FENNEL *(FOENICULUM VULGARE)* MANAGEMENT AND NATIVE SPECIES ENHANCEMENT ON SANTA CRUZ ISLAND, CALIFORNIA

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ABSTRACT

Fennel *(Foeniculum vulgare)* an invasive, perennial herb known from Santa Cruz Island, California, underwent a population explosion for many years during the past decade after the removal of feral and domestic animals. Potentially occurring in large monocultural stands over three meters in height, fennel heavily impacted native and endemic plant species. An eight-year study showed that digging fennel out of the ground was the most effective eradication tool. Herbicide application was also effective, but this required periodic reapplication for this effectiveness to be maintained. Unfortunately for native plant species, both removal methods were often followed by the invasion of other exotic plant species that continued to inhibit native plant species. Recovery of native species is greatest with a 30 to 40% reduction in fennel cover. When fennel was cut in early May and the resulting litter was removed, native perennial species averaged over sixty percent of the total nonfennel perennial abundance with a mean richness of three species from 1993 to 1998. This management strategy encouraged natural successional processes towards the historical predisturbance native shrub and tree vegetation, and it discouraged a successional shift towards an exotic annual grassland.

Keywords: Santa Cruz Island, California, fennel, Foeniculum vulgare, exotic species, eradication, native species enhancement, and restoration.

INTRODUCTION

Regions possessing Mediterranean-type climates are most heavily impacted by introduction of invasive nonnative species that are encouraged by the settlement and development activities of humans (Mooney 1988). Island ecosystems are especially vulnerable to these invasions because the largely-endemic species assemblages lack defenses sufficient to ward off invaders (Vitousek 1988). The biota of Santa Cruz Island, California, has been subjected to these selective forces for at least seven thousand years, with the last 150 years most likely exerting the greatest selective pressure (Junak et al. 1995). This pressure is the result of the interaction of four introduced species whose life histories have had the largest ecosystem-level impacts: pigs, sheep, cattle, and fennel.

Fennel has been on Santa Cruz Island for more than a century (Brenton and Klinger 1994). Pigs and sheep were introduced to the island in the 1850s and formed substantial feral populations that became the likely avenues of fennel introduction (Beatty and Licari 1992). Greene (1887) reported that fennel was well established on hillsides near Prisoners Harbor in 1888. Cattle ranching and roads were the probable vectors of dispersal over the past 100 years (Beatty and Licari 1992).

In 1978, The Nature Conservancy acquired a conservation easement on the western 90% of Santa Cruz Island and became the sole owner of this parcel in 1987 (Junak et al. 1995). Between 1981 and 1987, The Nature Conservancy eliminated more than 36,000 feral sheep from this portion of the island and then removed approximately 1,500 head of cattle in 1988 (Brenton and Klinger 1994). With this elimination of all large grazing herbivores and the end of a five-year drought in 1991, fennel underwent a rapid and substantial expansion of its range to dominate approximately 10% of the island's area (Brenton and Klinger 1994). The thickest patches of fennel were located where grazing animals once created the most disturbance: holding areas, watering holes, and the flatlands throughout the central valley of the island (Dash and Gliessman 1994).

Fennel is an erect perennial herb of the family Apiaceae. The leaves have sheathing bases and become pinnately dissected two to four times with thread-like pinnae. The stems are smooth and exude a white, powdery coating. The plant reaches average heights from one to two meters but has been observed at heights over three meters (W. Colvin, pers. obs. 1996). It blooms from February (Junak et al. 1995) through September (W. Colvin, pers. obs. 1996). Fennel thrives on well-drained, loamy soil, and occurs across a broad life zone between the temperatures of 4 to 27°C, annual precipitation of 300 to 2600 mm, and soil pH between 4.8 and 8.3 (Simon 1984).

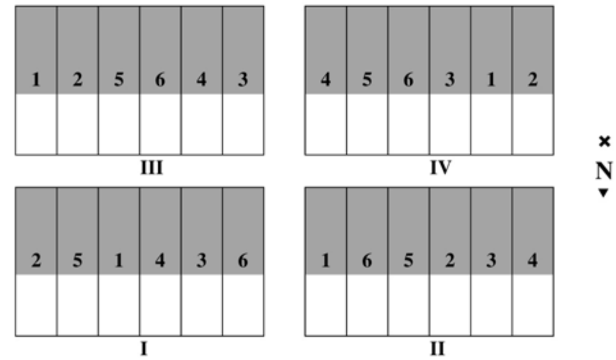
Several researchers have reported allelopathic potential for fennel. Allelopathic compounds are secondary plant chemicals with the potential for phytotoxicity. Chaturvedi and Muralia (1975) were the first to investigate the allelopathic potential of plants in the family Apiaceae using a rapid bioassay technique. They found that fennel seed extracts produced the strongest inhibitory effects on growth and germination against cumin *(Cuminum cyminum*), followed by carum (*Carum copticum),* carrot *(Daucus carota* L.*)*, and coriander (*Coriandrum sativum* L.*).* Aoki (1990) found that fennel leaf extracts inhibited the germination and growth of rye *(Secale cereale),* radish (*Raphanus sativa* "red pak"), and lettuce (*Lactuca sativa* Burpee's "Green Ice Loosehead") in laboratory bioassays and had the same effect on rye and lettuce in greenhouse studies. Granath (1992) was the first to investigate the allelopathic potential of fennel leaf extracts on seeds collected from Santa Cruz Island. For nonnative grasses, it was found that fennel leaf extracts stimulated growth of wild oat *(Avena fatua)*, decreased growth of ripgut grass *(Bromus diandrus)* and soft chess *(Bromus hordeaceus),* and left the growth of barley *(Hordeum murinum* ssp. *leporinum)* unchanged. Germination remained unchanged for all species except soft chess, which exhibited a decline as fennel leaf extract concentrations increased. Regarding native species, Colvin (1996) found that fennel leaf extracts suppressed the growth of beach evening primrose *(Camissonia cheiranthifolia),* germination of mountain garland *(Clarkia unguiculata),* and germination and growth of California poppy *(Eschscholzia californica),* white baby lupine *(Lupinus nanus),* and desert bluebells *(Phacelia campanularia).* Fennel appears to inhibit its own germination and growth as well (Colvin 1996).

MATERIALS AND METHODS

Dash and Gliessman (1994) outlined the initial protocol for this field study. No changes have occurred to that protocol in the interim; however, the focus of the project has changed in two ways. Based on the findings of Dash (1993), a program of native species enhancement onto the study site was instituted in September 1995. Seeds of native perennials were collected on the island and broadcast by hand into the southern halves of each treatment area within the four replicates. The northern halves of each treatment were left unenhanced as intra-plot controls (Figure 1). Perennial species richness and abundance were tallied and comparisons between native and exotic species determined between treatments as well as any differences in recruitment between the enhanced and unenhanced portions of the treatments. Observations by Colvin (1996) prompted the construction of a fence in February 1998 around the study site to exclude feral pigs from introducing further experimental biases into future results.

Site Description

The experiment occurred on the north-facing slope of the Central Valley floor south of the Santa Cruz Island Fault and north of the South Ridge Road. It was approximately 0.5 km east of the University of California Field Station. The experimental treatments were randomly assigned to six plots within rows referred to as blocks and replicated four times (Figure 1). It was bounded by the Valley Road to the north and in proximity to the eucalyptus grove at Camino de la Casa to the east.



The size of each treatment measures 5.4 x 15.4 meters

TREATMENTS:

1. Control - leave fennel untouched
2. Cut and leave cuttings - leave fennel on the surface as mulch
3. Cut and remove cuttings - remove plant material from treatment
4. Dig - dig out root system and remove from plot
5. Herbicide - fennel cut and stems sprayed only from 1990 to 1992
6. Cut and remove cuttings twice - repeat treatment Spring and Summer

Figure 1. Randomized fennel treatments assigned to the experimental field plots on Santa Cruz Island from May 1990 to September 1998 (adapted from Dash and Gliessman, 1994). Each treatment was replicated four times. Shaded areas were enhanced by hand broadcasting native seed collected on the island. Unshaded areas were left alone as intra-plot controls.

RESULTS

When fennel was left alone, fennel coverage averaged over 90% within the study plots for eight years (Figure 2). When it was dug out of the ground, there was no fennel cover after five years. All three of the cut fennel manipulations maintained an average fennel coverage between 60 and 70% for eight years regardless of whether the resulting litter was removed. When the herbicide Roundup® was applied from 1990 to 1992, fennel coverage was lowest after two years and returned to that of the various cutting manipulations after eight years.

Annual nonfennel biomass reached a peak in 1993 for all treatments (Figure 3). Biomass was greatest where herbicide was applied, followed by cutting fennel twice per year and removing the resulting litter. In 1993, the control possessed the lowest quantity of nonfennel annual biomass while the cut, cut and remove, and dig manipulations possessed moderate quantities. By 1998, total annual nonfennel biomass decreased below 100 g/m^2 in all treatments. When fennel was left alone, the quantity of annual nonfennel biomass remained lowest. The percentage of nonnative species in the total annual nonfennel density approached 100% across all treatments from 1991 to 1997, except for the control treatment in 1997 where it approached 80% (Table 1).

Perennial nonfennel abundance reached a peak across all treatments after six years (Figure 4). In 1998, all three of the cut fennel manipulations achieved a mean abundance of 120 individuals per plot regardless of whether the resulting litter was removed. Digging fennel out of the ground resulted in a mean abundance of over 80 individuals per plot.

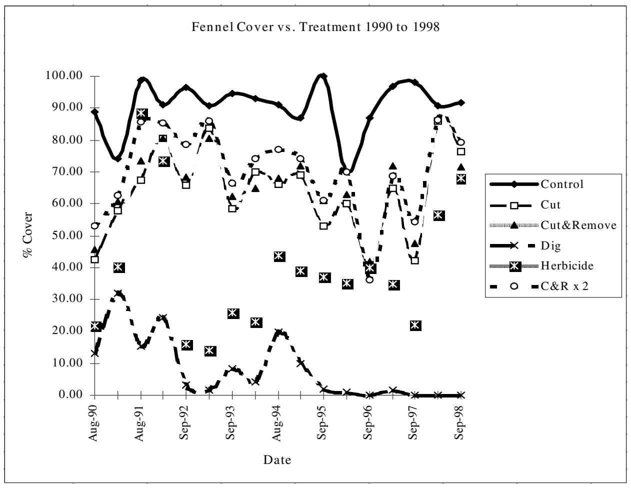


Figure 2. Percent cover of fennel within the experimental plots on Santa Cruz Island from 1990 to 1998.

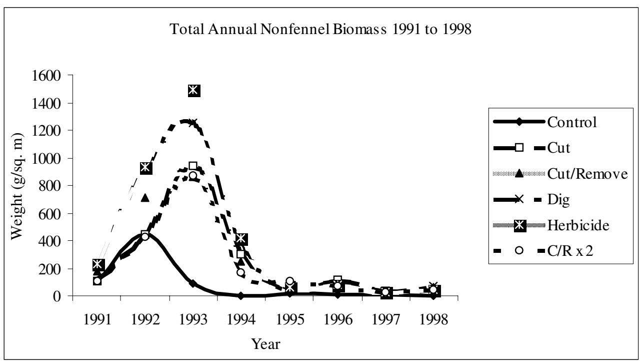


Figure 3. Total annual nonfennel biomass (g/m^2) within the experimental plots on Santa Cruz Island from 1991 to 1998.

Table 1. The percentage of exotic annual species within the total nonfennel annual density in the study plots on Santa Cruz Island, CA from 1991 to 1997.

	1991	1992	1993	1994	1995	1996	1997
Control	100%	100%	99%	100%	100%	99%	80%
Cut	100%	100%	100%	100%	97%	99%	99%
Cut and remove	100%	98%	99%	99%	98%	100%	98%
Dig	98%	100%	100%	100%	100%	100%	99%
Herbicide	100%	99%	100%	100%	100%	100%	100%
Cut and remove twice	100%	99%	100%	99%	100%	99%	95%

Herbicide application resulted in a mean abundance of over 60 individuals per plot. When untreated, mean perennial abundance never exceeded one individual per square meter. The percentage of native perennials within the total nonfennel perennial abundance was greatest when fennel was cut and the litter removed in May, followed by cutting fennel and removing the litter twice per year from 1993 to 1998 (Table 2). The percentage of native perennials rarely exceeded 10% when fennel was dug out of the ground during the same time frame. When fennel was untreated, cut, or treated with an herbicide, the percentage of native perennials was highly variable from 1993 to 1998. Native perennial richness was greatest with a mean of four species when fennel was cut and left on the ground from 1993 to 1998 (Table 3). With a mean of three species, native perennial richness was equal for the other treatments during the same time frame. When fennel was left alone or dug out of the ground, native perennial richness was lowest with a mean of two species. No noticeable differences existed in native species abundance or richness between the enhanced and unenhanced portions of the plots.

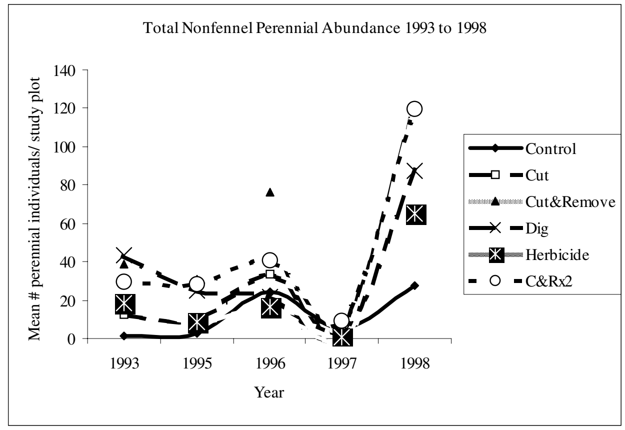


Figure 4. The mean number of perennial individuals within the experimental plots on Santa Cruz Island in the total nonfennel perennial abundance from 1993 to 1998.

Table 2. The percentage of native perennials within the total nonfennel perennial abundance in the study plots on Santa Cruz Island, CA from 1993 to 1998.

	1993	1995	1996	1997	1998
Control	20%	80%	89%	36%	63%
Cut	16%	38%	78%	40%	49%
Cut and remove	55%	69%	82%	50%	50%
Dig	4%	4%	13%	75%	3%
Herbicide	14%	21%	65%	0%	61%
Cut and remove twice	52%	53%	64%	89%	54%

Table 3. Native perennial species richess (s) within the study plots on Santa Cruz Island, CA from 1993 to 1998.

	1993	1995	1996	1997	1998
Control	1	2	3	2	2
Cut	3	3	5	4	3
Cut and remove	3	4	3	1	3
Dig	2	3	3	1	2
Herbicide	4	3	4	0	4
Cut and remove twice	4	3	4	1	3

DISCUSSION

Any management strategy that seeks to remove fennel from Santa Cruz Island should include restoration of total ecosystem relationships to fennel-affected areas so that natural successional processes encourage the recruitment of native species rather than introduced ones. Santa Cruz Island ecosystem preservation has been a focus of efforts by The Nature Conservancy to protect remnants of California's natural heritage (VanVuren and Coblentz 1989). The predisturbance plant communities associated with our study's location were probably chaparral and oak woodland (Minnich 1980). Fennel and nonfennel biomass indices from the past eight years must be examined so that an effective management policy can be developed.

After eight years, fennel coverage remained unchanged on average in the untreated study plots. The most successful method of fennel eradication from the study plots was by digging plants out of the ground and removing the resulting litter. Herbicide application was the second most successful technique of eradication but required periodic reapplication. Whereas, all three of the variations in cutting fennel and either leaving or removing the resulting litter produced moderate rates of fennel decline. Trends in nonfennel biomass must be examined to determine which fennel removal technique encourages the greatest recovery of native species. The quickest method to eradicate fennel may not be the most desirable management objective if other invasive exotic species replace it, yellow star thistle *(Centaurea solstitialis)* for example (W. Colvin, pers. obs. 1996).

One hundred years of grazing by domestic and feral animals have left a preponderance of exotic annual and perennial seeds in the seed bank. The allelopathic potential of fennel appears to suppress the germination and recruitment of both native and exotic, annual and perennial, plant species based on the results of both laboratory bioassays and the field study plots. A reduction in fennel coverage appears to release these seeds from the direct interference of allelopathic fennel compounds and allow other plant species to increase in abundance, richness, and diversity. Although annual nonfennel biomass remained below 150 g/m^2 across all treatments over the past four years, exotic annual plant species dominated native annual plant species throughout the entire course of this study. These species, primarily associated with European grasslands, were not part of the predisturbance condition of the site. For this reason, increasing the recruitment of native perennials over exotic perennials should be a primary goal of any fennel eradication policy. This was achieved when fennel was cut and the litter removed in May. When this method was used, native perennial plants comprised over sixty percent on average of the total nonfennel perennial abundance with a mean richness of three native species in the field study plots from 1993 to 1998. This occurred regardless of whether the enhancement of the southern halves of each treatment with native seed was effective. It was expected that enhancement of the southern halves of each treatment with native seed would further promote native perennial recruitment; however, the results of the past three years remain inconclusive.

It is suspected that the rooting activities of the feral pig *(Sus scrofa)* nullified any benefits the native species enhancement protocol instituted in 1995 may have produced. Damage to ecosystem structure and function by feral pig feeding activities on Santa Cruz Island is well documented (VanVuren 1984; Peart et al. 1994). Since 1994, the feral pig population appears to have increased. This coincides with the dramatic decrease in annual nonfennel biomass observed throughout all six plot manipulations over the past four years. Although statistical correlation between these two phenomena was not attempted, the study site contained large quantities of pig scat and established game trails by 1996 that were not present in 1994 (S. Gliessman, pers. comm. 1996). For this reason, a fence was constructed around the study site in 1998.

Biological control of fennel populations by introducing known pathogens has never been proposed. Several pathogens have been identified for fennel around the world. In India, the fungi *Fusarium solani* (Gupta and Srivastava 1978), *Ramularia foeniculi* (Lakra 1993), and *Sclerotinia sclerotiorum* (Sehgal and Agrawat 1971) have been identified as the causal agents of fennel soft rot. In Italy, bacterial soft rot of fennel is caused by *Erwinia carotova* (Mazzuchi and Dalli 1974) and fungal soft rot by *Phomopsis foeniculi* (Evidente et al. 1994). California is known to contain three reported fennel pathogens. Koike et al. (1992) reported the fungus *Cercosporidium punctum* as the causal agent of fennel rot in Monterey County, and it is known to occur in Santa Barbara and Santa Cruz Counties as well. Recently, the bacterium *Pseudomonas syringae* was implicated in causing a foliar disease of fennel (Koike et al. 1993). In the Salinas Valley, fennel has been used as a rotation crop with lettuce where fennel stem rot caused by the fungus *Sclerotinia minor* was first reported (Koike 1994). Although precedent exists for the successful introduction of biocontrols to manage other exotic species introductions to Santa Cruz Island (Wenner and Thorp 1994), research must be performed before any of these fennel pathogens can be introduced as biocontrol agents to make certain that they will not switch to other hosts in the family Apiaceae that are native to the island.

Ecological invasion by exotic species is a pandemic phenomenon that has caused ecological as well as economic havoc to private and public lands (Schneider 1994). Native plant species on the California Channel Islands have been negatively impacted by the exotic species introductions caused from human activities and the continuous disturbance caused by introduced animals (Junak 1996). On Santa Cruz Island, California, exotic species represent twenty six percent of the island's total plant species (Junak et al. 1995). Eradication of one exotic species, however minimal the effort, is another human activity that has the potential to create the disturbance required for the successful invasion and recruitment of more exotic plant species where only one problem existed previously. In southern California where restoration did not occur to shrublands disturbed by anthropogenic activities as long as seventy-one years earlier, exotic annual species dominated disturbed sites with the few native perennial colonizers atypical of the late successional plant communities in the surrounding area (Allen et al. 1995). When restoration followed disturbance, they found exotic annuals were still prevalent, but native perennials established from seed and recovered best adjacent to native shrub vegetation.

Prioritization and coordination objectives for the removal of exotic species are necessary for successful implementation of these protocols to occur (Vitousek 1988; Westman 1990; Hiebert and Stubbendiek 1993; Leppla 1996). The management of Santa Cruz Island's natural resources is now under the jurisdiction of several public and private conservation and preservation agencies and entities. Cooperation between organizations is essential in this conglomeration of parties affected by exotic species introductions. Fennel and feral animals do not observe the jurisdictional boundaries of these management groups. Eradication goals and restoration objectives must be adaptable and flexible to deal with new types of situations. The foraging activities of feral pigs negatively impact the recovery and restoration of native plant species in fennel affected areas and further facilitates invasion by exotic plant species. The removal of feral animals on Santa Cruz Island must occur before native plant restoration is attempted. Fennel eradication and native plant restoration techniques developed for use in the Central Valley may not be appropriate or suitable for use on the North Slope or Cañada Christy areas of the island. Fennel and ranching coexisted on this island for over a century. All ranching operations ceased on the island in 1988. The study of fennel eradication is approaching a decade. It may take at least this amount of time or greater before an eradication strategy is fully implemented and restoration objectives are realized. Therefore, the protocol adopted must be cost effective. It will utilize a minimal amount of human resources over time while maximizing the recovery of native species using ecological seral succession.

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