trol methods (plowing, mowing) or broad spectrum herbicides (e.g., glyphosate).

Integrated methods of vegetation management should always be considered when planning nonnative plant control programs, and are essential for long-term control. Our models indicate that no single management method will be adequate for controlling fennel in all habitats, with the possible exception of biological control. But because there are no known biological control agents for fennel, a combination of herbicides and cultural methods will be needed in any comprehensive fennel management program that is undertaken in the Channel Islands.

To avoid an explosion of fennel (or a similar expansion of another nonnative species) such as what occurred on Santa Cruz Island, it may be necessary to reduce the number of grazers in a gradual fashion on other islands. If grazers are to be removed over a relatively short period of time, management programs should be designed to suppress outbreaks of nonnative species before they become unmanageable. In the end, the most effective way to manage nonnative plants is to prevent them from reaching levels where management is required. Once the need for management is recognized, it is probably too late for full control to ever be achieved.

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Nonnative Species Eradication and Native Species Enhancement: Fennel on Santa Cruz Island

Brett A. Dash[1] and Stephen R. Gliessman[2]

[1]Box #303 College Eight, University of California at Santa Cruz, Santa Cruz, CA 95064
Tel. (408) 423-9180; Fax (408) 423-9180
[2]Agroecology Program, University of Santa Cruz, Santa Cruz, CA 95076
Tel. (408) 459-4051

Abstract. Four seasons of field data on fennel (*Foeniculum vulgare* Mill.) removal and non-fennel plant species recovery, taken from experimental plots on Santa Cruz Island, have been collated and the results are the subject of this discussion. The most effective methods of reducing the percentage of fennel cover were (1) digging out and removing the fennel from the site, and (2) using an appropriate herbicide after cutting. The other 3 manipulations involved the one-time cutting of fennel, with the removal and non-removal of the resulting litter, and a cutting regime of spring cut and re-cut in summer with litter removal.

There were no significant differences in the fennel cover of the 3 cut treatments after 4 seasons, and the cover was only slightly less than in the control. The non-fennel biomass regeneration in all treatments, particularly the dig and herbicide treatments, favored nonnative species. Native species regeneration was most prominent in the cut-and-remove treatment, but the number of native individuals was too small to draw a well-founded conclusion. The allelopathic potential of fennel and its synergistic potential with nonnative species such as *Bromus diandrus* need to be investigated in terms of inhibiting the germination and growth of native species. Also, the effects of a fennel mulch in inhibiting fennel regeneration, as indicated in our research, bears further investigation. In researching recommendations, the focus has been not only on the effects of the treatments on fennel growth and development, but the treatment's effects on the allelopathic potential of fennel. Our goal is not just to eradicate fennel, and to have it replaced with another species that may be just as noxious and problematic; it is to better understand the conditions that favor a succession of native species that can replace fennel, and how much external input is required to coax that succession. Native species enhancement is one possibility. The main conclusion of the study is that restoring areas of fennel infestation to native species will need to be a project with a long-term successional outlook.

Keywords: Central Valley; Santa Cruz Island; fennel; noxious weed; allelopathy; succession; native species; enhancement; restoration.

Introduction

Fennel is an erect perennial herb in the family Apiaceae. Its leaves are pinnately finely dissected and thread-like. The plant attains 1–2 m in height and has a white powder coating on the stem. It blooms May to September, and the small, yellow flowers and occur in glaucous compound umbels of 15–40 rays. The fruit is laterally compressed, 5-ridged, and has a large single resin canal under each furrow (Anonymous 1926). Originally from the Mediterranean, fennel has become an aggressive invader in the western United States. The plant is common in heavily disturbed areas, especially in southern and central California where it has now naturalized (Hickman 1993).

Fennel was introduced to Santa Cruz Island in the 1850s (Beatty and Licari 1992) along with the importation of sheep and pigs. Prisoners Harbor is thought to be the point of entry. This invasive nonnative now grows abundantly on Santa Cruz Island, crowding out native vegetation in most of the places it grows.

Santa Cruz Island, in the northern chain of Channel Island off the California coast, is located 30 km southwest of Santa Barbara. It is approximately 38 km in length, averages 10 km in width, and covers an area of 249 km^2. The climate is Mediterranean, with mild temperatures, rainy winters, and dry summers. The interior central valley averages nearly 500 mm of annual precipitation (Minnich 1980). The largest of the Channel Islands, it harbors a variety of plant and wildlife, including at least 9 rare or endangered plants and 31 species of plant life believed to be found nowhere else in the world other than the northern Channel Islands (Anonymous 1988).

The island has been subjected to intense overgrazing by sheep, pigs, and other introduced domestic animals for more than a century. Historical records indicate that grazing, mostly by sheep, became important around 1850 at a time when these activities were widespread in the coastal plains and mountains of southern California (Minnich 1978; Brumbaugh 1980; Coblentz 1980). Herds increased rapidly to tens of thousands and had so much impact on the vegetation that Santa Cruz Island was "ravaged" by the time a survey was done in 1875 (Wheeler 1876). Such heavy disturbance of the native vegetation paved the way for invasion by nonnative species such as the annual grasses that now heavily dominate the once more common native perennial bunch grasses. It is of interest to note, however, that fennel only became problematic after the grazing animals were removed from the island in the late 1980s. According to Orrin Sage (1993, pers. comm.), who supervised the removal of cattle from the island in 1989, the worst patches of fennel are now located where grazing animals created the most disturbance: holding areas, watering holes, and the flatter areas throughout the Central Valley. Sheep and cattle find fennel palatable and were effective in keeping fennel growth in check. Fennel now grows in dense stands, its rapid spread possibly threatening some native island plant populations.

The removal of sheep and cattle was arranged for by The Nature Conservancy, current owners and managers of all but the eastern 10% of the island. Management policy is geared toward preserving and restoring the biological diversity of native species, especially island endemic species, while discouraging the spread of nonnative species. Fennel has become a major concern, and ongoing experimental research is being carried out to determine the most effective strategies for combatting the spread of this undesirable nonnative. The following experiment was set up by Natural History Field Quarter students from the University of California at Santa Cruz (UCSC) in 1990. The students felt compelled to investigate alternate methods to herbicide, as was proposed by The Nature Conservancy, in an attempt to rid Santa Cruz Island of fennel. Data have been collected biannually, 1990–1993, under the guidance of S.R. Gliessman of the Environmental Studies Board at USCS.

Methods

The field experimental design consists of 4 replicates of each of the 6 treatments in a randomized block configuration, making a total of 24 experimental plots (Fig. 1). The array of 5.4- x 15-m plots was located in the Central Valley on Santa Cruz Island, just west of the Main Ranch. The plots were set up on 2 May 1990. The 6 treatments were assigned to the 4 replicate plots using a random numbers table. The manipulations decided upon were:

1. *Control*—Leave fennel untouched.
2. *Cut and leave cuttings*—The fennel was cut down and left on the surface as mulch.

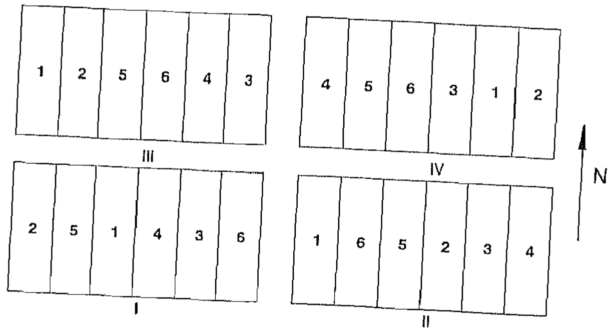

Figure 1. Random fennel treatment assignments on experimental plots, Santa Cruz Island, May 1990–September 1993. The size of each treatment measures 5.4 x 15 m. Treatments are (1) control—leave fennel untouched; (2) cut and leave cuttings—leave fennel on the surface as mulch; (3) cut and remove cuttings—remove plant material from treatment; (4) dig—dig out root system and remove from treatment; (5) cut and apply herbicide—cut fennel and spray stalks; and (6) cut and remove cuttings twice—repeat treatment Spring and Summer.

3. *Cut and remove cuttings*—The fennel was cut down, and plant material was removed using a pitchfork and rake.
4. *Dig*—Each fennel plant was dug with picks and pickaxes taking as much of the root system as possible, and removed from plots.
5. *Cut and apply herbicide*—The plot was cut and then sprayed with Roundup® at the manufacturer's rec ommended dosage, or standing crop of fennel was sprayed without cutting.
6. *Spring cut, summer cut, and clear*—The fennel was cut in May and litter removed. Then, regrowth was cut down in August, and all fennel litter removed by raking.

These treatments allow an assessment of (a) the effects on fennel biomass, (b) the effects on the allelopathic potential of fennel, (c) the ability of nonnative species to set up and maintain dominance, and (d) the ability of native species to establish themselves.

Cutting (Treatments 2 and 3) was chosen as a relatively cheap and easy way to knock down fennel with the potential for larger-scale mechanization with hand-held cutters, or even a tractor-mounted mower. The difference between the 2 treatments—leaving the litter as opposed to raking it up and removing it—was intended to monitor the possible allelopathic effects of a fennel mulch on new growth of both fennel and non-fennel biomass. Digging (Treatment 4) was applied under the assumption that removal of the taproot system would be quite effective in eliminating fennel growth. Treatment 5, cutting followed by the use of herbicide, was chosen as a potentially quick and thorough method of eradication. Treatment 6 was originally designed as a burn treatment. But, due to the extremely dry conditions caused by years of drought, the

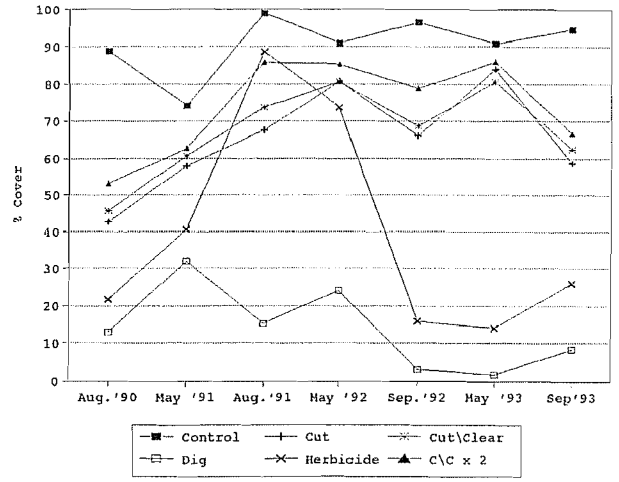

Figure 2. Changes in percent cover in the fennel experimental plots on Santa Cruz Island, August 1990–September 1993.

potential for starting a brush fire was deemed too great, and the idea was dropped. (Data subsequently taken from an accidental burn site at China Harbor by Susan Beatty will be mentioned later in this paper.) It was decided to run another allelopathic test treatment. The fennel growth that occurred after the first cutting in May would be cut and removed again in August before the winter rains could leach toxins from the fresh growth into the soil.

Fennel data collected from the field in both spring and late summer/early fall of all years measure the percent cover of each treatment as well as height, number of clumps, and number of stalks per plant along the transects. Fennel cover (Fig. 2) was calculated by measuring the amount of open space along a diagonal transect bisecting each treatment. The open space was calculated into a percentage of the transect, and the remainder was taken as the percent cover of fennel. On the transect, the number of clumps (plants) was tallied and for each plant that was touched by the transect, the number of stalks was recorded. To complete the picture, the height of each plant was measured.

Non-fennel data consist of the documentation of number of species and individuals taken from each treatment. The non-fennel biomass was recorded as both number of individuals and number of species (Table 1). The native species were then separated from nonnative species and recorded separately. All non-fennel biomass was returned to UCSC and dried at 70° C for 48 hr then weighed. The weight of non-fennel biomass and the average weight per individual were calculated. Non-fennel biomass collection changed in response to increasing abundance of non-fennel biomass. Three subplots per treatment were randomly chosen each season and the non-fennel biomass sorted into species, counted, dried, and weighed. However, the subplots varied in size over the years, due to the sheer numbers of individual plants in some subplots. Subplots varied in size, from 0.25 m² to 0.50 m² to 0.75 m² to 1.00 m². All measurements have been standardized for this report.

Results

Fennel cover

Treatment 4 was most effective in preventing fennel regrowth throughout the experiment (Fig. 2). Treatment 5 was also very effective initially, but required repeated applications of herbicide to keep the fennel back. The original application of Roundup® to cut stalks in May 1990 was effective in reducing fennel cover to 21.7% (Aoki 1990), but by August 1991 the fennel had recovered well. This resulted in the highest percent coverage of all treatments: 88.5% (Granath 1992). Roundup® was reapplied to cut stalks in August 1991 with little effect (see Fig. 2), and again, but to foliage, in May 1992. The May 1992 application, applied to foliage, was effective in reducing the cover to around 15% through May 1993. It is apparent that applications of the herbicide to the foliage provide more effective translocation of toxins to the rootstock than do applications to cut stalks. Also, it appears that the herbicide is more effective when applied in the peak growth period of the plant. Additionally, the use of a surfactant that allows the herbicide to adhere to the plant may increase the effectiveness of the treatment. It remains to be seen whether there will be another resurgence of fennel growth in this treatment. The other 3 treatments—2, 3, and 6—all showed a significant reduction in percent cover after the first treatment. However, all 3 treatments followed a similar pattern of vigorous regrowth so that by May 1992 they all showed a slight but not significant reduction in terms of the control despite repeated treatments. Additionally, these 3 treatments show almost identical patterns of fluctuation in regrowth, indicating a similar response to physical factors.

Associated species

Average numbers of individuals/sq m decreased markedly from 1991 to 1993 in Treatment 1, and only slightly from 1992 to 1993. In 1992 both the weight/sq m and the average weight/individual increased only to decline again in the 1992–1993 period. This result indicates the continual crowding out of associated species by the fennel as it progressively established dominance from 1990 onward. The 3 cut treatments (2, 3, and 6) showed a continued increase in non-fennel biomass. Increases in fennel biomass were fairly consistent in these 3 treatments in 1991–1992. However, in 1993, the increase in Treatment 2 was 235% compared to an increase of 84%

Table 1. Associated species per m² extracted from the fennel experimental plots on Santa Cruz Island, May 1991, May 1992, and May 1993.

	Treatment #1			Treatment #2			Treatment #3			Treatment #4			Treatment #5			Treatment #6		
	1991	1992	1993	1991	1992	1993	1991	1992	1993	1991	1992	1993	1991	1992	1993	1991	1992	1993
Bromus diandrus	310	190	121	159	251	768	98	231	400	174	585	272	90	280	224	194	258	360
Bromus hordaceous	230	o	4	25	28	103	64	20	34	32	28	21	64	51	33	33	30	46
Avena fatua	5	9	2	1	3	80	4	10	8	14	163	53	7	12	15	×	1	5
Convovulvus arvensis	6	2	×	×	4	10	3	5	11	2	2	25	1	×	2	2	2	3
Centaurea solstitialis	1	2	1	7	20	4	9	1	23	11	27	27	17	31	11	0	2	11
Hordeum leporinum	11	1	o	19	×	×	7	14	1	6	26	1	1	10	2	4	3	o
Festuca megalura	5	o	o	10	1	87	8	1	19	×	4	9	9	3	3	11	×	17
Lolium multiflora	3	o	o	1	2	3	o	2	9	o	1	4	o	1	4	1	2	17
Medicago minima	19	o	o	26	o	1	41	1	o	41	×	1	40	2	2	2	o	19
Anagalis arvensis	5	o	o	3	o	2	2	1	12	3	1	7	o	×	3	o	o	11
Erodium macrophyllum	2	o	o	3	4	o	8	×	1	28	5	×	10	11	o	2	6	0
Marubium vulgare	3	×	o	3	1	8	×	×	3	o	o	o	o	o	×	×	×	×
Cardaria draba	10	6	19	11	3	15	×	×	1	16	o	2	o	o	o	o	o	o
Brassica campestris	o	o	×	o	o	×	1	×	×	1	4	58	4	o	3	o	4	o
Alophecus sp.	o	o	×	o	o	1	o	o	12	o	o	7	o	o	1	o	o	1
Malva parviflora	o	o	o	o	o	o	×	o	o	1	o	o	o	1	o	o	o	1
Salsola tragus	o	o	o	o	7	o	o	5	o	o	2	o	o	1	o	o	o	o
Silene galica	o	o	o	o	o	o	o	o	o	×	o	×	o	o	×	o	o	1
Hordeum marinum	o	o	o	o	o	×	o	o	3	o	o	o	o	o	o	o	o	o
Vulpia bromoides	o	o	2	o	o	3	o	o	o	o	o	o	o	o	×	o	o	o
Bromus rubens	o	o	o	o	o	o	o	o	1	o	o	o	o	o	o	o	o	o
Calandrinia maritima	o	o	o	o	o	o	o	o	o	4	o	o	o	o	o	o	o	o
Cerastium glomeratum	o	o	o	1	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Nonnative individuals	610	210	149	269	324	1,085	245	291	538	333	848	487	243	403	303	249	308	494
Nonnative species	13	7	9	14	12	16	14	15	16	15	13	15	10	13	15	11	11	13
Bromus carinatus	o	×	o	o	o	2	o	2	5	o	2	o	o	o	o	o	o	o
Lupinus bicolor	o	o	o	o	o	o	o	o	×	7	o	×	o	1	o	×	o	o
Stipa pulchra	o	o	o	o	o	o	o	3	o	o	2	o	o	2	o	o	2	o
Baccharis pilularis	1	o	×	o	o	o	o	o	×	o	o	o	o	o	o	o	o	o
Galium californicum	o	o	o	o	o	×	o	o	o	o	o	o	o	o	o	o	o	o
Anaphalis margaritacea	o	o	o	o	o	o	o	o	×	o	o	o	o	o	o	o	o	o
Native individuals	1	< 1	< 1	0	0	2	0	5	6	7	4	< 1	0	3	0	< 1	2	0
Native species	1	1	1	0	0	2	0	2	4	1	2	1	0	2	0	2	0	0
Total individuals	611	210	149	269	324	1,087	245	296	544	340	852	487	243	405	303	249	310	494
Total species	14	8	10	14	12	18	14	17	20	16	15	16	10	15	15	12	12	13

o = Not present.
× = Average < 1 individual.

Table 2. Perennial species count in the fennel experimental plots on Santa Cruz Island, October 11, 1993. All figures are averages across 4 replicates measuring 15 m × 5.4 m each.

	Control	Cut	Cut/Rem	Dig	Herbicide	C\R × 2
Native species						
Baccharis pilularis	0.25	0.25	6.25	0.75	0.50	9.25
Gnaphalium canescens ssp. *microcephalum*	0.00	0.50	5.00	1.00	1.50	4.25
Stipa pulchra	0.00	1.25	9.75	0.00	0.25	1.00
Heterotheca grandifolia	0.00	0.00	0.00	0.00	0.00	0.75
Fm. Asteraceae	0.00	0.00	0.00	0.00	0.25	0.00
Average number of individuals per replicate	0.25	2.00	21.00	1.75	2.50	15.25
Average number of species per replicate	0.25	1.50	3.00	1.25	1.00	2.75
Nonnative species						
Convovulus arvensis	0.00	2.00	5.00	16.75	0.75	1.50
Marubium vulgare	1.00	2.75	8.00	3.50	1.00	7.50
Brassica nigra	0.00	0.00	0.25	6.00	4.25	1.00
Centaurea vulgare	0.00	5.50	4.25	15.25	7.75	4.25
Anagalis arvensis	0.00	0.25	0.00	0.00	2.25	0.00
Average number of individuals per replicate	1.00	10.50	17.50	41.50	16.00	14.25
Average number of species per replicate	0.50	3.00	3.25	3.25	2.50	3.00
Combined species						
Average number of individuals per replicate	1.25	12.50	37.50	43.25	18.50	29.50
Average number of species per replicate	0.75	4.50	6.25	4.75	3.50	6.00

in Treatment 3 and an increase of 46% in Treatment 6. Again, the 3 cut treatments reveal a close similarity in weight/sq m, with the only significant difference being a 64% increase over Treatments 2 and 6 in 1992. The average weight/individual increased in all 3 treatments from 1991 to 1992; then Treatments 2 and 3 declined while Treatment 6 continued to increase. The fact that the 2 cut-and-remove treatments both contained fewer, but larger, individuals indicates that the removal of the fennel litter may allow individuals to become established and mature into healthier plants than the cut-and-leave treatment. Although the cut-and-leave treatment contained more individuals, they were smaller; this may have been an effect of the allelopathic potential of the fennel litter. In Treatment 4, non-fennel biomass increased rapidly and peaked in 1992. In 1993, the number of individuals decreased by 39%. However, both weight/m² and average weight/individual have continued to climb. These results were predictable, in that this treatment opened the system to the invasion of early successional species. As the more successful individuals, primarily nonnative species, have become established, they have grown rapidly and out-competed with other individuals in a bid for dominance. Treatment 5 contained the lowest individual count of the active treatment plots in 1991 and again in 1993. Weight/m² and average weight/individual has, similarly to Treatment 4, continued to grow steadily. Once again, we see competition for a resource space resulting in the dominance of healthy individuals primarily representing a few nonnative species.

Native species

Treatment 1 consistently averaged 0.25 individuals/m² and 1.00 species/m² right through the experimental period (May 1991–May 1993). These results indicate just how effective fennel is at crowding out native species. Possible causes are shading, allelopathy, and greater ability to compete for available moisture with its extensive root system. Treatment 2 contained no native individuals in 1991 and 1992. In 1993, 1.75 native individual/m² and 2.00 species/m² were recorded. Again, the slow recovery of natives in this treatment could be assigned to the allelopathic potential of the fennel litter and bears further investigation. Treatment 3 showed a steady increase of individuals/m², from 0.00 to 3.50 to 5.25 in 1991, 1992, and 1993, respectively. Species/m² increased from 0.00 to 2.00 to 4.00. This treatment shows promising results for the recovery of native species. Although the numbers are small, the trend is consistent. Additional data were collected in October 1993 that confirm this trend (Table 2). Removing the fennel litter may reduce the allelopathic effects of fennel enough to allow natives to gain a foothold. Treatment 6 yielded only 0.25 native individuals/m² on average in 1991 and 1992, and none in 1993. An average of 1.00 species/m² in 1991 and 1992 was recorded in Treatment 6. These results were unexpected considering the results recorded in Treatment 3. However, the poor recovery of native species in this treatment can be explained through observation. The second cutting of this treatment in August removed the only major vegetative cover, fennel regrowth, opening up the treatment to the intensity of summer solar radiation. All 4 replicates in this treatment appeared to be drier and were devoid of perennial species except around the edges where some shading was present from adjacent plots. It appears that this treatment creates too much disturbance to allow regeneration of perennial native species during the spring and summer seasons. Very little competition during the season of maximum growth could account for Treatment 6 having a slightly higher percentage cover of fennel than the other cut treatments. The average number of native individuals in the Treatment 4 increased from 2.50 to 3.75, then plummeted to 0.25 in 1993. The increase and subsequent drop in the number of native individuals is probably reflective of the nonnative species establishing dominance over native species as they competed for the opened system that the dig treatment created. The number of species/m^2 rose from 1.00 in 1991 to 2.00 in 1992, and fell back to 1.00 in 1993. Treatment 5 failed to produce any native individuals in 1991 and 1992. However, in 1992, averages of 1.25 individuals/m^2 were recorded, as were 2.00 species/m^2. These results indicate a similar scenario to the dig treatment. (All species and their abundance are recorded in Tables 1a and 1b).

Diversity

The Shannon/Weiner Index of Diversity was used to determine relative diversity of species among the 6 treatments (Table 3). The control treatment was calculated to have the lowest diversity. Additionally, this treatment recorded the lowest evenness (distribution of species) and lowest richness (number of species present). Treatment 4 returned the highest diversity index owing to the best evenness count and a high nonnative richness. However, the native richness count was very low. Treatment 2 recorded a moderate diversity figure due to poor evenness and only average nonnative richness, but showed good native richness. Treatment 6 showed a slightly better diversity rating than Treatment 2 and the second-highest richness, but the poorest nonnative richness and zero native richness reduce its rating. Treatment 6 produced the lowest diversity index of all the active treatments, due to consistently poor ratings for evenness, nonnative richness, and a native richness of zero. Treatment 3 had the second-best diversity, with good evenness, the highest nonnative richness, and the best native richness.

Discussion

Drastic measures can be taken to reduce fennel biomass on Santa Cruz Island. Digging the fennel out below the crown, and the application of Roundup® are the 2 most effective methods of immediately reducing fennel biomass. But is there an urgency to do so, and what is the goal of fennel management?

If reducing fennel biomass is the only aim of a fennel-management plan, then either of the above methods would be satisfactory, although each has significant drawbacks. Digging the fennel out is possible using a cutting tool dragged behind a tractor that moves along 4–6 in. below the soil surface (Gliessman 1993, pers. comm.). This is by far the most effective way to remove fennel, but it also creates the greatest impact in terms of ecosystem disturbance. Herbicide does not cause as much physical disturbance, but causes serious biological disturbance. (Additionally, repeated applications seem to be required.) The results are the same: any existing native species are destroyed, and the system is opened to the invasion of nonnative species that are more able to compete for disturbed areas. Ripgut brome (*Bromus diandrus*) and yellow star thistle (*Centaurea solstitialis*) are just 2 examples of noxious weeds that are replacing the fennel in the experimental plots under these 2 treatments. The major problem with these treatments is that, under this regime of disturbance, we are encouraging the replacement of 1 invasive, noxious weed with another that may become just as great a problem in the future. Burning fennel, another heavy disturbance method suggested as a possible solution, is not effective in reducing fennel biomass, but actually promotes it. "My conclusions are that performing prescription burns in island vegetation that contains fennel will enhance the colonization and establishment of fennel, and perhaps harm the recovery of native vegetation in the process" (Beatty 1992).

Conversely, we are seeing a more consistent appearance of native species in the low-impact plots where fennel is merely cut and removed or left lying. The numbers are small, but the emerging trends are very encouraging (see Table 2). There are a greater number of both individuals and species showing up in Treatments 2 and 3. The fact that in Treatment 6 fennel is cut twice and the litter removed may be too much disturbance and is affecting native species regeneration. Simply cutting the fennel once in May causes minimal disturbance to the ecosystem while removing the shading effect and reducing seeding potential. Removing the litter reduces the allelopathic potential of the fennel, while regrowth offers some shading, hence soil moisture retention and protection for native seedlings. This plan of action seems to favor the regeneration of native species. Additionally, assistance could be provided in the dispersing of native seeds, since most are wind dispersed and their eventual siting is extremely random.

A multiplicity of factors affects the establishment of vegetation types: soil profile, aspect, history, and rainfall, to name a few. The explosion of fennel on Santa Cruz Island has coincided with not only the removal of livestock from the island, but the ending of a 5-yr drought (Fig. 3). Only 4 yr have passed since livestock were removed from the island and fennel became a nuisance. This is an extremely short time in terms of succession. With the relief of grazing pressure from the grasslands, some of these areas are likely, eventually, to return to chaparral or oak woodland. Both vegetation types exclude fennel (Beatty, 1992). A survey of the floristics of Santa Cruz Island indicates that the area of the Central Valley where the fennel experiment is located may have been an oak woodland before grazing activities began. Some successional activity is already evident by the growth of a few coast live oak (*Quercus agrifolia*) just to the north of the UCSC field station and behind the barn at the Main Ranch (L. Laughrin 1993, pers. comm.). Oaks exclude fennel from the area under the canopy, through a probable alliance of shading and allelopathy. By way of observation, some native species—coyote bush (*Baccharis pilularis*), for example—are able to establish themselves in extremely dense fennel stands and reproduce very successfully.

It appears that fennel was best able to take advantage of the huge change in ecosystem management and weather that occurred in 1989. The question is whether fennel can prevail in the long term as other species recover from the effects of intense grazing and drought. My feeling is that, as on the mainland, the fennel stands on Santa Cruz Island will come under increasing pressure from other species as succession progresses. My hope is that the stands will eventually become limited to areas of prime fennel habitat: roadsides, washes, and drainages. If desired, more intensive control strategies could then be selectively applied.

Recommendations

In managing fennel, any human interference in the system results in conditions that promote native species to succeed fennel. A combination of cutting fennel and a native species enhancement program may prove to be an effective route to fennel management. However, more study needs to be done. The existing experiment has been expanded to include a native species enhancement experiment to evaluate the effectiveness of a seeding program. More research is needed on the allelopathic potential of fennel, and its synergistic potential with other nonnative

Table 3. Diversity index of associated species in the fennel experimental plots on Santa Cruz Island, May 22, 1993. (Note: Higher numbers are more desirable.)

Treatment	Diversity[a]	Evenness[b]	Richness[c] (Nonnative)	Richness (Native)
Control	0.647	0.467	4.00	0.50
Cut	1.076	0.510	8.25	0.50
Cut/Remove	1.187	0.521	9.75	1.00
Dig	1.552	0.690	9.50	0.25
Herbicide	1.038	0.515	7.50	0.00
Cut/Rem × 2	1.092	0.572	6.75	0.00

[a] Shannon/Weiner Index of Diversity [b] Evenness = distribution between species. [c] Richness = number of species present.

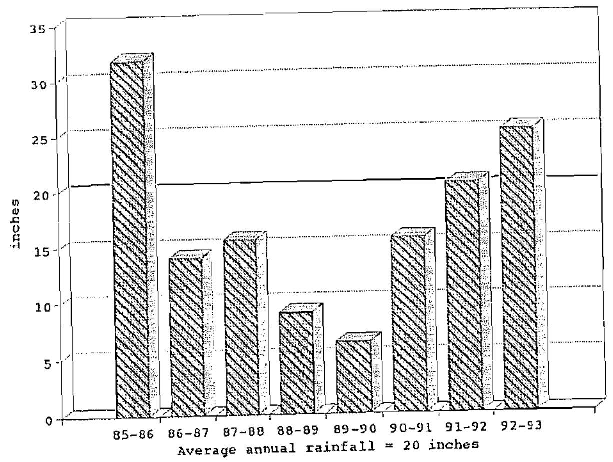

Figure 3. Annual precipitation at Main Ranch, Central Valley, Santa Cruz Island, 1985–1992.

species such as ripgut brome in excluding native species. These investigations should be specifically directed toward collecting data on the inhibitory effects on the germination of native species. Additionally, the inhibitory effects of a fennel mulch on fennel regrowth, as indicated in Treatment 2, bears further investigation. Such an effect may prove to be a useful tool in fennel management.

Conclusion

The key concept is a succession of native species. A fennel-management plan rooted in the promotion of this concept supports the general management plan of Santa Cruz Island, the restoration aims of The Nature Conservancy, and clearly makes sense. It may well be possible to foster native species in the successional march through a native seed enhancement program. However, succession takes time. We must remember that the vegetation on Santa Cruz Island has been ravaged for well over 100 yr by intense grazing pressure. It will take time to recover. We cannot hope to "restore" the vegetation on Santa Cruz Island in the near future, but we can assist in the speeding up of the successional processes. As our research indicates, a successful fennel management plan must be based on a long-term, "low impact" approach—a successional approach.

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Removal of Feral Honey Bee (*Apis mellifera*) Colonies from Santa Cruz Island

Adrian M. Wenner[1] and Robbin W. Thorp[2]

[1]*Department of Biological Sciences, University of California, Santa Barbara, CA 93106*
Tel. (805) 893-2838; Fax (805) 893-8062
[2]*Department of Entomology, University of California, Davis, CA 95616*
Tel. (916) 752-0482; Fax (916) 752-1537

Abstract. Of all 5 northern Channel Islands, only Santa Cruz Island has had European honey bees, introduced by a beekeeper more than 110 yr ago. Feral honey bees spread over the island and apparently have reduced visitation by many of the more than 100 native bee species from much of that ecosystem. We began our feral colony removal project in 1988. During the first 3 yr, we hunted colonies and gathered background data on plant visitation by honey and native bees. Feral colony removal began at the end of the third year. More than 200 colonies have been located, of which more than 150 have been eliminated. Preliminary data indicate that native bees have been rebounding with the release of competition from feral European honey bees. After removal of sheep and cattle, introduced sweet fennel, yellow star-thistle, horehound, and yellow mustard experienced an explosive range expansion, providing a virtually unlimited supply of food for the remaining feral colonies on the eastern half of the island. An anticipated arrival of parasitic mites (*Varroa*) on the island will almost certainly help eradicate the genetically uniform feral host honey bees, with no injury to native bee or wasp fauna.

Keywords: Feral honey bees; *Apis mellifera*; Africanized honey bees; native bees; ecosystem restoration; foraging ranges; nonnative weeds; bee colony distribution; feral animal removal; biological control; *Varroa*; Santa Cruz Island.

Introduction

The introduction of nonnative species often has devastating effects on native plants and animals (Shafer 1990), sometimes causing extinctions (Atkinson 1989; Howarth and Medeiros 1989). The control or elimination of nonnative species is, therefore, essential if one is to restore and retain species diversity (Soulé 1990). Removal of nonnative organisms from parks and preserves is also viewed as a necessary move to preserve a sound ecosystem (Temple 1990). Even Charles Darwin (1859) recognized the apparent impact that nonnatives can have, in his observation that the introduced European honey bee (*Apis mellifera*) was "rapidly exterminating the small stingless native bee" on the Australian subcontinent.

We now enter our seventh year of a phased removal of nonnative European honey bees from Santa Cruz Island (Fig. 1), one-half of the island at a time. The fundamental question we address is "Will removing an introduced insect species change habitat quality for native plants and pollinators and also restore and/or increase species diversity and abundance?" This experiment provides an exceptional opportunity to study the ecological impact of this important nonnative species on the native flora and fauna.

According to species diversity and equilibrium theory (MacArthur and Wilson 1967; reviewed by Shafer 1990), such a large island and/or island complex should not have the remarkably depauperate flora and fauna it now has. Only about 15 species of land vertebrates (excluding birds and bats) have been found on the northern Channel Islands, compared to 10 times that number on the nearby mainland (Wenner and Johnson 1980).

Very likely a similar ratio holds for insects in general; for example, the approximately 100 species of native bees represent only one-tenth of the number found in California as a whole (in a wide spectrum of habitats), with Santa Cruz Island having the richest diversity of islands in the northern chain. Also, entire families of insects commonly found on the nearby mainland have no representatives on the islands.

Depauperate islands such as these can serve as test cases (Shafer 1990). Santa Cruz Island (and nearby islands) thus provides a simpler system than one can find on mainland sites; it has discrete boundaries, known populations of native species, and no possibility of repopulation—in this case by the target nonnative honey bees from proximate islands or from the mainland.