of post-removal monitoring. Although herbicides have been a topic of controversy in recent years, all current removal methods that have shown success require the application of herbicides either during initial treatments or for retreatments. For large *A. donax* infestations, the most cost-effective and universally applicable removal method is 3-6% glyphosate foliar spray. To minimize the use of herbicides, mechanical removal is recommended for large clumps when access allows for the use of heavy machinery. For moderate to small clumps, especially near urban areas and when overspray onto non-target species is an issue, the "bend and spray/hook" and "cut-stem" methods are the most effective. These methods should be used instead of foliar spray whenever possible to minimize the use of herbicides.

Prioritizing removal sites is the most important aspect of *A. donax* eradication. Removing the largest A. donax infestations as far upstream as possible will have the greatest chance of eradicating A. donax for most California watersheds. In some areas that are at high risk of wildfire, removing A. donax under riparian canopies should be a top priority. At the completion of this study, it is clear that A. donax eradication is a long and arduous process that may take up to 20 years or more, but the success of past removal projects show that controlling A donax is feasible with proper planning. It is my hope tht these recommendations can be used for future removal projects in California, especially in central and northern California where the infestations are less widespread, making eradication entirely feasible.

Figures

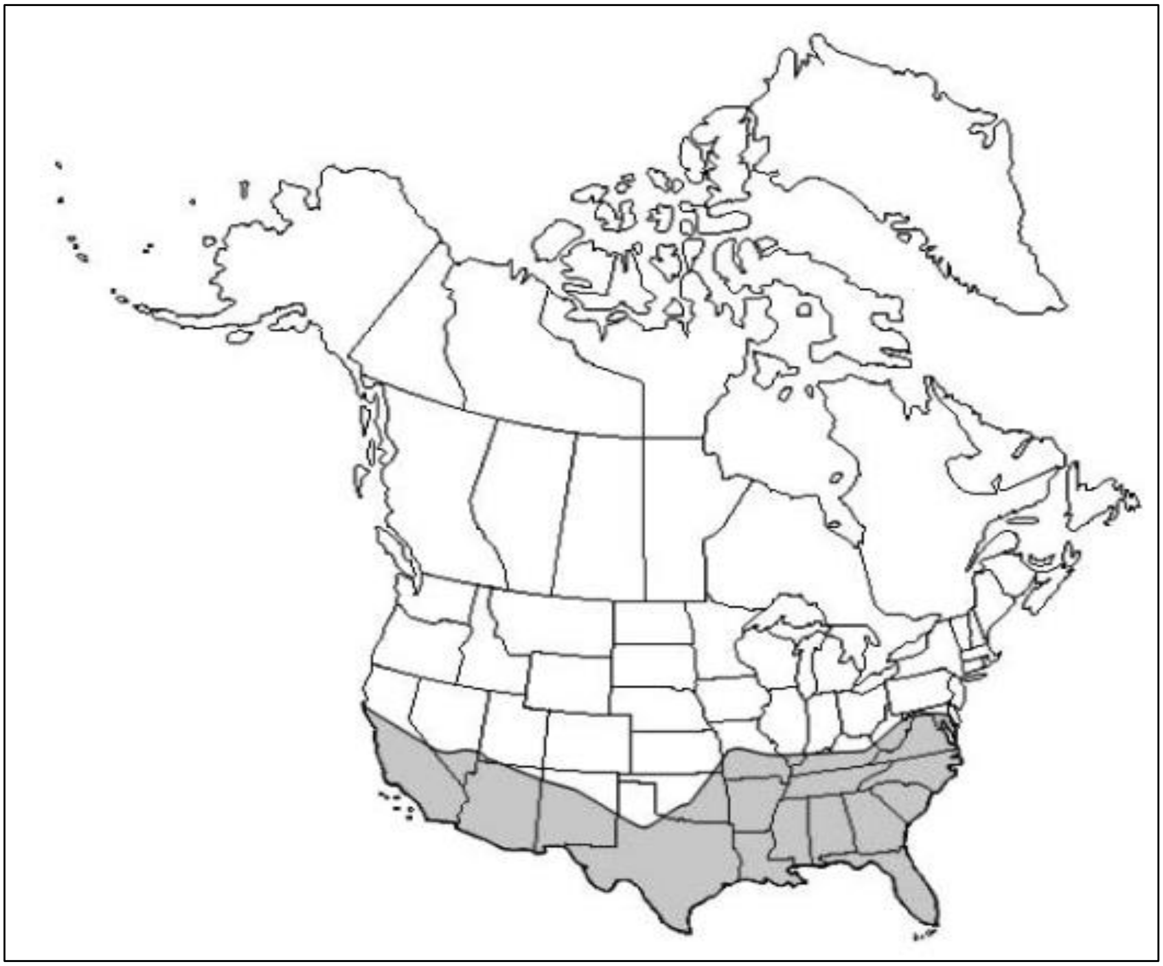


Figure 1: Distribution of *Arundo donax* across the United States, indicated by gray shading (taken from Lambert et al., 2010)

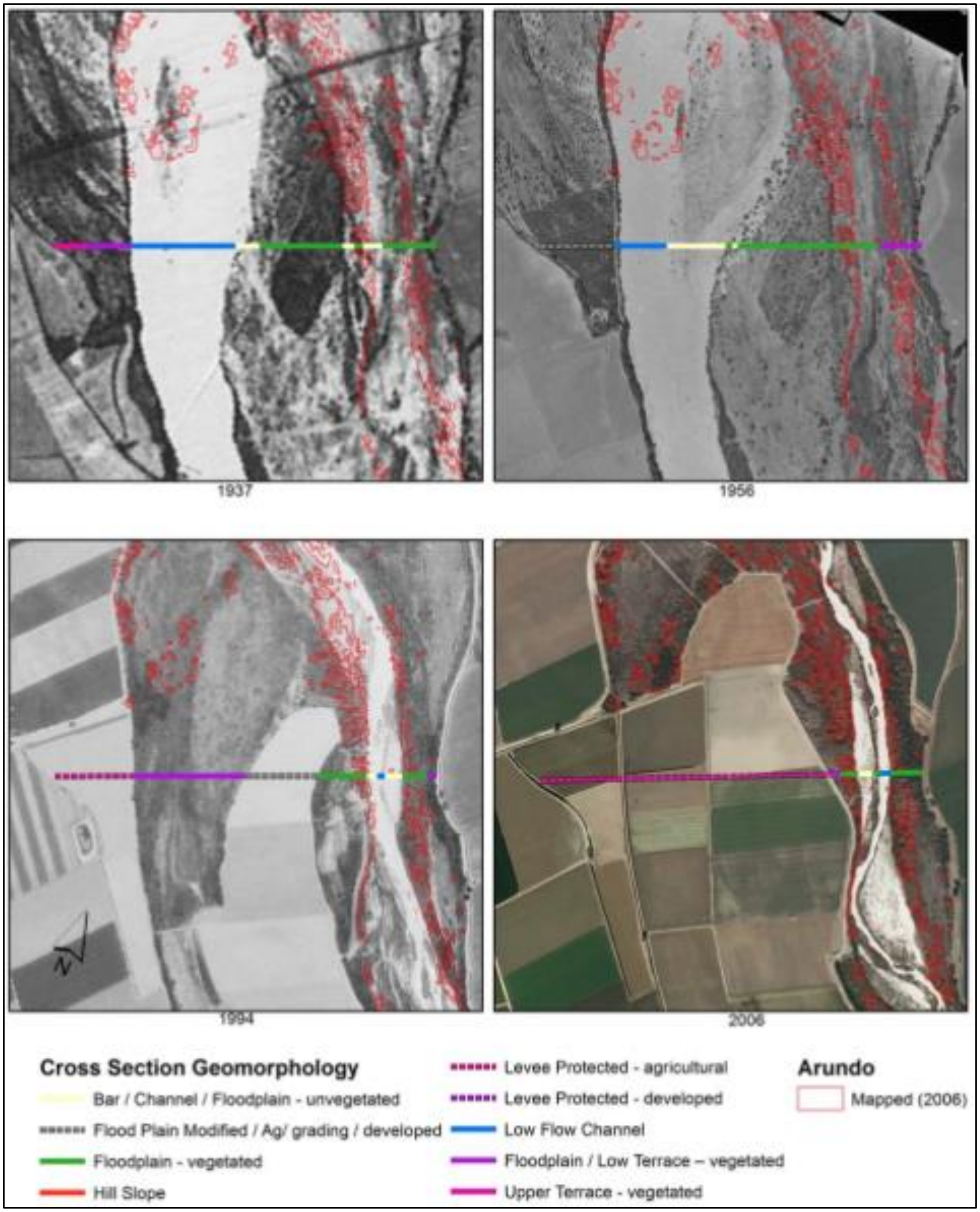


Figure 2. Anthropogenic changes to the Salinas watershed from 1937 to 2006. Notice the blue bar showing the low flow channel dramatically narrowing (taken from Cal-IPC, 2011)

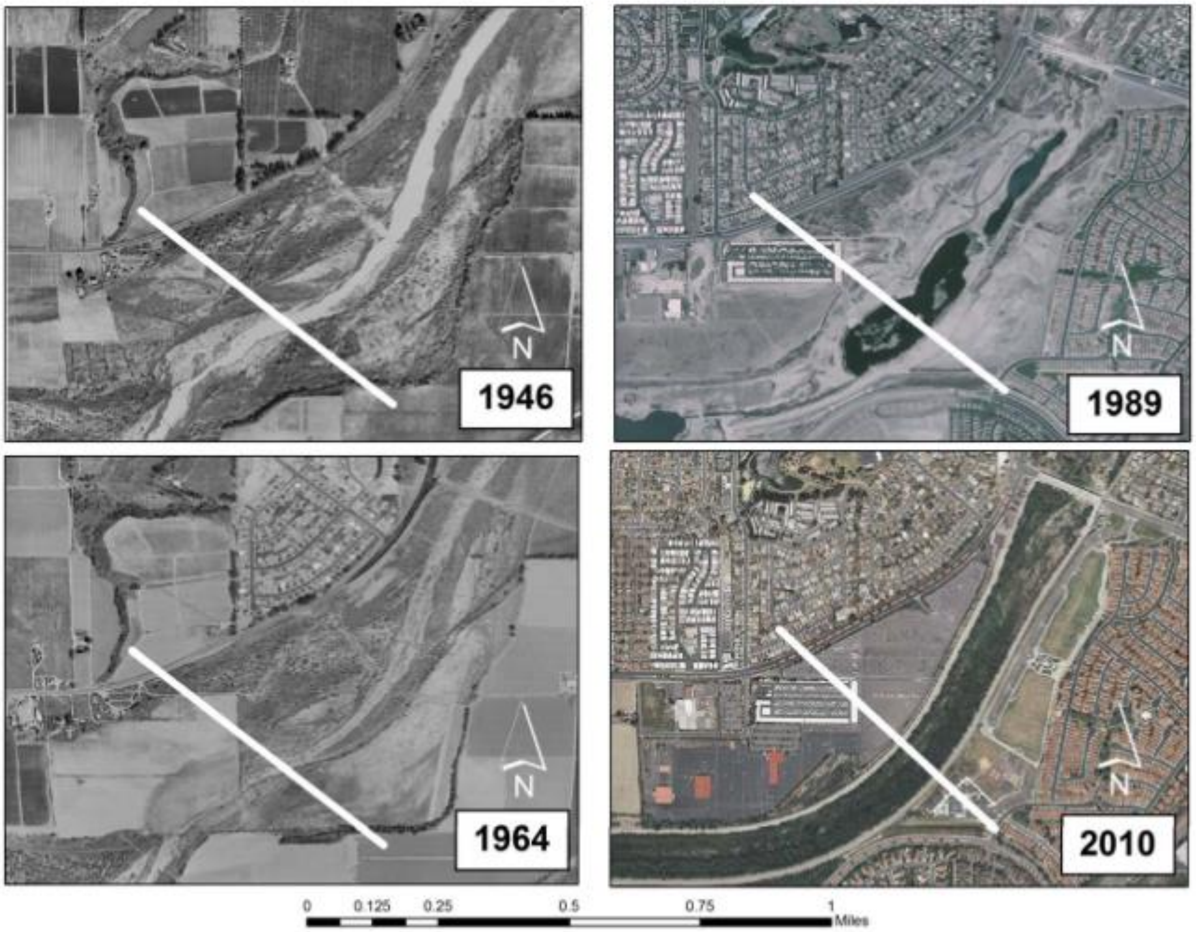


Figure 3. Anthropogenic changes to the San Luis Rey River from 1946 to 2010. Aerial photograph shows channelization of the river and intense urbanization of the surrounding area (taken from Cal-IPC, 2011)

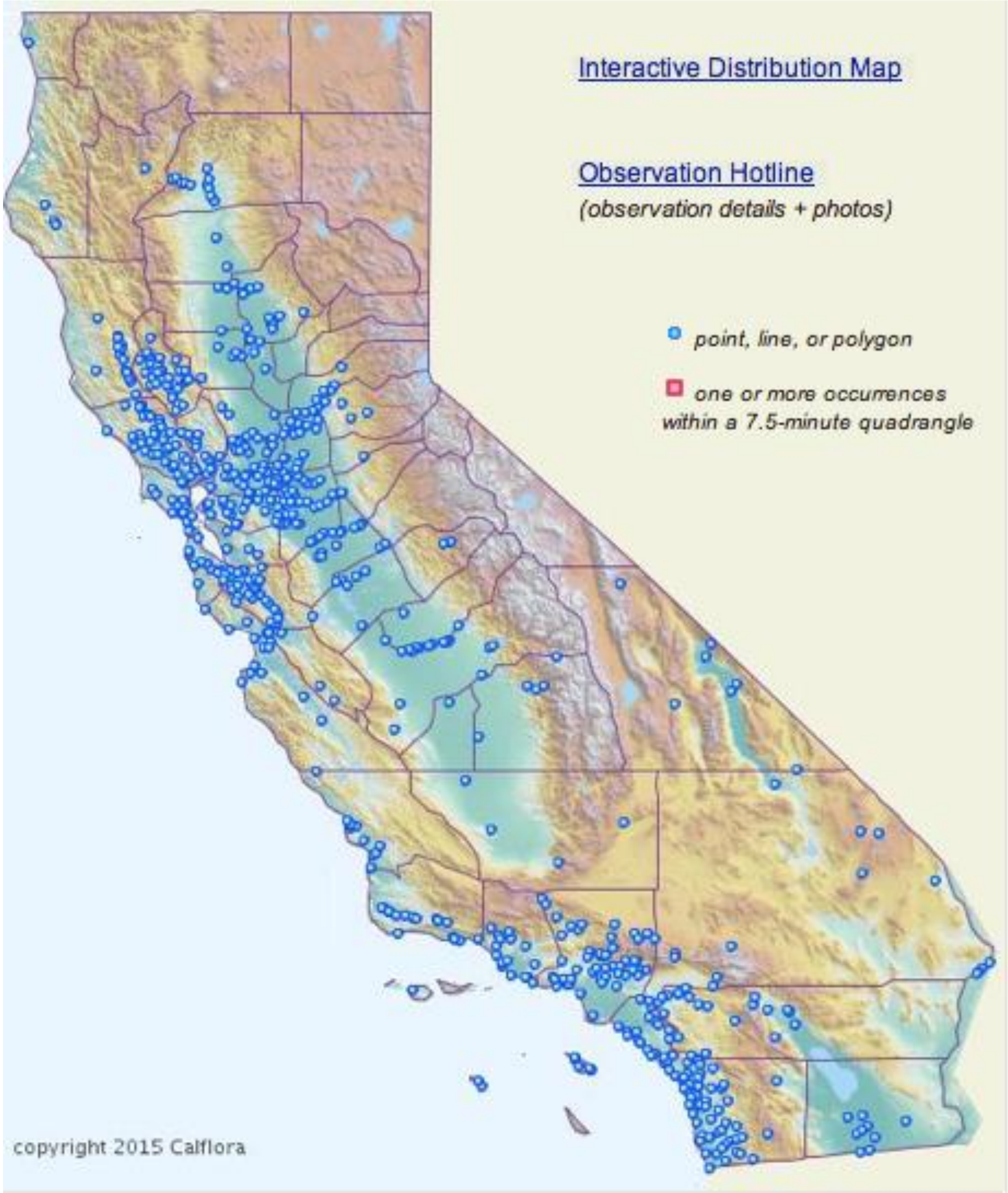


Figure 4. Current Distribution of *A. donax* in California. Blue dots indicate *A. donax* observed by citizen scientists (taken from Calflora 2015)

Figure 5. Mature (top) and immature (bottom) stands of *A. donax* encroaching on rivers (taken from Oakins, 2014 and Bredenburg, 2012)

Figure 6. Dislodged *A. donax* stacked behind the River Road Bridge on the Santa Ana River from a 2004 flood (taken from Cal-IPC, 2011)

Figure 7. Aftermath of a fire that burned an *A. donax* stand in the San Luis Rey River, leaving mostly ash and very little unburned material (taken from Cal-IPC, 2011).

Figure 8a. *A. donax* resprouting shortly after a wildfire before any native vegetation (taken from Cal-IPC, 2011)

Figure 8b. Monopolization of *A. donax* (1-2 meters tall) one year after a wildfire (taken from Cal-IPC, 2011)

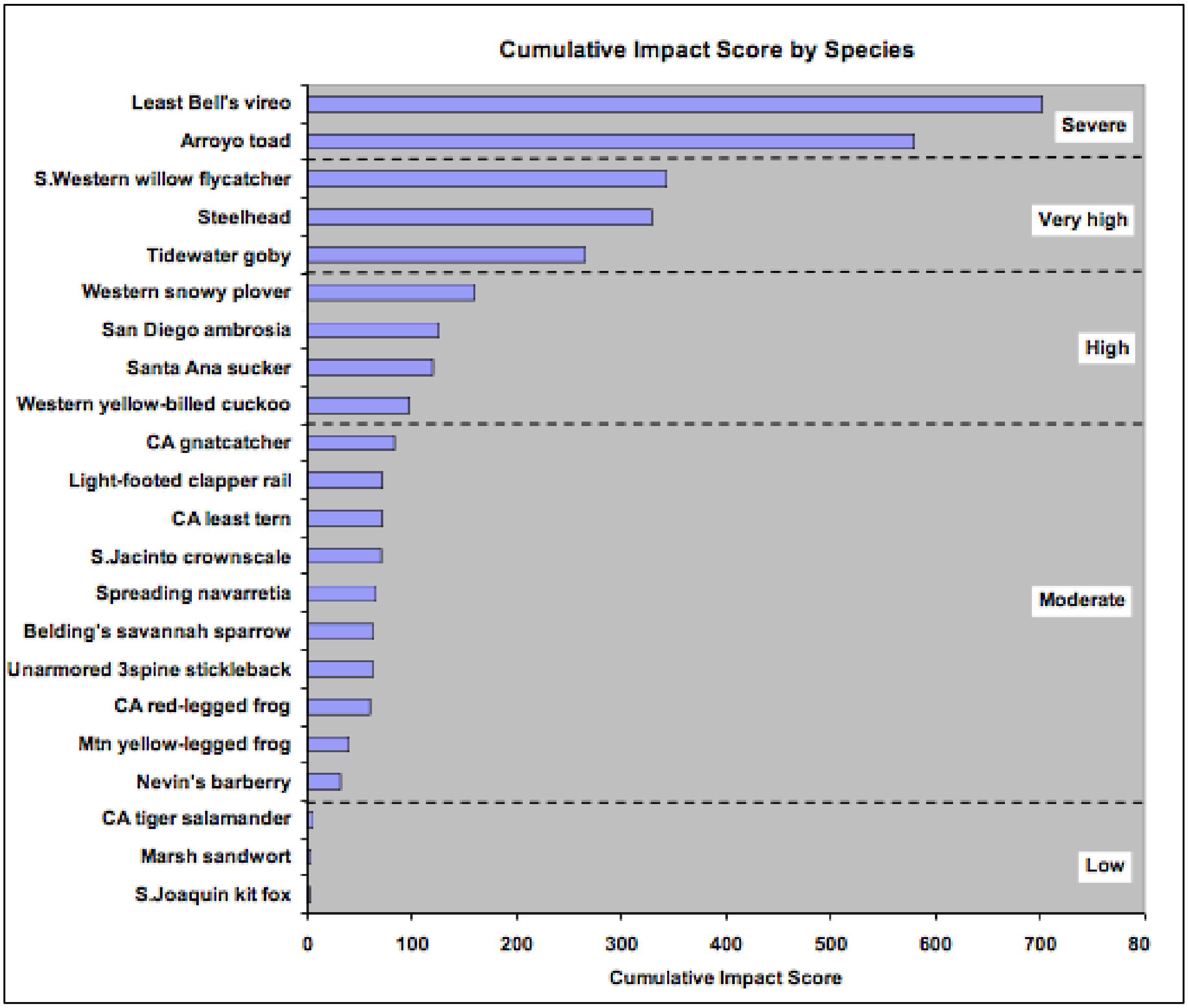


Figure 9. *A. donax* cumulative impact scores by species for various California riparian animals. Impact scores were based on the potential for *A. donax* to reduce the abundance of a particular species. Species that more exclusively rely on riparian habitats have higher impact scores (taken from Cal-IPC, 2011)

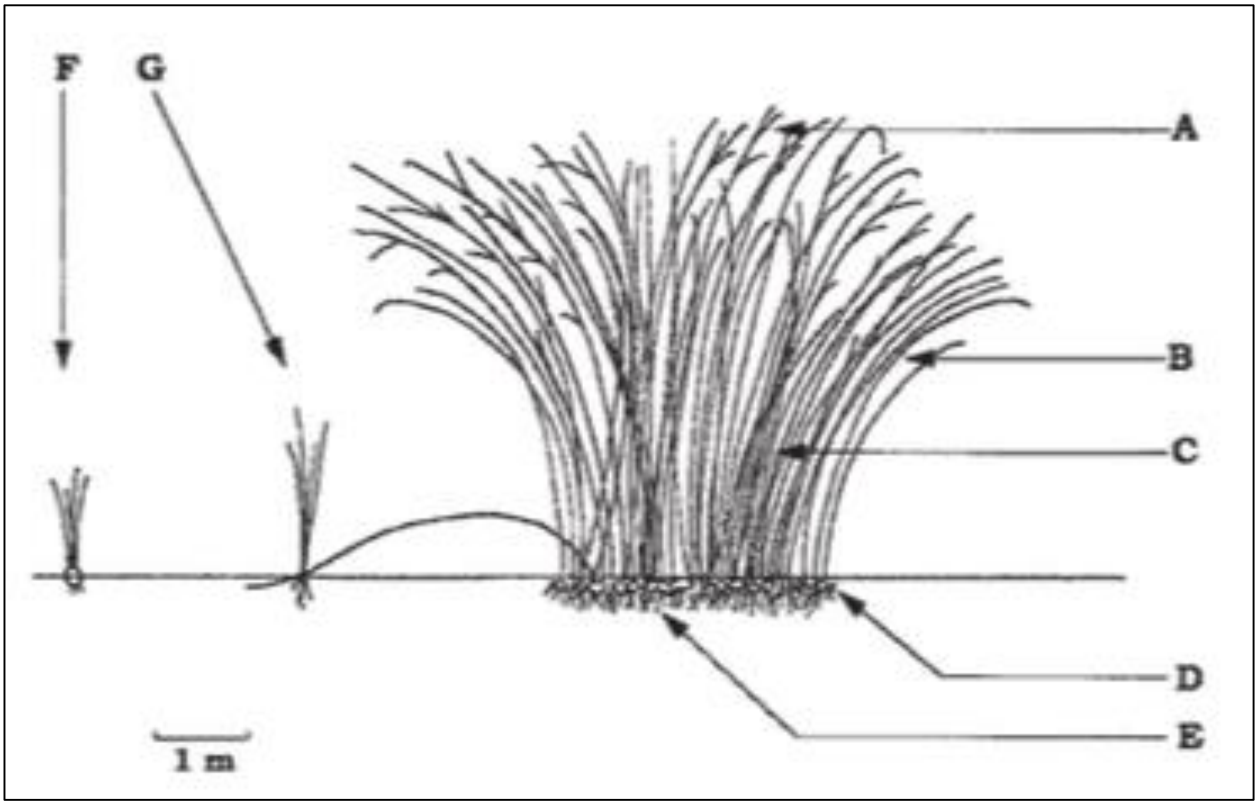


Figure 10. *A. donax* lateral expansion via layering. (G) shows an *A. donax* stem bending to make contact from the ground. Notice the new growth emerging from the bent stem.

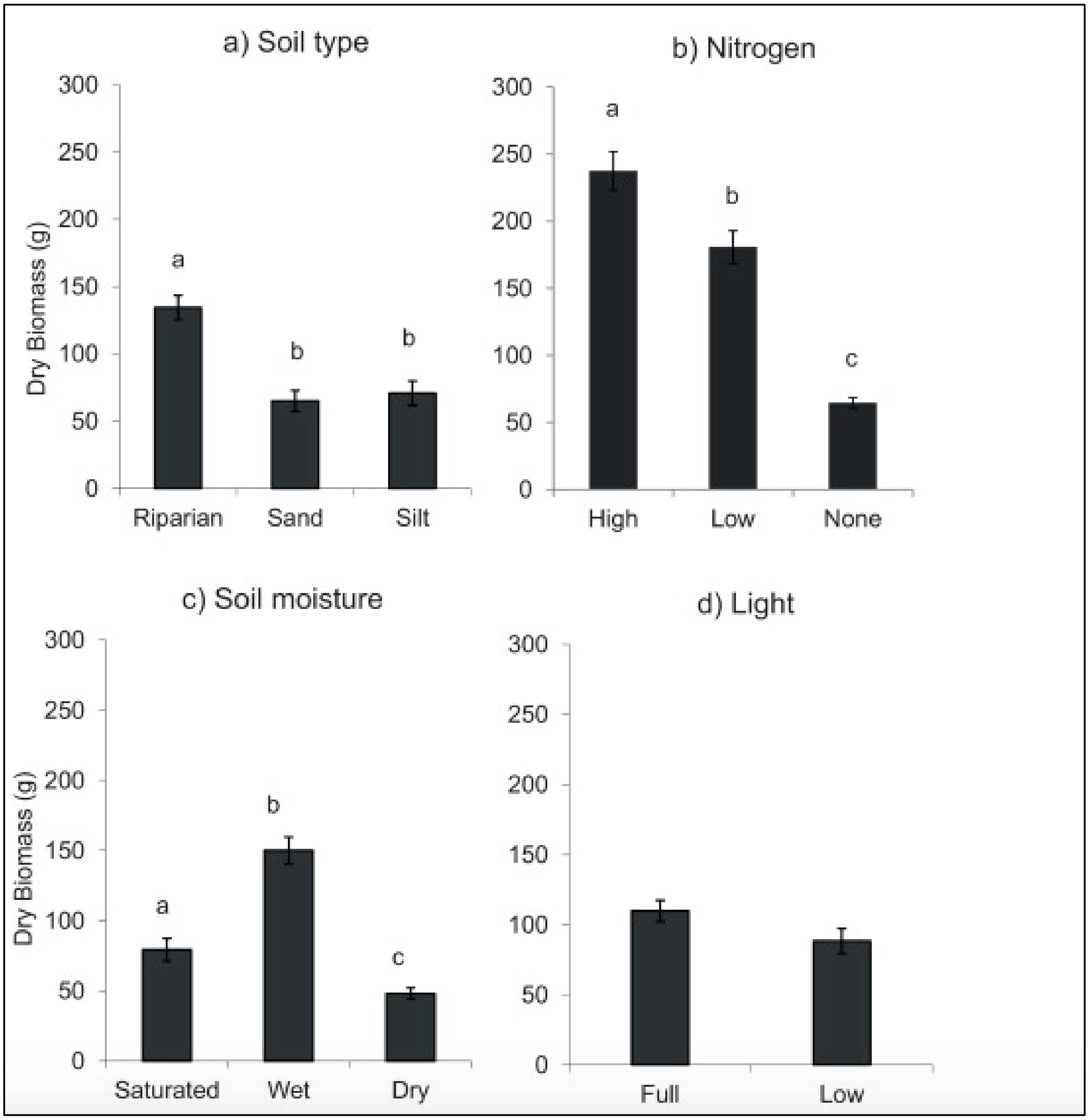


Figure 11: Total dry biomass of *A. donax* exposed to different a) soil types b) nitrogen levels c) soil moisture and d) light. This figure shows that riparian soils high in nitrogen and moisture support more intense growth of *A. donax* (taken from Lambert et al., 2013)

Figure 12. San Timoteo Canyon study area highlighted in green. Orange dots represent the individual study plots (taken from Howe, 2014)

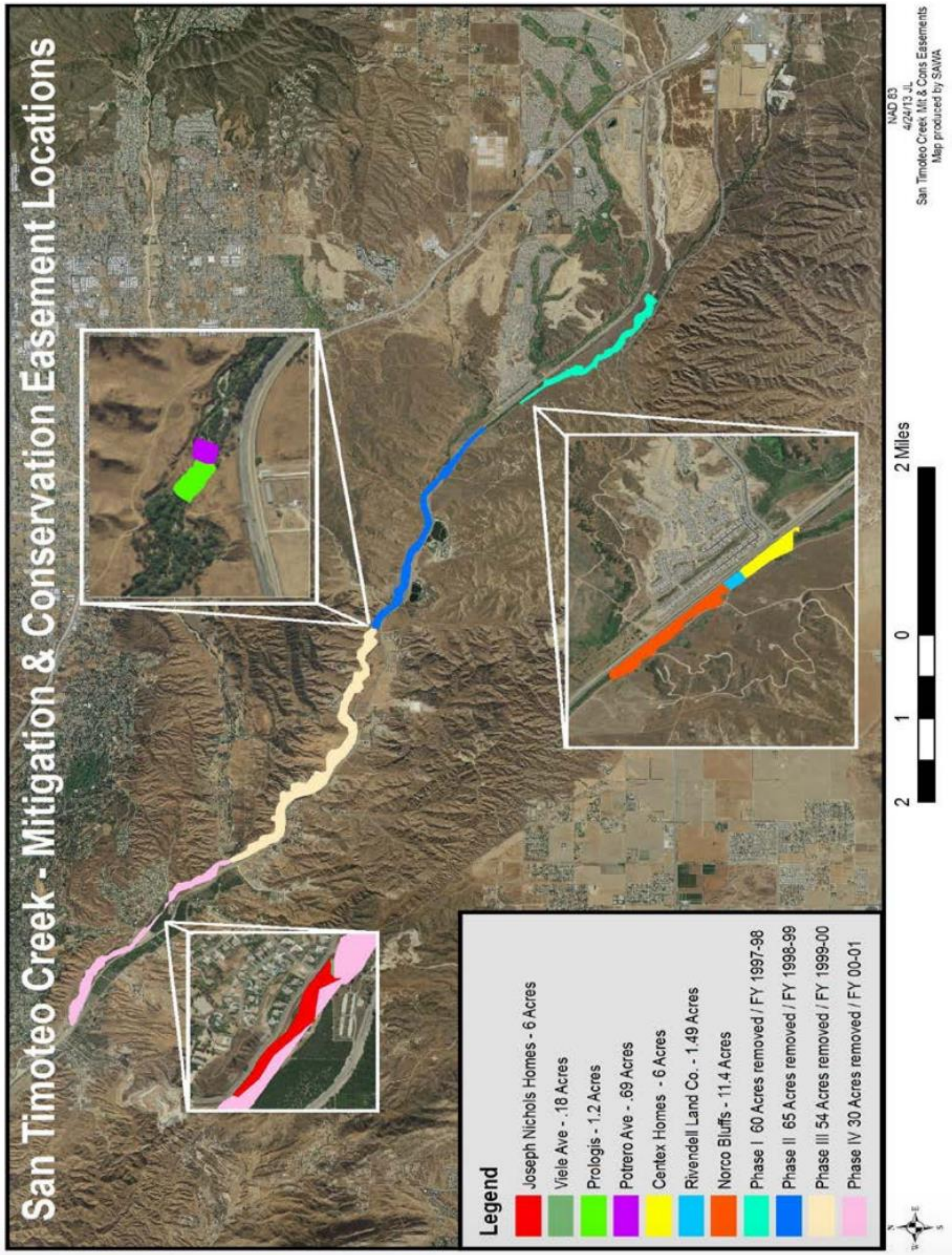
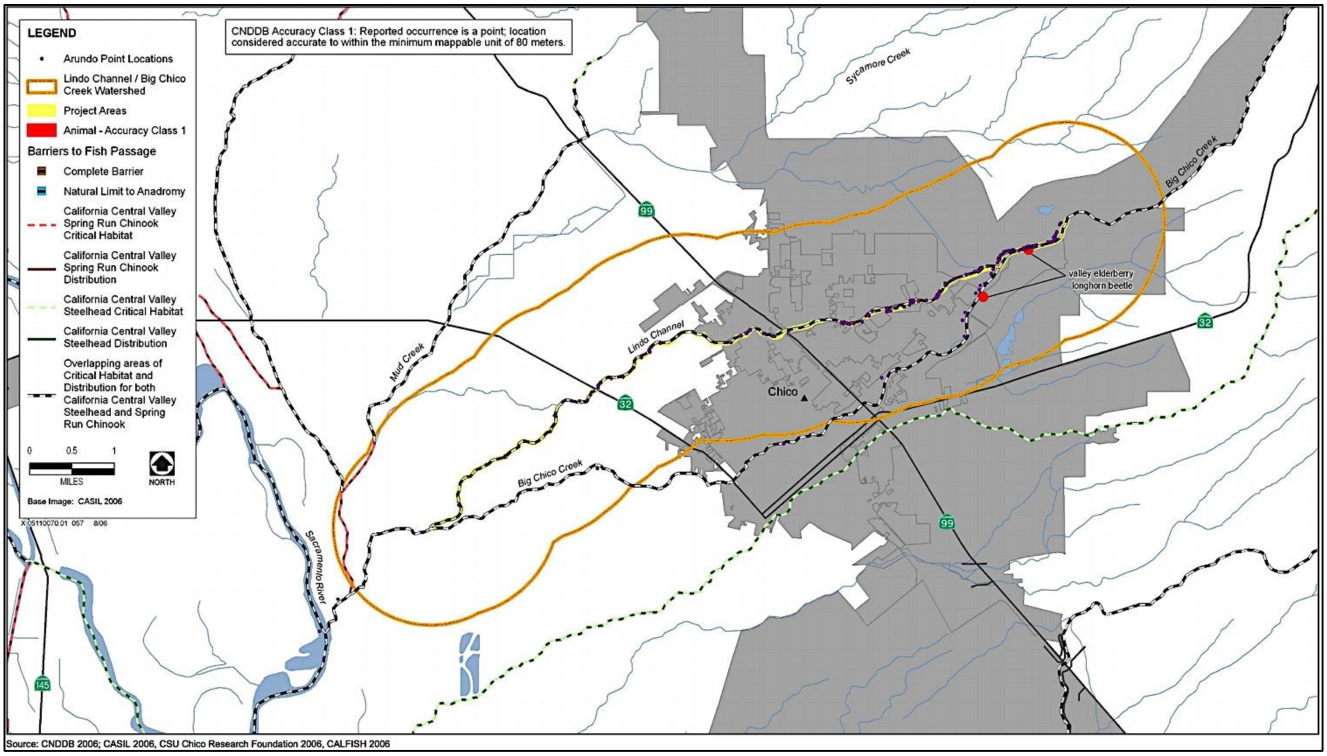


Figure 13. Previous IERCD *A. donax* removals. Current study site is located in the light pink area (taken from Howe, 2014)

Figure 14: Washout study area in San Timoteo Canyon. Notice the eroded hillside in the upper left portion of the photo and new vegetation growing over the disturbed soil (taken from Howe, 2014)

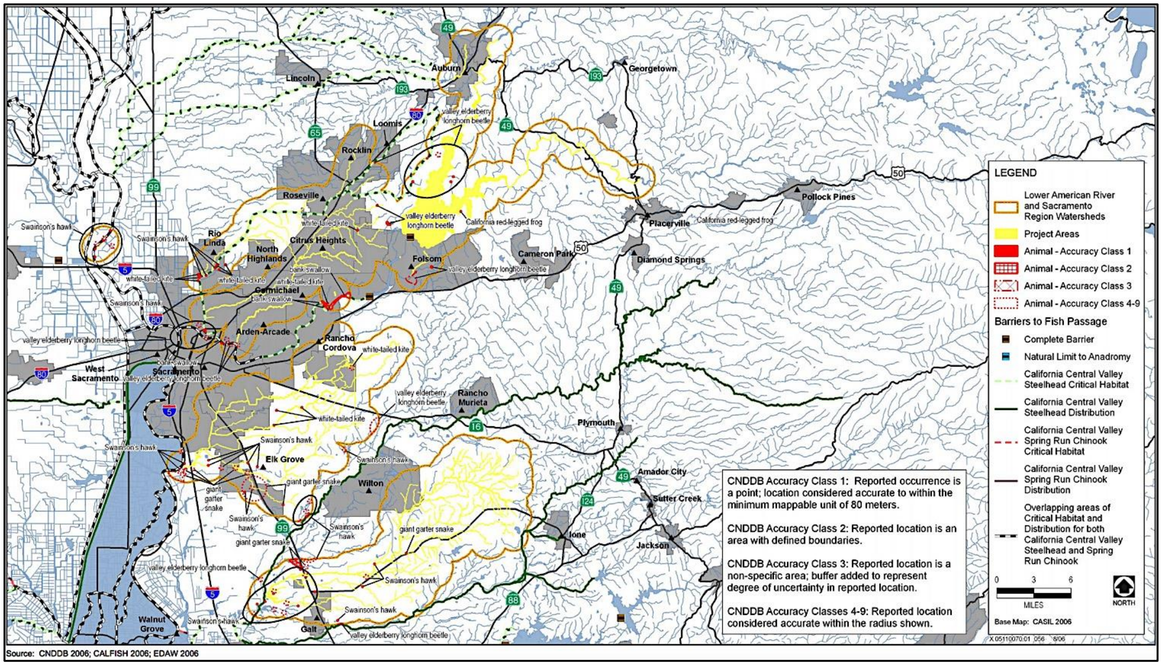
Figure 15: Plot 16 in San Timoteo Canyon. Area treated for *A. donax* 2 years prior with dead *A. donax* still in place. The control method used in this area is not specified (taken from Howe, 2014)

Figure 16: Aerial view of the project site in Camp Pendleton. Removals took place in all *A. donax* infested areas on the section of the Santa Margarita River pictured



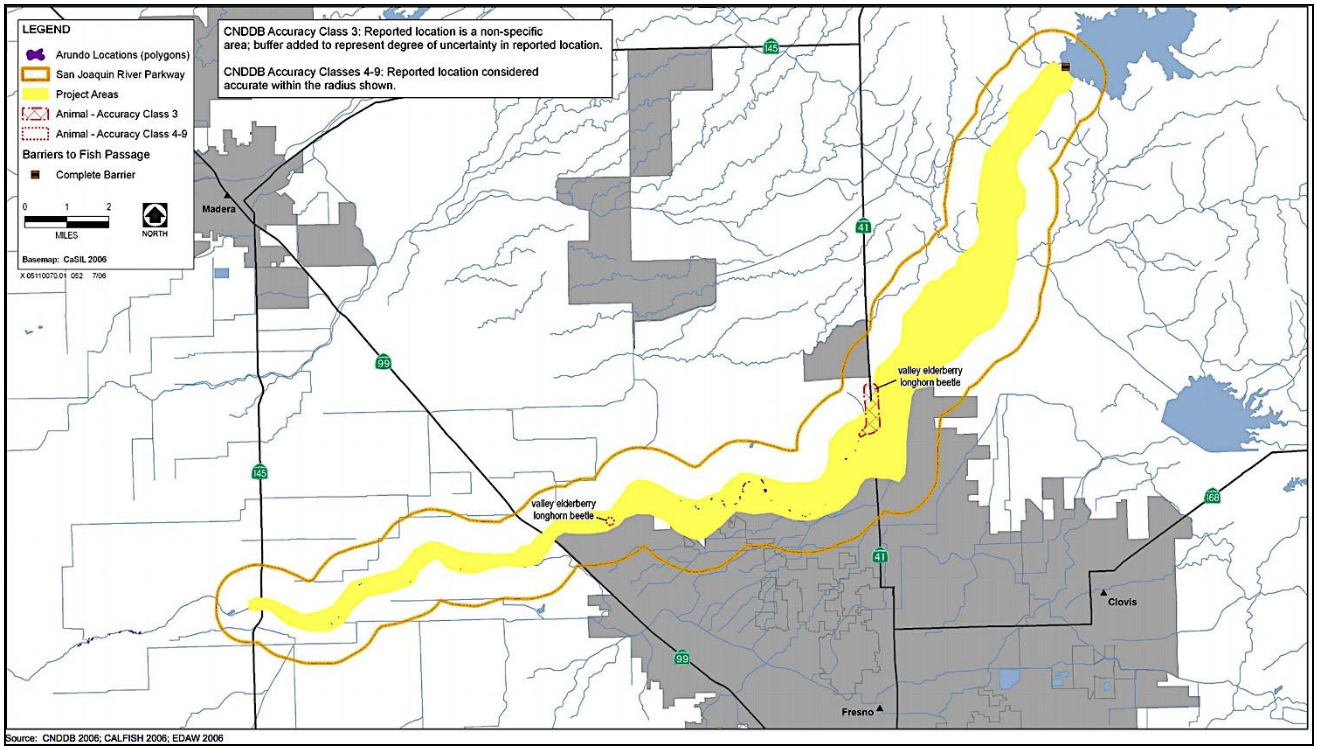
Source: CNDDB 2006; CASIL 2006, CSU Chico Research Foundation 2006, CALFISH 2006

Figure 17a: SEC Lindo Channel/Big Chico Creek partner location (taken from SEC, 2010)



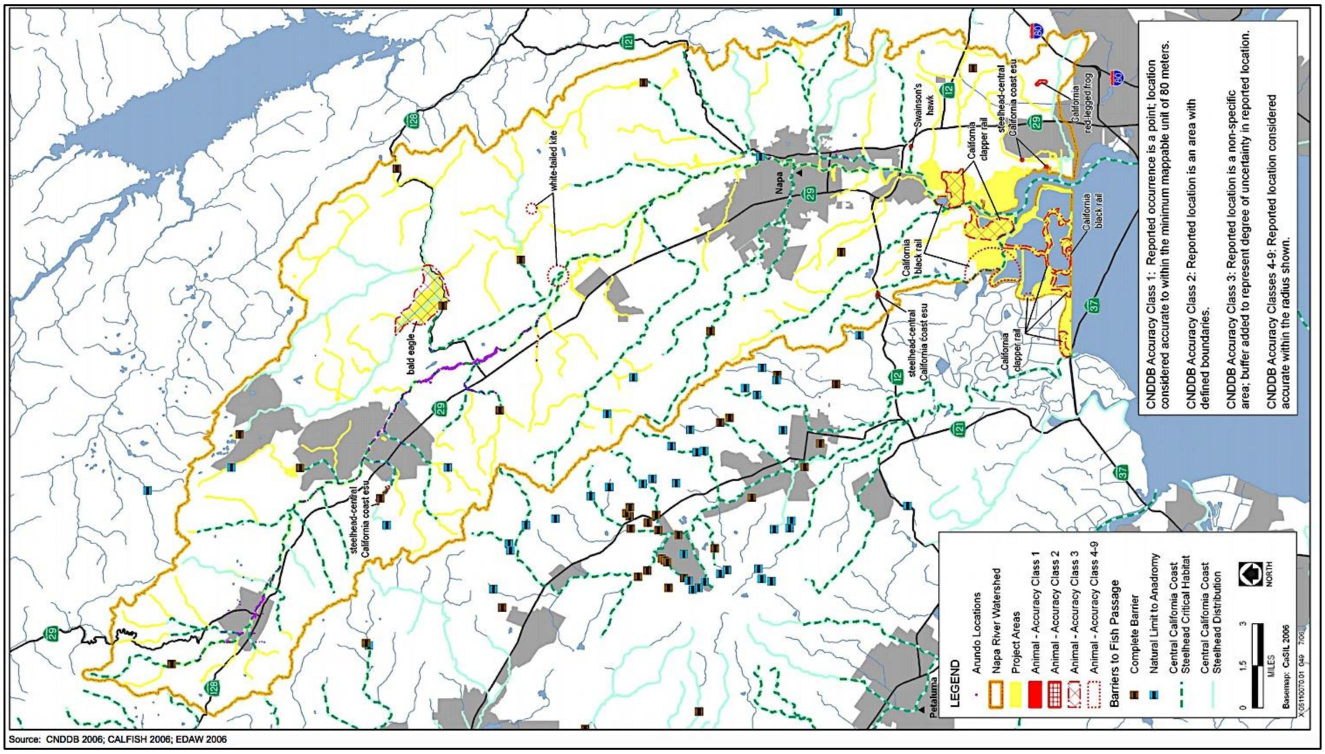
Source: CNDDB 2006; CALFISH 2006; EDAW 2006

Figure 17b: SEC Lower American River and Sacramento region watersheds partner locations (taken from SEC, 2010)



Source: CNDDB 2006; CALFISH 2006; EDAW 2006

Figure 17c: SEC San Joaquin River Parkway partner location (taken from SEC, 2010)



Source: CNDDB 2006; CALFISH 2006; EDAW 2006

Figure 17d: SEC Napa River watershed partner location (taken from SEC, 2010)

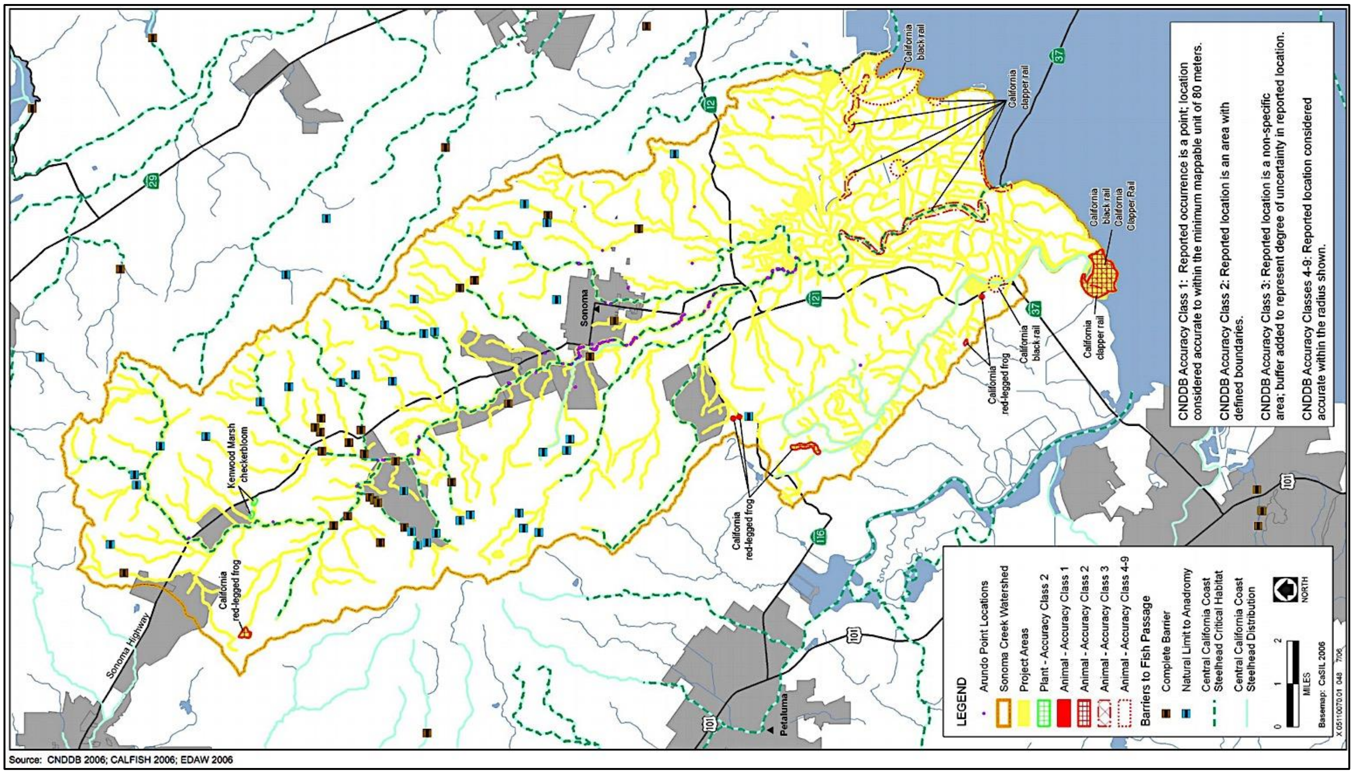


Figure 17e: SEC Sonoma Creek watershed partner location (taken from SEC, 2010)

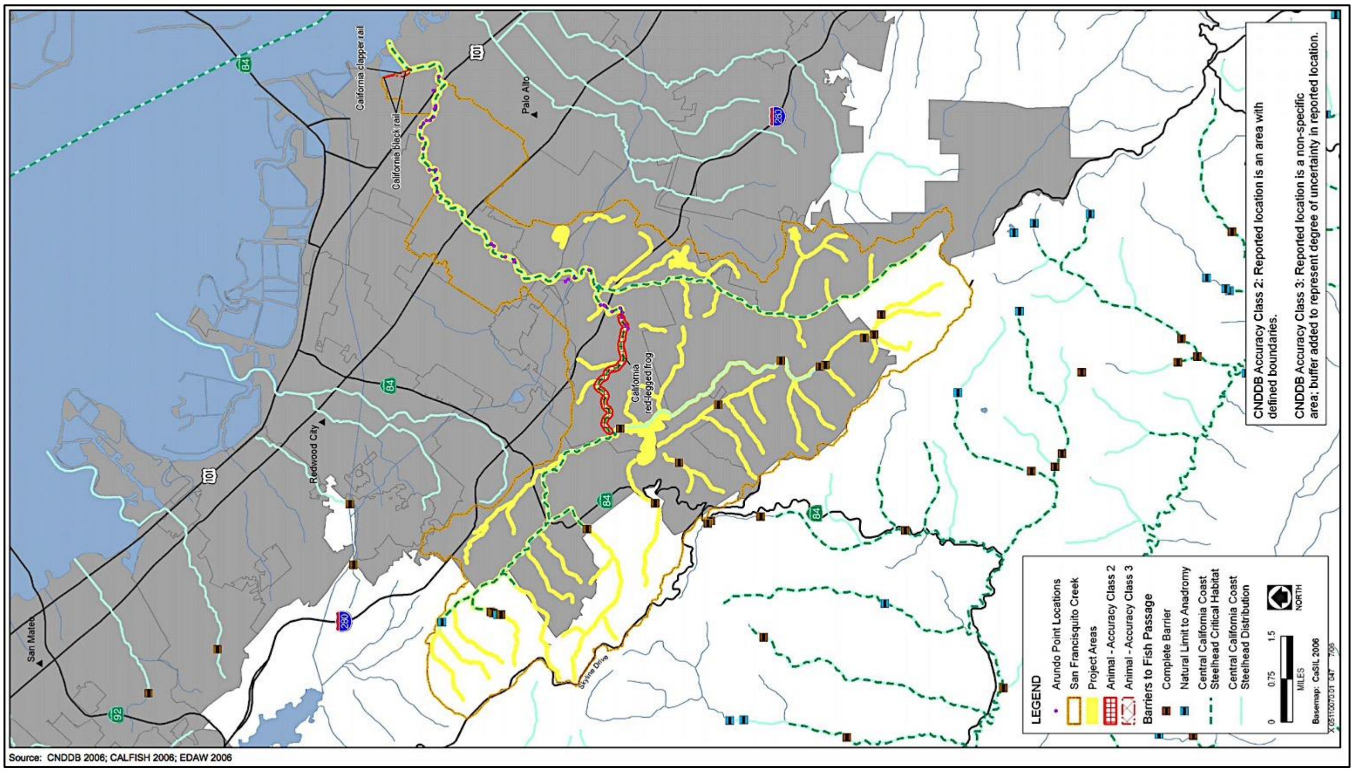


Figure 17f: SEC San Francisquito Creek watershed partner location (Taken from SEC, 2010)

Arundo donax Control Method Decision Tree

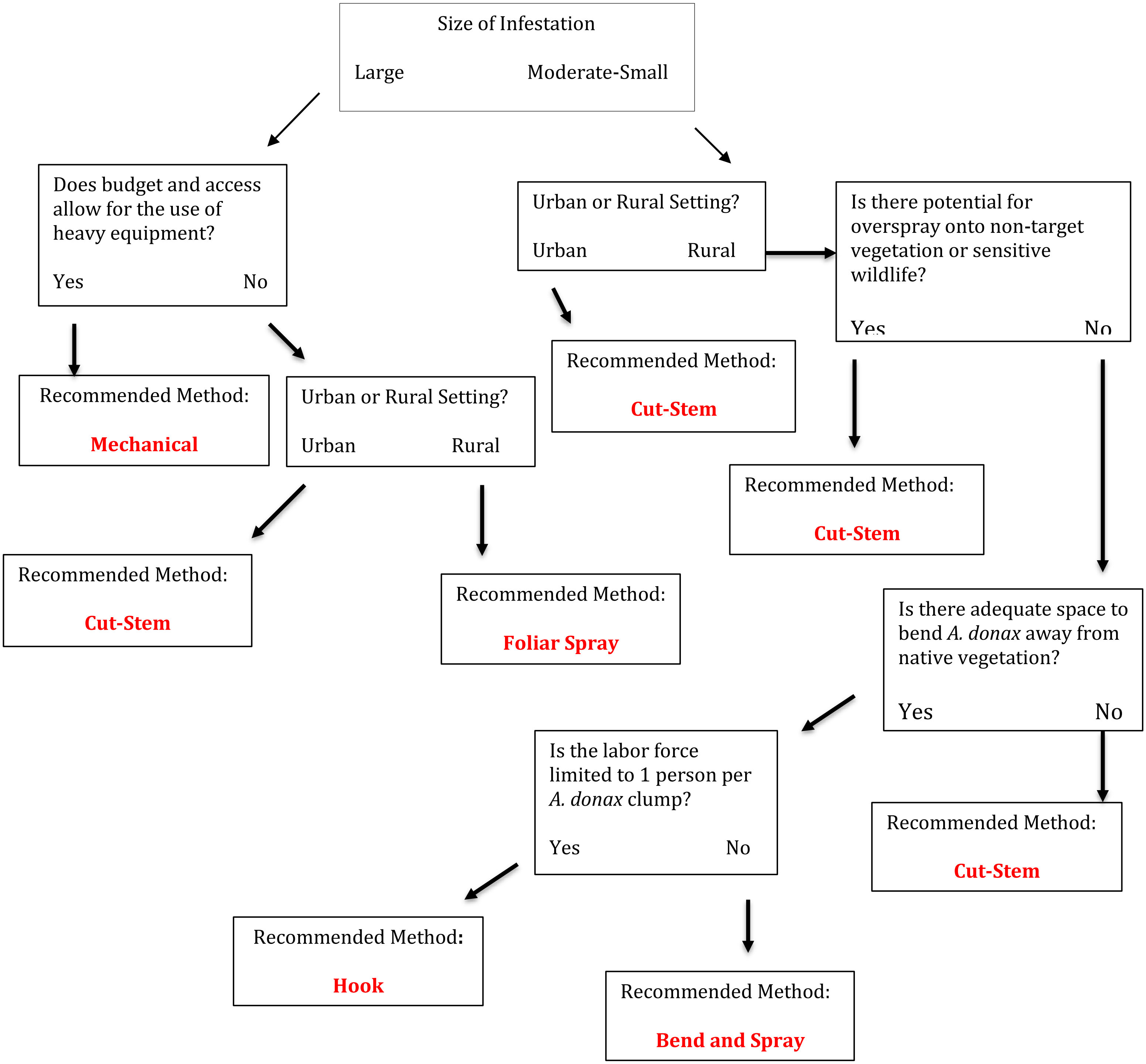
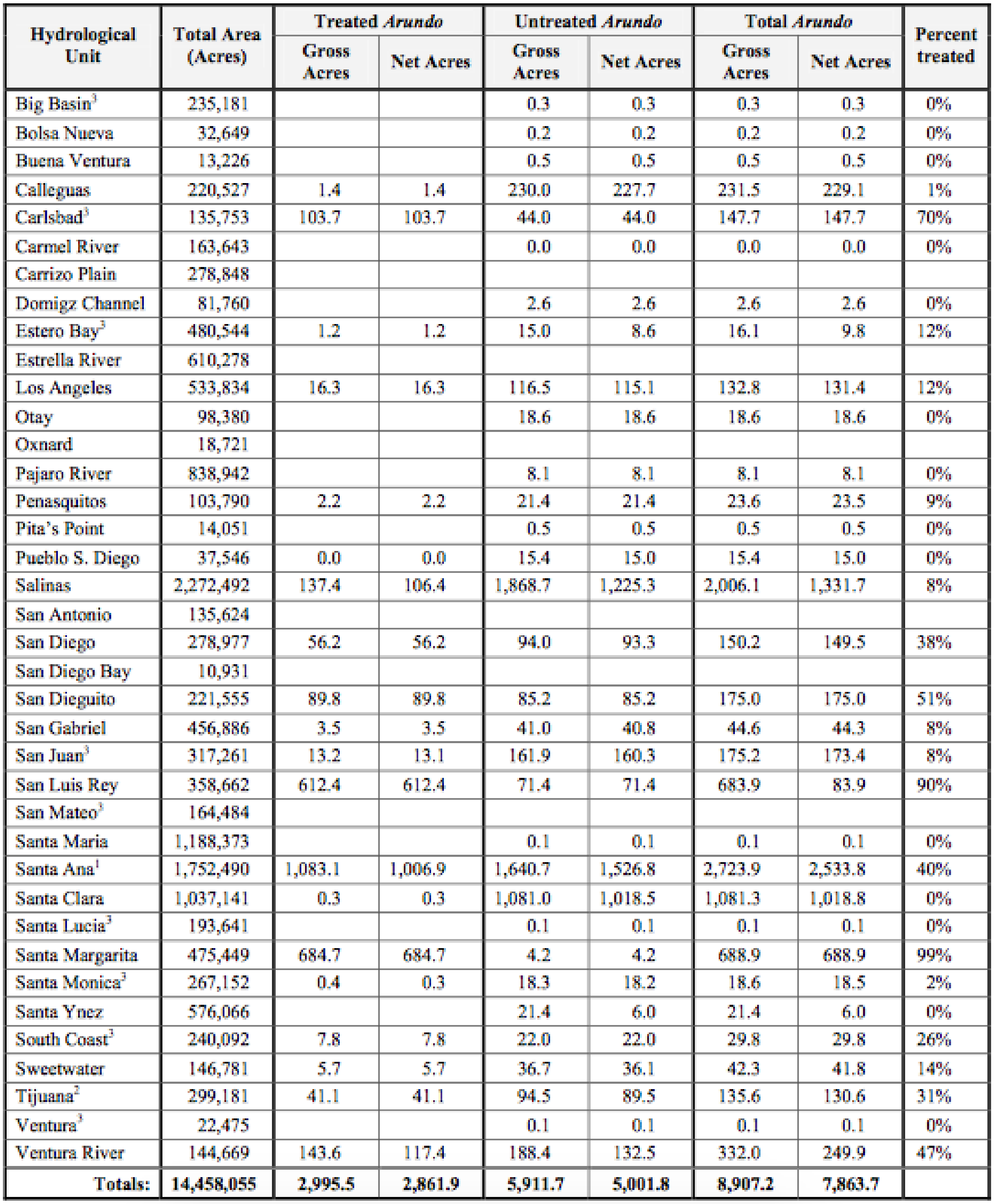


Figure 18: *A. donax* Control Method Decision Tree

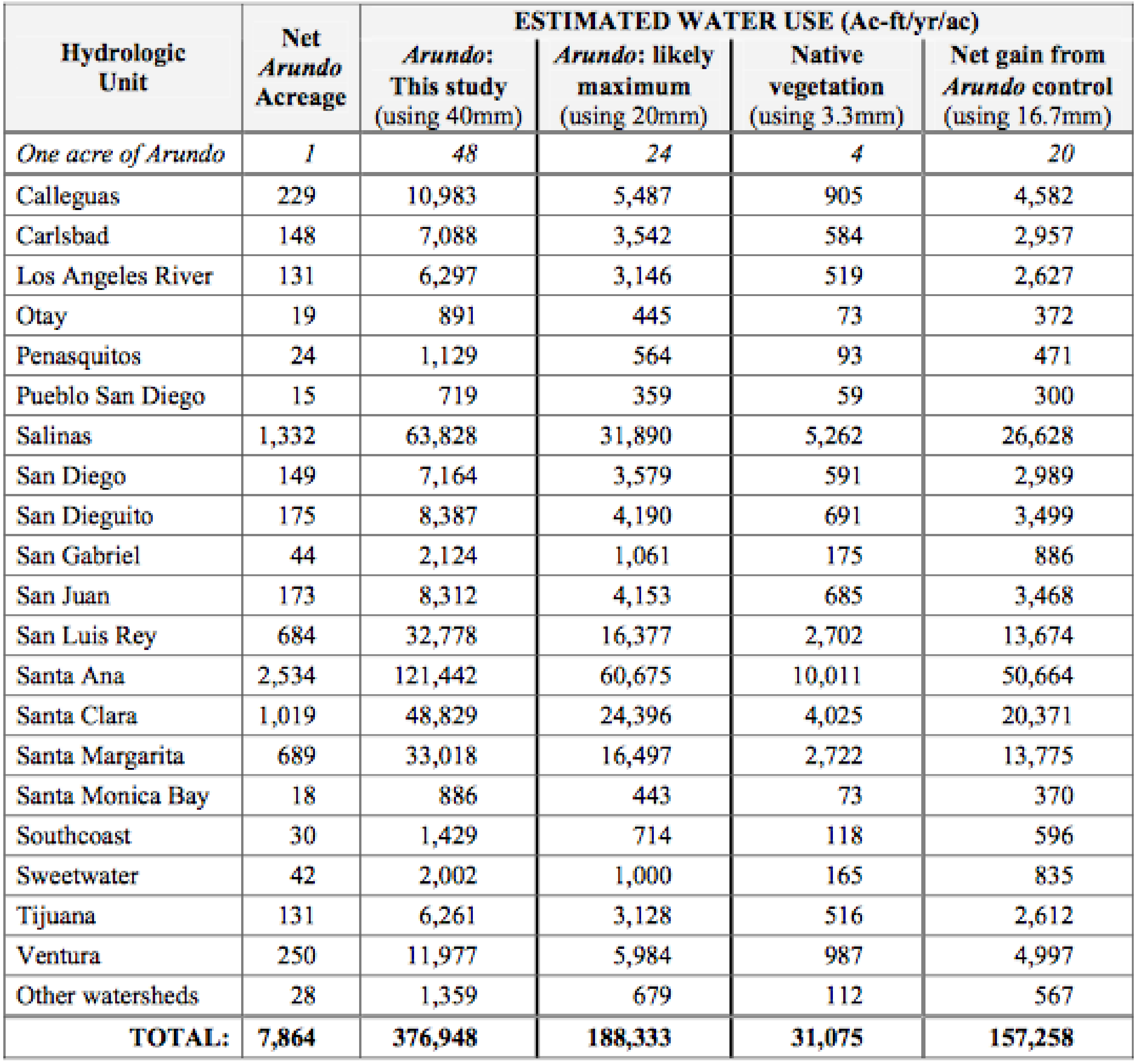
Tables

Table 1. *A. donax* acreage in central and southern California by hydrologic unit and percent of the treatment area (taken from Cal-IPC, 2011)



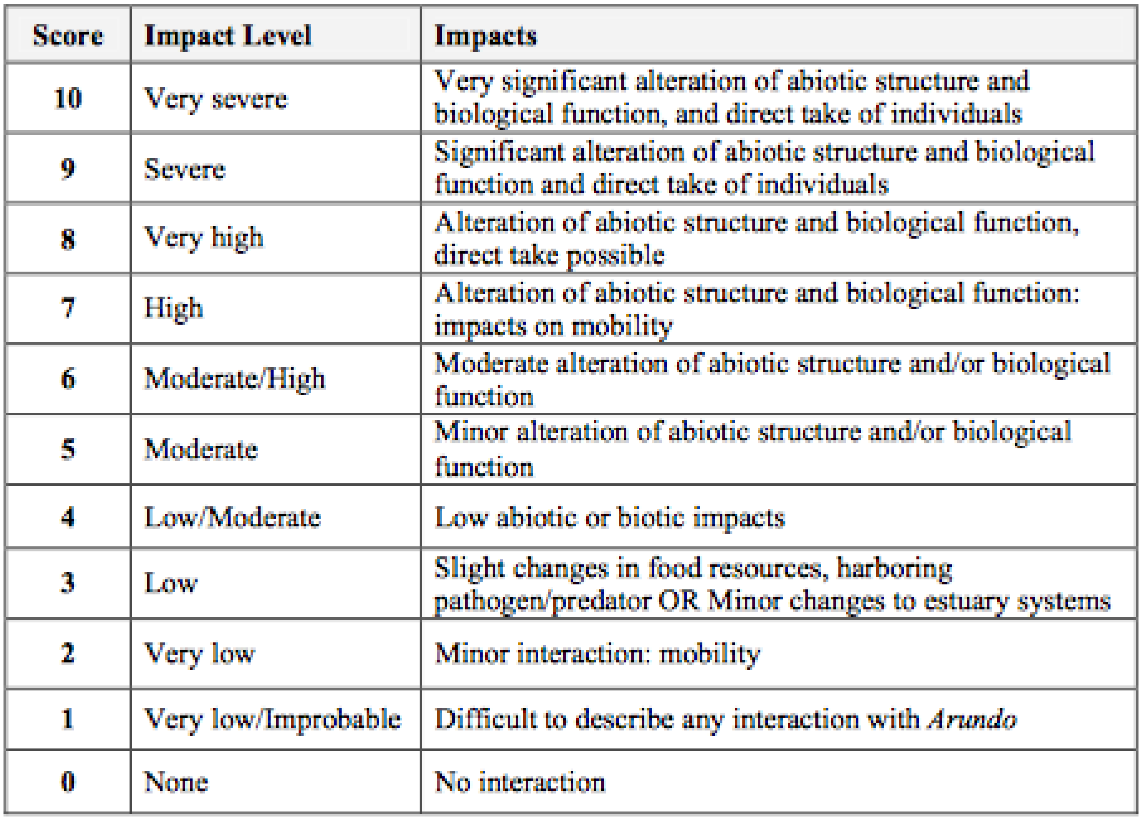
Hydrological Unit	Total Area (Acres)	Treated *Arundo*		Untreated *Arundo*		Total *Arundo*		Percent treated
		Gross Acres	Net Acres	Gross Acres	Net Acres	Gross Acres	Net Acres	
Big Basin[3]	235,181			0.3	0.3	0.3	0.3	0%
Bolsa Nueva	32,649			0.2	0.2	0.2	0.2	0%
Buena Ventura	13,226			0.5	0.5	0.5	0.5	0%
Calleguas	220,527	1.4	1.4	230.0	227.7	231.5	229.1	1%
Carlsbad[3]	135,753	103.7	103.7	44.0	44.0	147.7	147.7	70%
Carmel River	163,643			0.0	0.0	0.0	0.0	0%
Carrizo Plain	278,848							
Domigz Channel	81,760			2.6	2.6	2.6	2.6	0%
Estero Bay[3]	480,544	1.2	1.2	15.0	8.6	16.1	9.8	12%
Estrella River	610,278							
Los Angeles	533,834	16.3	16.3	116.5	115.1	132.8	131.4	12%
Otay	98,380			18.6	18.6	18.6	18.6	0%
Oxnard	18,721							
Pajaro River	838,942			8.1	8.1	8.1	8.1	0%
Penasquitos	103,790	2.2	2.2	21.4	21.4	23.6	23.5	9%
Pita's Point	14,051			0.5	0.5	0.5	0.5	0%
Pueblo S. Diego	37,546	0.0	0.0	15.4	15.0	15.4	15.0	0%
Salinas	2,272,492	137.4	106.4	1,868.7	1,225.3	2,006.1	1,331.7	8%
San Antonio	135,624							
San Diego	278,977	56.2	56.2	94.0	93.3	150.2	149.5	38%
San Diego Bay	10,931							
San Dieguito	221,555	89.8	89.8	85.2	85.2	175.0	175.0	51%
San Gabriel	456,886	3.5	3.5	41.0	40.8	44.6	44.3	8%
San Juan[3]	317,261	13.2	13.1	161.9	160.3	175.2	173.4	8%
San Luis Rey	358,662	612.4	612.4	71.4	71.4	683.9	83.9	90%
San Mateo[3]	164,484							
Santa Maria	1,188,373			0.1	0.1	0.1	0.1	0%
Santa Ana[1]	1,752,490	1,083.1	1,006.9	1,640.7	1,526.8	2,723.9	2,533.8	40%
Santa Clara	1,037,141	0.3	0.3	1,081.0	1,018.5	1,081.3	1,018.8	0%
Santa Lucia[3]	193,641			0.1	0.1	0.1	0.1	0%
Santa Margarita	475,449	684.7	684.7	4.2	4.2	688.9	688.9	99%
Santa Monica[3]	267,152	0.4	0.3	18.3	18.2	18.6	18.5	2%
Santa Ynez	576,066			21.4	6.0	21.4	6.0	0%
South Coast[3]	240,092	7.8	7.8	22.0	22.0	29.8	29.8	26%
Sweetwater	146,781	5.7	5.7	36.7	36.1	42.3	41.8	14%
Tijuana[2]	299,181	41.1	41.1	94.5	89.5	135.6	130.6	31%
Ventura[3]	22,475			0.1	0.1	0.1	0.1	0%
Ventura River	144,669	143.6	117.4	188.4	132.5	332.0	249.9	47%
Totals:	**14,458,055**	**2,995.5**	**2,861.9**	**5,911.7**	**5,001.8**	**8,907.2**	**7,863.7**	

Table 2. Estimated water use of *A. donax,* native vegetation, and net water savings from *A. donax* control (taken from Cal-IPC, 2011)



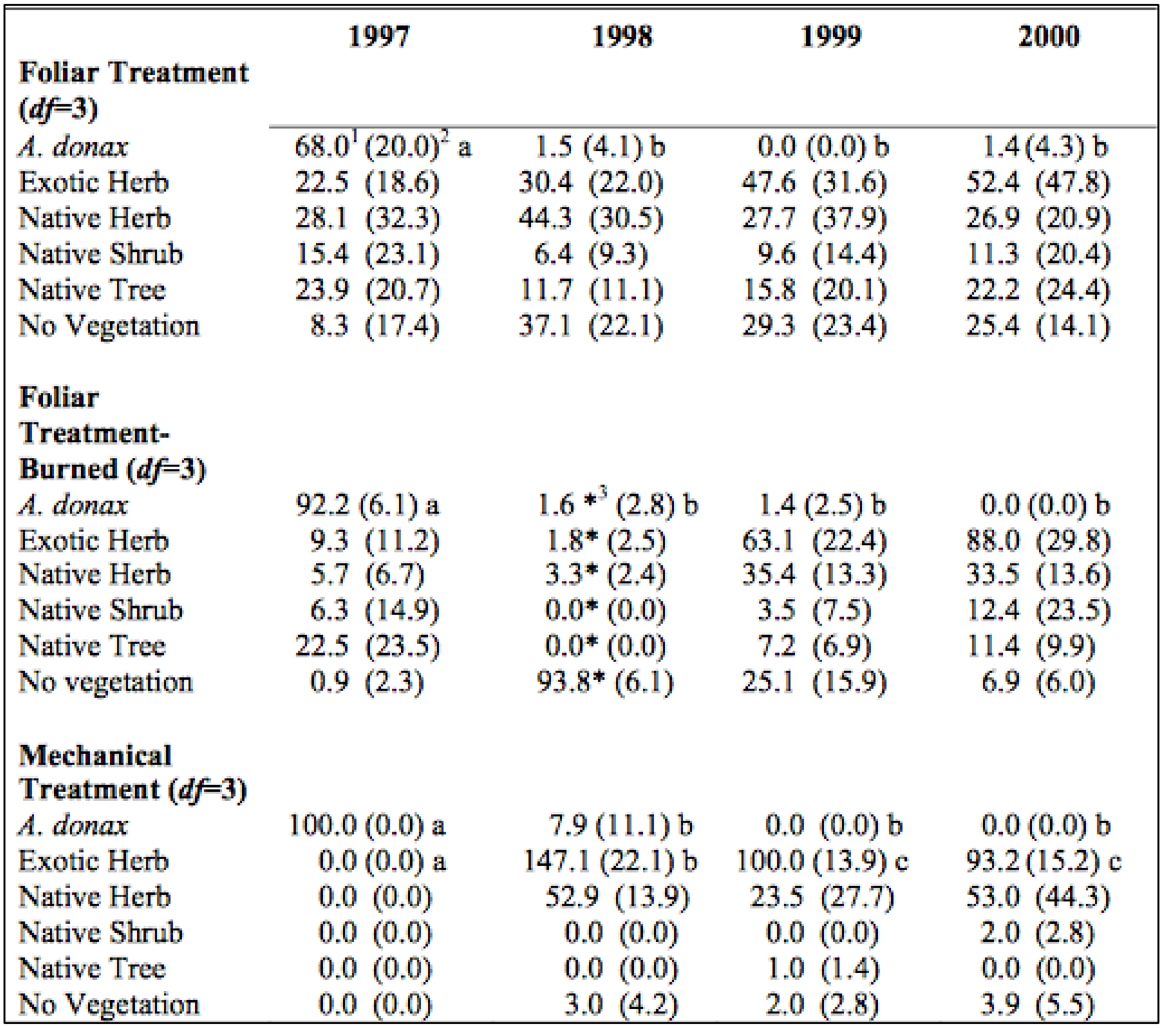
Hydrologic Unit	**Net *Arundo* Acreage**	**ESTIMATED WATER USE (Ac-ft/yr/ac)**			
		***Arundo*: This study** (using 40mm)	***Arundo*: likely maximum** (using 20mm)	**Native vegetation** (using 3.3mm)	**Net gain from *Arundo* control** (using 16.7mm)
One acre of Arundo	*1*	*48*	*24*	*4*	*20*
Calleguas	229	10,983	5,487	905	4,582
Carlsbad	148	7,088	3,542	584	2,957
Los Angeles River	131	6,297	3,146	519	2,627
Otay	19	891	445	73	372
Penasquitos	24	1,129	564	93	471
Pueblo San Diego	15	719	359	59	300
Salinas	1,332	63,828	31,890	5,262	26,628
San Diego	149	7,164	3,579	591	2,989
San Dieguito	175	8,387	4,190	691	3,499
San Gabriel	44	2,124	1,061	175	886
San Juan	173	8,312	4,153	685	3,468
San Luis Rey	684	32,778	16,377	2,702	13,674
Santa Ana	2,534	121,442	60,675	10,011	50,664
Santa Clara	1,019	48,829	24,396	4,025	20,371
Santa Margarita	689	33,018	16,497	2,722	13,775
Santa Monica Bay	18	886	443	73	370
Southcoast	30	1,429	714	118	596
Sweetwater	42	2,002	1,000	165	835
Tijuana	131	6,261	3,128	516	2,612
Ventura	250	11,977	5,984	987	4,997
Other watersheds	28	1,359	679	112	567
TOTAL:	**7,864**	**376,948**	**188,333**	**31,075**	**157,258**

Table 3. *A. donax* impact score categories for sensitive species, calculated from observed reductions in riparian wildlife in *A. donax* infested watersheds (taken from Cal-IPC, 2011)



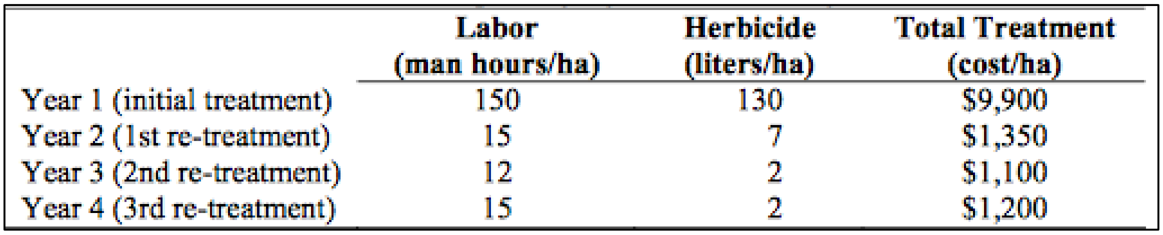
Score	**Impact Level**	**Impacts**
10	Very severe	Very significant alteration of abiotic structure and biological function, and direct take of individuals
9	Severe	Significant alteration of abiotic structure and biological function and direct take of individuals
8	Very high	Alteration of abiotic structure and biological function, direct take possible
7	High	Alteration of abiotic structure and biological function: impacts on mobility
6	Moderate/High	Moderate alteration of abiotic structure and/or biological function
5	Moderate	Minor alteration of abiotic structure and/or biological function
4	Low/Moderate	Low abiotic or biotic impacts
3	Low	Slight changes in food resources, harboring pathogen/predator OR Minor changes to estuary systems
2	Very low	Minor interaction: mobility
1	Very low/Improbable	Difficult to describe any interaction with *Arundo*
0	None	No interaction

Table 4. Mean percent absolute cover by life form for all *A. donax* treatment methods. Initial treatments took place in 1997 with three additional retreatments between 1998-2000 (taken from Lawson et al., 2005)



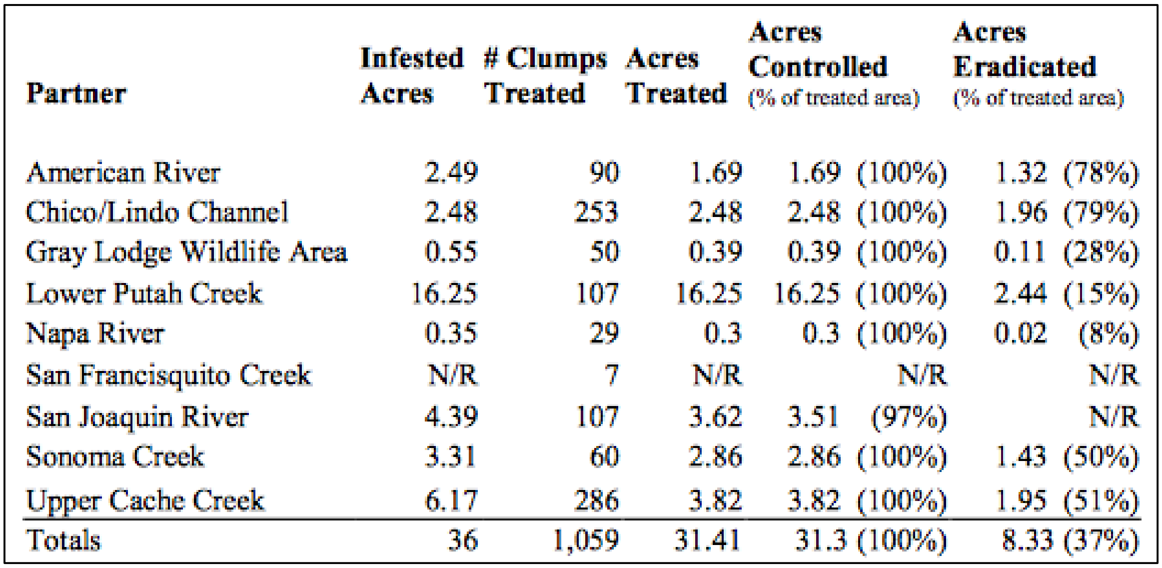
	1997	1998	1999	2000
Foliar Treatment (*df*=3)				
A. donax	68.0[1] (20.0)[2] a	1.5 (4.1) b	0.0 (0.0) b	1.4 (4.3) b
Exotic Herb	22.5 (18.6)	30.4 (22.0)	47.6 (31.6)	52.4 (47.8)
Native Herb	28.1 (32.3)	44.3 (30.5)	27.7 (37.9)	26.9 (20.9)
Native Shrub	15.4 (23.1)	6.4 (9.3)	9.6 (14.4)	11.3 (20.4)
Native Tree	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)

Table 5. Labor, herbicide, and cost per ha for foliar treatment of *A. donax* for the Santa Margarita *Arundo donax* control project (taken from Lawson et al., 2005).



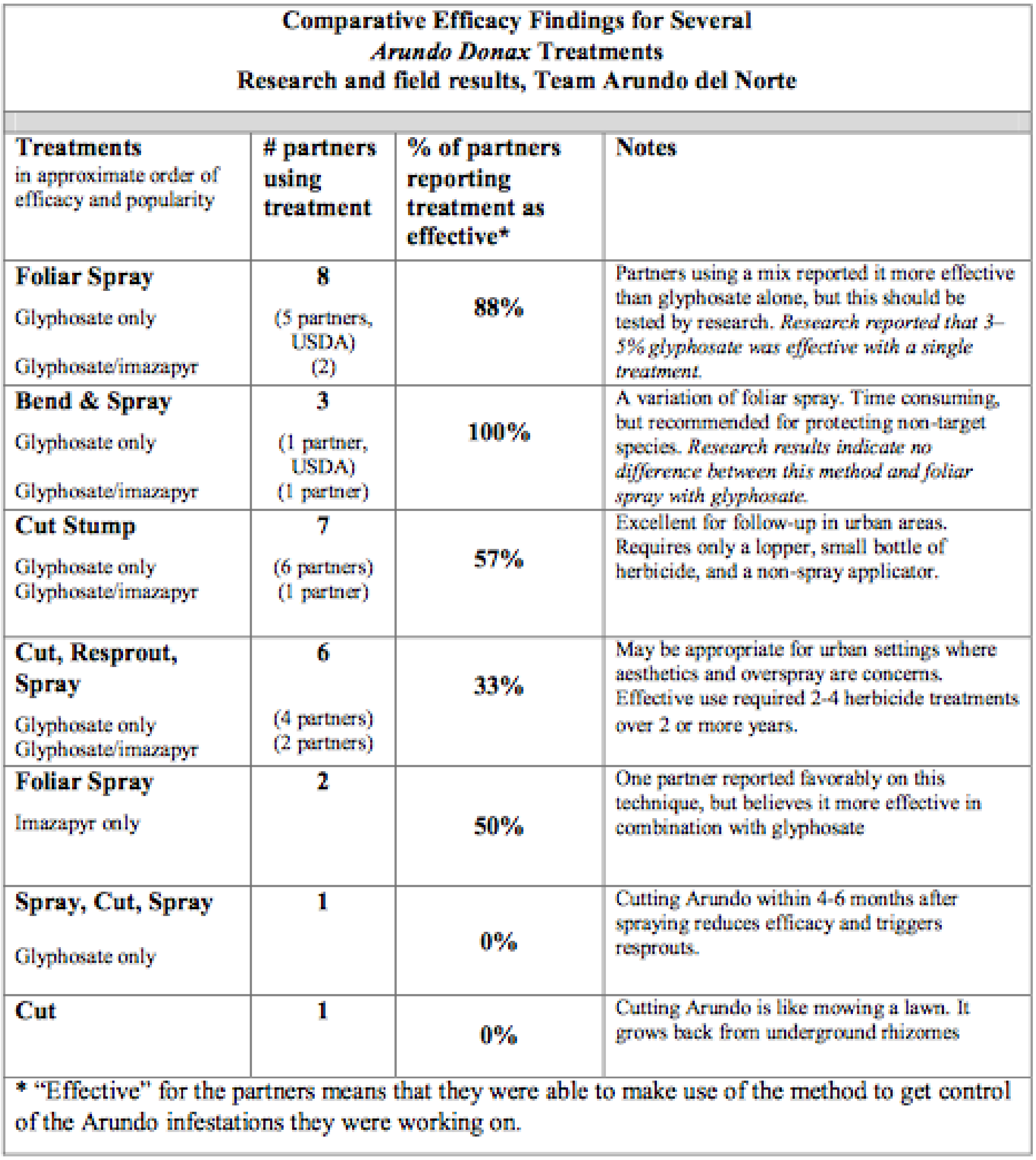
	Labor (man hours/ha)	**Herbicide (liters/ha)**	**Total Treatment (cost/ha)**
Year 1 (initial treatment)	150	130	$9,900
Year 2 (1st re-treatment)	15	7	$1,350
Year 3 (2nd re-treatment)	12	2	$1,100
Year 4 (3rd re-treatment)	15	2	$1,200

Table 6. Acres of *A. donax* controlled and eradicated as reported by partners of the Sonoma Ecology Center *Arundo donax* Eradication Program (taken from SEC, 2010). *Note: Data from the Walnut Creek partner data is not included for undisclosed reasons



Partner	**Infested Acres**	**# Clumps Treated**	**Acres Treated**	**Acres Controlled** (% of treated area)	**Acres Eradicated** (% of treated area)
American River	2.49	90	1.69	1.69 (100%)	1.32 (78%)
Chico/Lindo Channel	2.48	253	2.48	2.48 (100%)	1.96 (79%)
Gray Lodge Wildlife Area	0.55	50	0.39	0.39 (100%)	0.11 (28%)
Lower Putah Creek	16.25	107	16.25	16.25 (100%)	2.44 (15%)
Napa River	0.35	29	0.3	0.3 (100%)	0.02 (8%)
San Francisquito Creek	N/R	7	N/R	N/R	N/R
San Joaquin River	4.39	107	3.62	3.51 (97%)	N/R
Sonoma Creek	3.31	60	2.86	2.86 (100%)	1.43 (50%)
Upper Cache Creek	6.17	286	3.82	3.82 (100%)	1.95 (51%)
Totals	36	1,059	31.41	31.3 (100%)	8.33 (37%)

Table 7. Efficacy of *A. donax* treatments reported by partners of the Sonoma Ecology Center *Arundo donax* Eradication Program. Percentages were calculated based off of the proportion of partners and USDA researchers successfully using a particular method to remove *A. donax* to those reporting unsuccessful control. The number of partners and USDA researchers using a particular method is listed in the second column to the left. See the bottom row for a definition of "effective" control of *A. donax* (taken from SEC, 2010)

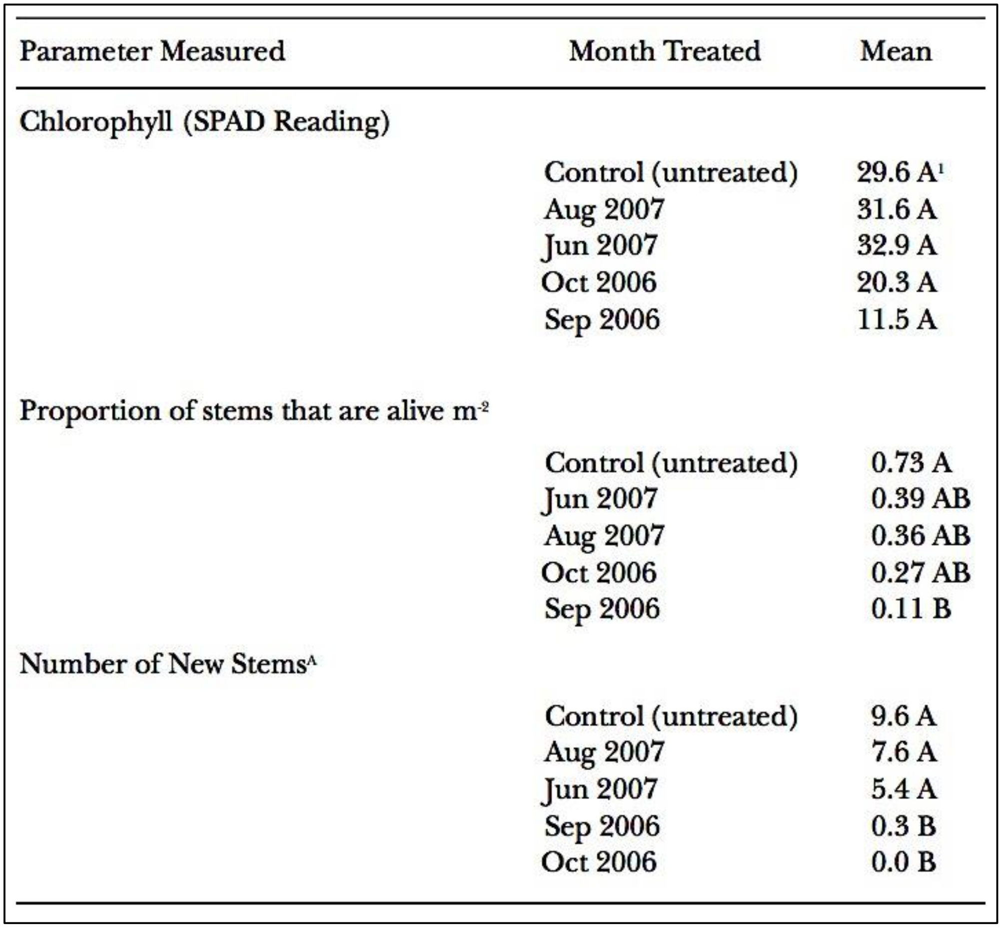


Comparative Efficacy Findings for Several
Arundo Donax **Treatments**
Research and field results, Team Arundo del Norte

Treatments in approximate order of efficacy and popularity	**# partners using treatment**	**% of partners reporting treatment as effective***	**Notes**
Foliar Spray Glyphosate only Glyphosate/imazapyr	**8** (5 partners, USDA) (2)	**88%**	Partners using a mix reported it more effective than glyphosate alone, but this should be tested by research. *Research reported that 3–5% glyphosate was effective with a single treatment.*
Bend & Spray Glyphosate only Glyphosate/imazapyr	**3** (1 partner, USDA) (1 partner)	**100%**	A variation of foliar spray. Time consuming, but recommended for protecting non-target species. *Research results indicate no difference between this method and foliar spray with glyphosate.*
Cut Stump Glyphosate only Glyphosate/imazapyr	**7** (6 partners) (1 partner)	**57%**	Excellent for follow-up in urban areas. Requires only a lopper, small bottle of herbicide, and a non-spray applicator.
Cut, Resprout, Spray Glyphosate only Glyphosate/imazapyr	**6** (4 partners) (2 partners)	**33%**	May be appropriate for urban settings where aesthetics and overspray are concerns. Effective use required 2-4 herbicide treatments over 2 or more years.
Foliar Spray Imazapyr only	**2**	**50%**	One partner reported favorably on this technique, but believes it more effective in combination with glyphosate
Spray, Cut, Spray Glyphosate only	**1**	**0%**	Cutting Arundo within 4-6 months after spraying reduces efficacy and triggers resprouts.
Cut	**1**	**0%**	Cutting Arundo is like mowing a lawn. It grows back from underground rhizomes

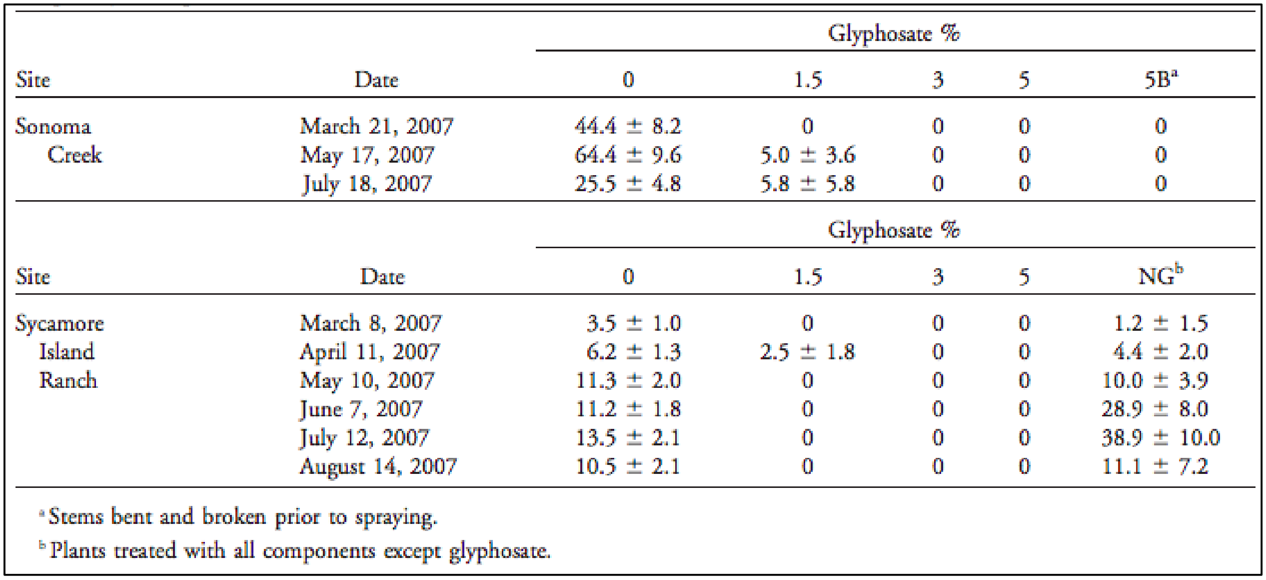
* "Effective" for the partners means that they were able to make use of the method to get control of the Arundo infestations they were working on.

Table 8: Effect of glyphosate application timing on Chlorophyll (SPAD units), proportion of living stems per m^{-2}, and mean number of new stems produced 1 year after treatment. SPAD (Soil-Plant Analysis Development) is the concentration of Chlorophyll per leaf unit area (taken from Spencer et al., 2011)



Parameter Measured	Month Treated	Mean
Chlorophyll (SPAD Reading)		
	Control (untreated)	29.6 A[1]
	Aug 2007	31.6 A
	Jun 2007	32.9 A
	Oct 2006	20.3 A
	Sep 2006	11.5 A
Proportion of stems that are alive m^{-2}		
	Control (untreated)	0.73 A
	Jun 2007	0.39 AB
	Aug 2007	0.36 AB
	Oct 2006	0.27 AB
	Sep 2006	0.11 B
Number of New Stems[A]		
	Control (untreated)	9.6 A
	Aug 2007	7.6 A
	Jun 2007	5.4 A
	Sep 2006	0.3 B
	Oct 2006	0.0 B

Table 9. Number of new stems per m^{-2} emerging in 2007 on plants receiving herbicide treatment at Sonoma Creek and Sycamore Island Ranch. Experiment used three different glyphosate concentrations (1.5%, 3%, and 5%) to determine whichof these concentrations is most effective in killing *A. doanx* (taken from Spencer et al., 2008).



		Glyphosate %				
Site	Date	0	1.5	3	5	5B[a]
Sonoma Creek	March 21, 2007	44.4 ± 8.2	0	0	0	0
	May 17, 2007	64.4 ± 9.6	5.0 ± 3.6	0	0	0
	July 18, 2007	25.5 ± 4.8	5.8 ± 5.8	0	0	0

		Glyphosate %				
Site	Date	0	1.5	3	5	NG[b]
Sycamore Island Ranch	March 8, 2007	3.5 ± 1.0	0	0	0	1.2 ± 1.5
	April 11, 2007	6.2 ± 1.3	2.5 ± 1.8	0	0	4.4 ± 2.0
	May 10, 2007	11.3 ± 2.0	0	0	0	10.0 ± 3.9
	June 7, 2007	11.2 ± 1.8	0	0	0	28.9 ± 8.0
	July 12, 2007	13.5 ± 2.1	0	0	0	38.9 ± 10.0
	August 14, 2007	10.5 ± 2.1	0	0	0	11.1 ± 7.2

[a] Stems bent and broken prior to spraying.

[b] Plants treated with all components except glyphosate.

Table 10: Factors Influencing the Decision to Employ Passive or Active Revegetation in *A. donax* Infested Habitats

Passive Revegetation	**Active Revegetation**
Removal area on floodplain or within channel (floods at least once a year)	Removal area in higher terraces not exposed to flooding (at least once a year)
Diverse riparian forest upstream	Low diversity of riparian forest upstream
All *A. donax* removed upstream	Some *A. donax* remains upstream
Removal area not habitat for sensitive species	Immediate restoration of habitat for sensitive species required
Low risk of erosion	High risk of erosion
Small removal area	Large removal area
Low budget	Adequate soil moisture (irrigation may be required)
	High budget

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