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Modeling the expansion and control of fennel (*Foeniculum vulgare*) on the Channel Islands

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Abstract. Fennel is a perennial herb introduced to Santa Cruz Island from Europe in the late 1800s. It now dominates a substantial proportion of grasslands throughout central and northeastern Santa Cruz Island and is continuing to expand its range. Though it has been on the island for more than 100 yr, the current distribution and abundance did not occur until grazing pressures were removed in the 1980s and a 5-yr drought ended in 1991. A pilot program examining the effects of (1) spraying fennel with different formulation/concentration combinations of the herbicide Garlon®, (2) manual cutting, and (3) seasonal application of herbicide has been underway for 2 yr. Spraying in the wet season has been found to be the most important factor for reducing fennel cover, where reductions of 50–90% were observed. Based on information from several sources, we have developed state-transition models of fennel expansion and control in grassland/coastal scrub and riparian communities. Implications of the models are discussed, especially the need for integrated management programs when fennel or other nonnative plants reach levels where management is no longer an option but a necessity.

Keywords: Fennel; Santa Cruz Island; nonnative plants; restoration; herbicides; state-transition models.

Introduction:

A "weed" has been defined in many ways, and has typically included physical attributes and concerns over economic impacts. Only recently have terms such as "exotic," "alien," and "invasive" been used in definitions of a weed. Indeed, the invasion of nonnative plants into natural communities is now a principal concern for ecologists and land managers (D'Antonio and Vitousek 1993; Smith 1985). Nonnative plants have a great ability to adapt to their surroundings and can rapidly expand their range and begin to dominate some communities. This often results in displacement of native species, alteration of community structure, and change in nutrient cycles (D'Antonio and Vitousek 1993, Loope 1992).

Nonnative plants comprise 19–46% of the vascular plant species on California's Channel Islands (S. Junak, pers. comm.), but their influence extends beyond the number of species (Table 1). As is the case on mainland California, some plant communities on the Channel Islands are now dominated by nonnative plants (grasslands, coastal scrub) (Halvorson 1992). Four different agencies manage the Channel Islands, and the resource management goals of each include preserving and restoring the islands natural communities. An important step in this process includes controlling or eliminating nonnative plants.

Fennel (*Foeniculum vulgare*) is a nonnative species of special concern in the Channel Islands. On Santa Cruz Island it has undergone an unprecedented expansion of its range in the last 3 yr, and now dominates almost 10% of the island's area. This has resulted in a severe decrease in species richness of herbaceous plants, such that European

Table 1. The proportion of nonnative plant species on California's Channel Islands (Steve Junak 1993, pers. comm.).

Island	Nonnative Species (%)
Santa Barbara	25
Anacapa	26
San Miguel	25
San Nicolas	46
San Clemente	30
Santa Catalina	30
Santa Rosa	19
Santa Cruz	24

annual grasses are the only group of herbaceous plants typically found in areas of dense fennel (Beatty 1991). Fennel is continuing to expand its range and increase in density where it already occurs on Santa Cruz Island (Beatty and Licari 1992; Klinger unpublished data). Although it isn't able to successfully invade shrub communities with closed canopies (Beatty and Licari 1992), there is concern about the ecological effects of fennel's expansion on grassland, coastal scrub, and some riparian communities.

In this paper we give an overview of the factors that led to the rapid explosion of fennel, outline ongoing control efforts, and present a conceptual state-transition model, predicting under what conditions a similar explosion of fennel may occur and how vegetation communities can be expected to respond when fennel control programs are implemented.

Factors Leading To Fennel Expansion

Fennel has been present on Santa Cruz Island for more than 100 yr. Prior to 1991, it was present but at low abundance in many grassland areas of the island, but was never considered a dominant component of the vegetation communities except in a few local areas.

We hypothesize that four factors were responsible for the expansion of fennel. Individually, none of the factors was significant enough to cause the expansion, but in combination they were responsible for the tremendous release that began in 1991.

The first factor is that fennel evolved in the Mediterranean region under similar climactic conditions as the coastal areas of California, hence it was "pre-adapted" to the Santa Cruz Island climate. The second factor is that vegetative growth and seed production of fennel peak simultaneously in the mid to late summer when virtually all other herbaceous species have died or ceased growth. This greatly reduces competition for resources from other herbaceous species at a critical time in fennel's life cycle (Beatty and Licari 1992).

We hypothesize that the most important factor contributing to the recent expansion of fennel was the rapid removal of cattle and feral sheep from Santa Cruz. Livestock were probably the primary vectors of fennel dispersal, but as the only large grazers on the island they also held fennel in check. At one time there were at least 50,000 sheep on Santa Cruz, and between 1,000–7,000 cattle at other times. Between 1981 and 1987 The Nature Conservancy eliminated more than 36,000 feral sheep from the western 90% of Santa Cruz, then in 1988 removed the remaining cattle (approximately 1,500 head) over a 6–mo period. There are now no large grazing mammals on the western 90% of the island.

The final factor was proper environmental conditions. Despite its pre-adaptation to the island's environment, competitive ability, and removal of its predators, the expansion of fennel did not occur until 1991 when a 4–5 yr drought ended (Table 1). As rainfall levels increased between 1991–1993, the distribution and cover of fennel increased in grassland and coastal scrub communities (Fig. 1). Present estimates are that fennel is expanding at the edge of its range at the rate of 3.0 m/yr (Beatty and Licari 1992).

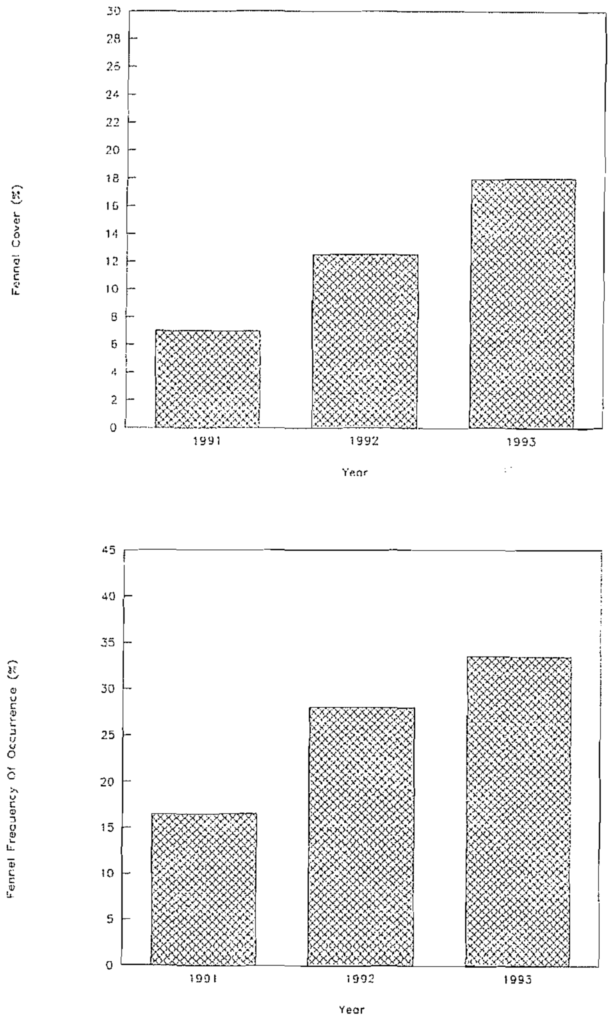

Figure 1. Percent cover and frequency of occurrence (total percent plots occupied) of fennel on Santa Cruz Island, California.

Control Efforts

Two projects are underway studying ways to control and reduce the distribution and abundance of fennel on Santa Cruz. Steve Gliessman and his students are studying the effects of different removal methods and will report their findings in this symposium. Since the spring of 1991, we have experimented with the herbicide Triclopyr (Garlon4®) as a chemical method of fennel control. We have tested 7 different herbicide formulation/concentration combinations (amine and ester formulations, 3.3, 4.5,

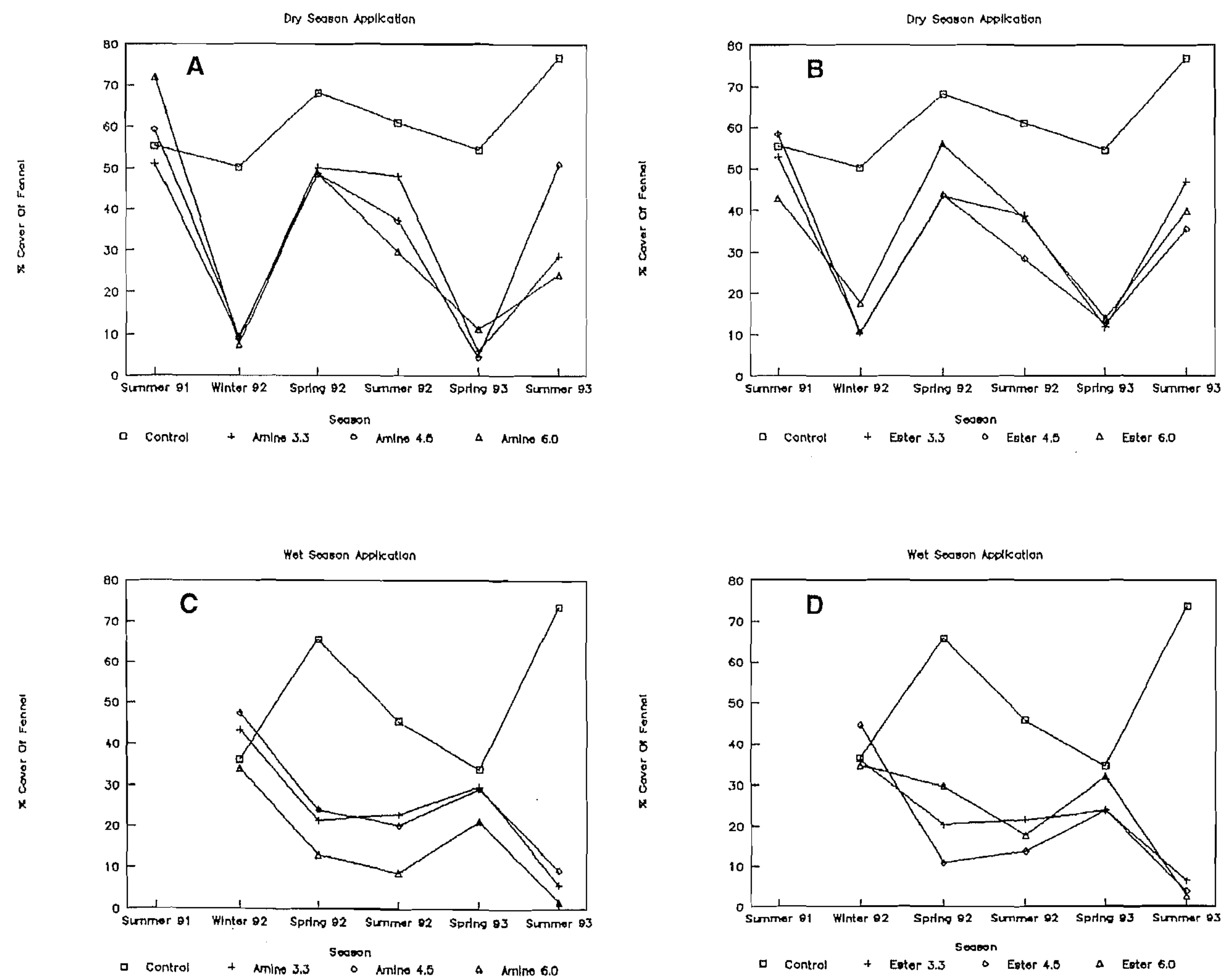

Figure 2. Changes in percent cover of fennel as a result of treatment with different formulation/concentration combinations of the herbicide Garlon® on Santa Cruz Island, California. Herbicide applications were done in the summers of 1991 and 1992 (Dry Season) and the winters of 1992 and 1993 (Wet Season).

and 6.0 lbs/100 gallons equivalent concentrations, plus unsprayed controls), 2 different seasons of application (wet and dry seasons), and cut/uncut conditions in a randomized block design (Brenton and Klinger, unpubl. data). Plots for each individual treatment combination were sprayed twice at approximately a 1-yr interval.

We found that Garlon4® is effective at reducing fennel cover, but that certain treatment combinations are significantly more effective than others. Fennel cover was reduced as much as 95% in some sprayed plots, but cover in plots treated during the dry season recovered and tended to approach that of the controls within a year after herbicide application (Figs. 2a, 2b), while cover in plots treated during the wet season did not. Cover in plots treated during the wet season continued to decrease after the second application (Figs. 2c, 2d), while cover in plots treated during the dry season was increasing. Cutting did not significantly increase the effectiveness of the herbicide, and the only difference between the different formulation/rate combinations was that the high concentration of amine reduced the fennel cover significantly more than the other combinations (Fig. 3). As fennel cover decreased, grass cover increased (Fig. 4), but the ratios of nonnative cover:native cover and nonnative species richness:native species richness did not change (Fig. 5).

Modeling Fennel Expansion And Control

Livestock grazing is probably the most important factor controlling fennel, especially by cattle (Beatty and Licari 1992). Cattle, goats, deer, and elk occur on Santa Rosa and/or Santa Catalina Islands, and there is a good possibility that fennel on these islands will undergo an expansion similar to the one on Santa Cruz when the grazers are removed.

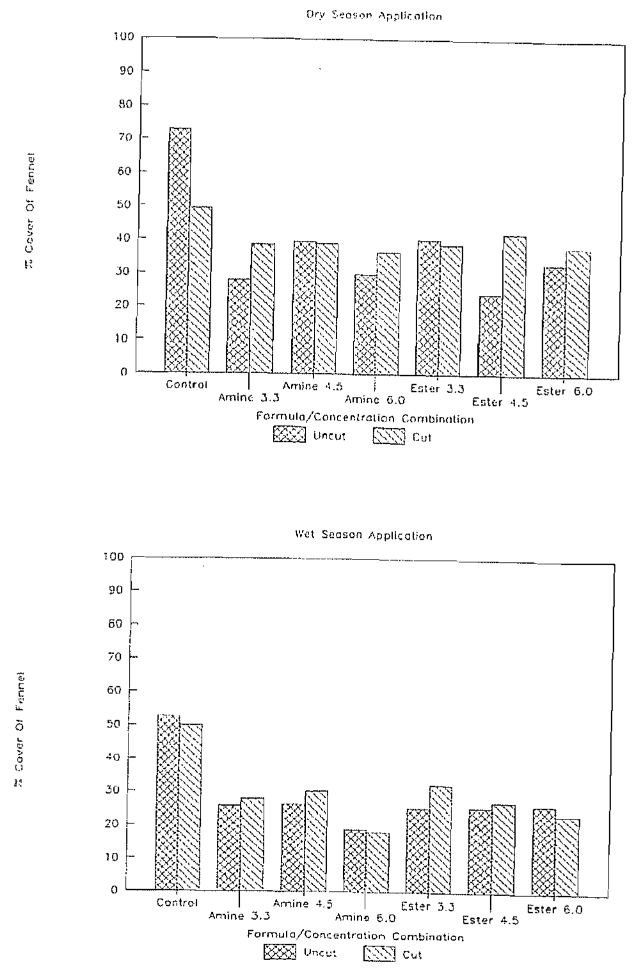

Figure 3. Percent cover of fennel in cut/uncut and different formulation/concentration combinations of the herbicide Garlon® on Santa Cruz Island, California. Herbicide applications were done in the summers of 1991 and 1992 (Dry Season) and the winters of 1992 and 1993 (Wet Season).

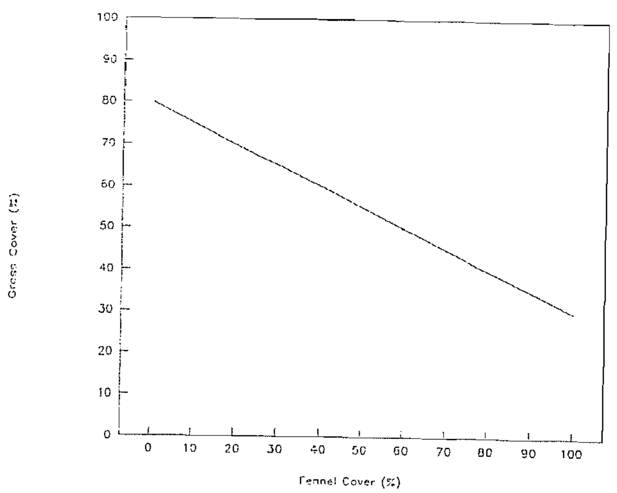

Figure 4. Correlation between the percent cover of annual grass with increasing cover of fennel on Santa Cruz Island, California, 1991–1993.

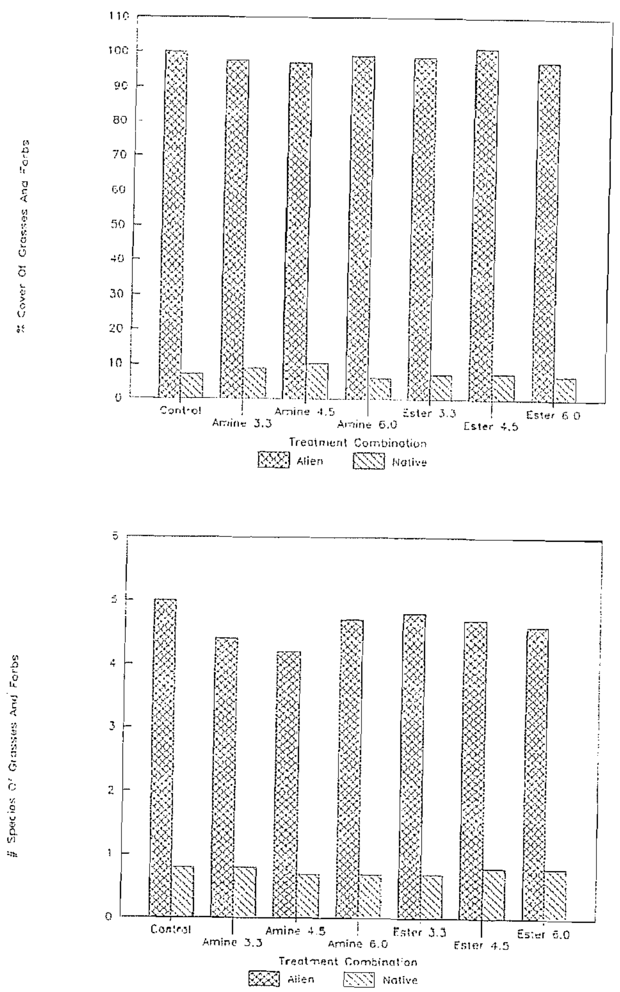

Figure 5. Percent cover and number of species of native and nonnative herbaceous species in experimental fennel control plots on Santa Cruz Island, California, 1991–1993.

We have designed a state-transition model (Westoby et al. 1989) to predict how different land use and environmental factors interact to affect the establishment, distribution, and abundance of fennel. Traditional successional models tend to assume a single persistent climax state. They tend to distort successional patterns by assuming alternative states don't exist or are transitory, or are so detailed that many of the aspects of succession that they try to represent become incomprehensible. The models can be tested but are difficult to modify since they assume only one state (Westoby et al. 1989). The advantages of state-transition models are that a set of specific "states" exist, and different transitions between the states occur as a result of natural processes (fire, succession, flooding, etc.) or land management actions. The states can vary in their persistence times, while transitions can be rapid or slow. The states and transitions summarize and abstract dynamic processes in a relatively understandable manner, and can be tested and modified as more information is accumulated.

We developed 2 models, one for grassland/coastal scrub communities and another for riparian communities. The models include 3 fundamental assumptions:

1. They are representative of Mediterranean climates. Although rainfall amounts vary from year to year, there is no evidence that the seasonal pattern of wet winters and dry summers typical of coastal Southern California has changed over the last centuries, so this assumption seems reasonable.
2. Communities where fennel presently occurs approximate the same vegetation structure that existed prior to fennel introduction. This assumption is most likely valid for riparian and coastal scrub communities, but it is difficult to evaluate for grasslands. There is reason to believe that coastal scrub has been reduced by grazers and probably converted to a grassland type (Brumbaugh 1980), but at this time there is only cursory evidence of the extent or location where this occurred. It is likely that there is more grassland on the Channel Islands now than 100–150 yr ago, but the successional patterns and species composition have been well established for at least a century, so the assumption is probably reasonable for grasslands.
3. Grazing mammals are the only significant predators of fennel. Although anise swallow-tailed butterflies occur on the islands, they are not abundant or dependent enough in their life history requirements to significantly affect fennel (A. Wenner 1992, pers. comm.). Information about insects on the Channel Islands is incomplete, but at present we have no reason to believe that significant insect predators on fennel exist.

Grassland/Coastal Scrub Model

The model for grassland/coastal scrub communities consists of 7 states and 7 transitions (Fig. 6). The fundamental states are a dynamic equilibrium between grassland (State 1-S1) and coastal scrub (State 2-S2) communities (Transition 1—no disturbance from grazing). This equilibrium is thought to be representative of the Channel Islands prior to European settlement and the introduction of livestock, fennel, and other European species. Both communities would have been composed of native shrubs and herbaceous species (*Artemisia californica*, *Rhus* sp., *Aristida* sp., *Stipa* sp., *Escholzia californica, Lotus* sp., *Lupinus* sp. *Trifolium* sp., *Sanicula arguta*). This transition (T1) is a result of natural successional and environmental processes.

Transitions 2 and 3 (T2 and T3) are characterized by grazing, but differ in the intensity of the grazing. Transition 2 represents moderate grazing and the conversion of S1 and S2 to States 3 or 4 (S3, S4). In S3 and S4 there is still significant amounts of herbaceous and shrub cover. The shrubs are comprised mainly of native species, but total cover and height is reduced from that in S1 or S2. The herbaceous species composition is dominated by nonnative grasses and forbs (*Erodium* sp., *Silene gallica, Hypochoeris glabra, Bromus* sp., *Hordeum* sp., *Avena* sp., *Vulpia* sp., *Lamarkia aurea, Brassica* sp., *Centaurea* sp.). It is possible that T2 could lead directly to State 6 (S6), but grazing pressure would have to be low and environmental conditions optimal for fennel establishment for an extended period of time. We do not have any evidence that this occurred and consider the possibility remote.

Transition 3 (T3) represents intense levels of grazing and leads directly to State 5 (S5). There is at least as much bare ground as vegetative cover, some populations of native species have been driven to local extinction, and what herbaceous cover exists is dominated by nonnative species. This state is typical of parts of several of the Channel Islands (Santa Rosa, Santa Catalina, San Clemente, east Santa Cruz).

Transition 4 (T4) represents the removal of grazing from S3 and S5 areas, and leads to conditions that enable fennel to rapidly increase in density and expand its range to a State 6 (S6) or State 7 (S7) condition. S3 areas will be converted directly to S6 and S4 to S7, but S5 areas will pass through a condition resembling S3.

Transitions 5–7 (T5, T6, T7) are hypothetical and intermediate and involve management actions whose ultimate goal is eliminating or controlling fennel. Transition 5 involves cultural methods of control, such as fire, mowing, and digging. If these activities are applied consistently over a number of years, it may be possible to convert S6 and S7 areas back to S1 or S2 conditions. Structurally, these S1 and S2 conditions would closely resemble the pre-grazing states, except that nonnative herbaceous species would be a significant but not necessarily dominant part of the flora. However, if cultural methods alone are used, it is unlikely that the reduction in fennel would be permanent (fire), or they would be so labor intensive that it would not be practical to do them on a large scale (digging, mowing).

Using herbicides in conjunction with cultural methods (T6) presents an opportunity to reduce or eliminate fennel over large areas. S6 areas may be converted to S3 conditions, and with continued application these could be converted to S1 conditions. To be cost effective though, herbicide application need to be done over relatively large areas. It will also be necessary to use herbicides only in areas where rare or desirable species are not at risk from herbicide action. For example, if herbicides were broadcast sprayed over large areas of an S7 condition, there would probably be substantial enough kill of shrubs that these areas would effectively be converted to a S3 condition.

Although no organisms are known which could be used, biological control (T7) would probably be the most selective, cost efficient, and effective method of fennel control. If one were found, the transition to S1 or S2

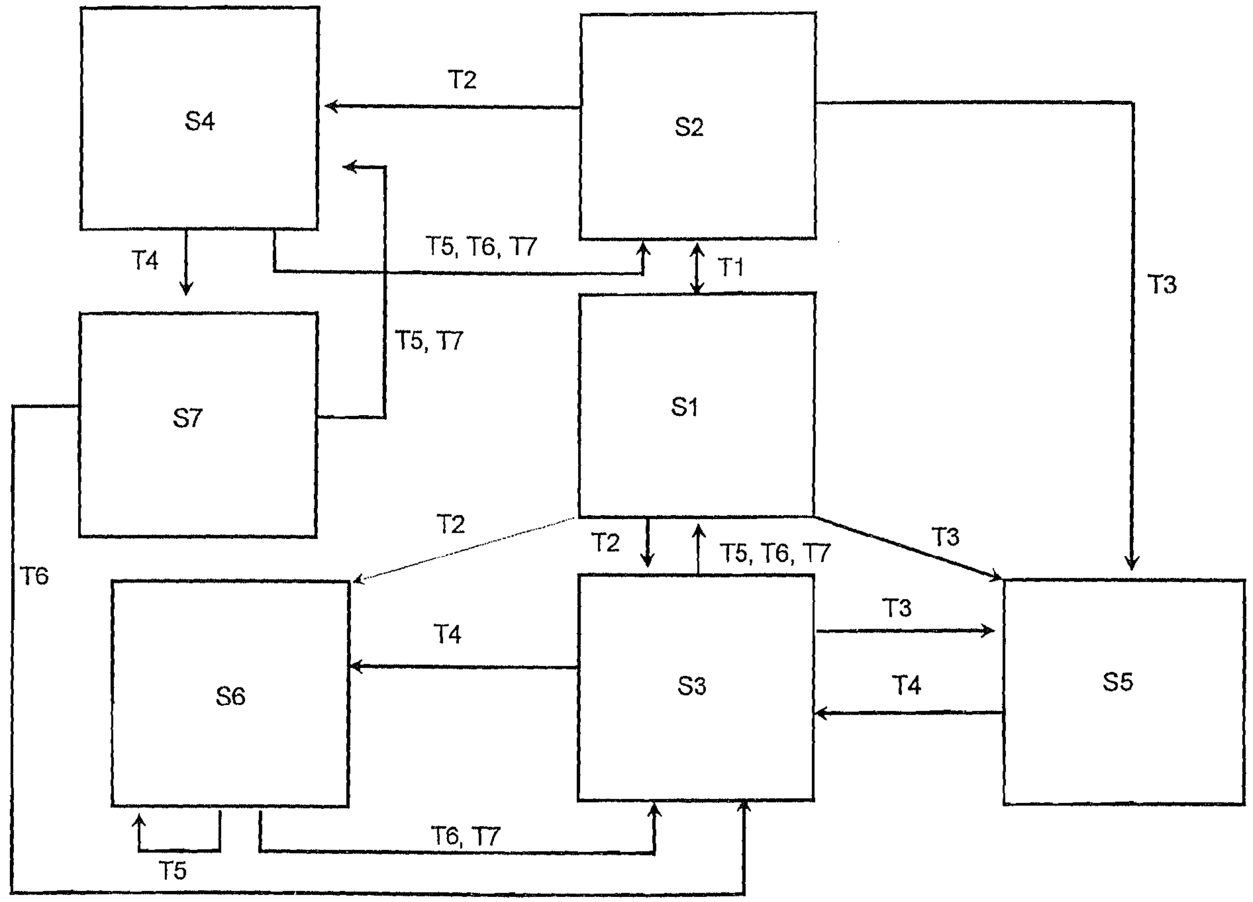

Figure 6. State-Transition model for grassland and coastal scrub communities in relation to fennel invasion on Santa Cruz Island, California. **S1:** State 1. Grassland community with mixture of native grasses and forbs. Fennel is not present. After conversion back from State 3 (S3), species composition is a mixture of native and nonnative grasses and forbs, but fennel is not present. **S2:** State 2. Coastal scrub community dominated by native shrubs, grasses, and forbs. Fennel is not present. **S3:** State 3. Grassland community dominated by nonnative grasses and forbs. Fennel is present, but is not a dominant part of the community composition or structure. **S4:** State 4. Coastal scrub community dominated by native shrubs and nonnative grasses and forbs. Fennel is present but is not a dominant part of the community composition and structure. **S5:** State 5. Heavily overgrazed community where bare ground and vegetation litter are the dominant features of the landscape. Species composition is a mixture of native and nonnative grasses and forbs, some shrubs, and fennel may be present but is not a dominant part of the community composition or structure. **S6:** State 6. Altered grassland community where fennel is the dominant species in terms of species composition and structure. Other herbaceous species consist almost entirely of nonnative grasses. **S7:** State 7. Coastal scrub community dominated by approximately equal amounts of native shrubs and fennel. Herbaceous species are mainly nonnative grasses and forbs. **T1:** Transition 1. No grazing. Successional pattern is a dynamic equilibrium between grassland and coastal scrub determined by natural processes (fire, weather changes). **T2:** Transition 2. Light to moderate levels of grazing. **T3:** Transition 3. Heavy grazing. **T4:** Transition 4. Grazers removed without further management. **T5:** Transition 5. Removal of fennel by cultural methods (cutting, plowing, burning). **T6:** Transition 6. Removal of fennel with herbicides or a combination of cultural methods and herbicides. **T7:** Transition 7. Biological control of fennel.

would be the same as T6 → S1 or T5 → S2. The most significant advantage of biological control is that it can be used in areas where herbicides cannot.

Riparian Model

The riparian model consists of 3 states and 4 transitions (Fig. 7). The fundamental difference between this model and the one for grassland/coastal scrub is that grazing can influence the system directly or indirectly. In the grassland/coastal scrub model, grazing animals were directly responsible for the establishment of fennel, but grazing is not necessary for fennel establishment in the riparian model. Grazers may be fenced out of riparian areas, but fennel seeds can be transported from adjacent communities by other animals, wind, or water. The fundamental step is the reduction of canopy cover in Transition 1 (T1), so that a closed canopy riparian area (State 1-S1) dominated by cottonwoods (*Populus* spp.), willows (*Salix* spp.) and oaks (*Quercus* spp.) is opened up and allows invasive species to become established. T1 could be driven

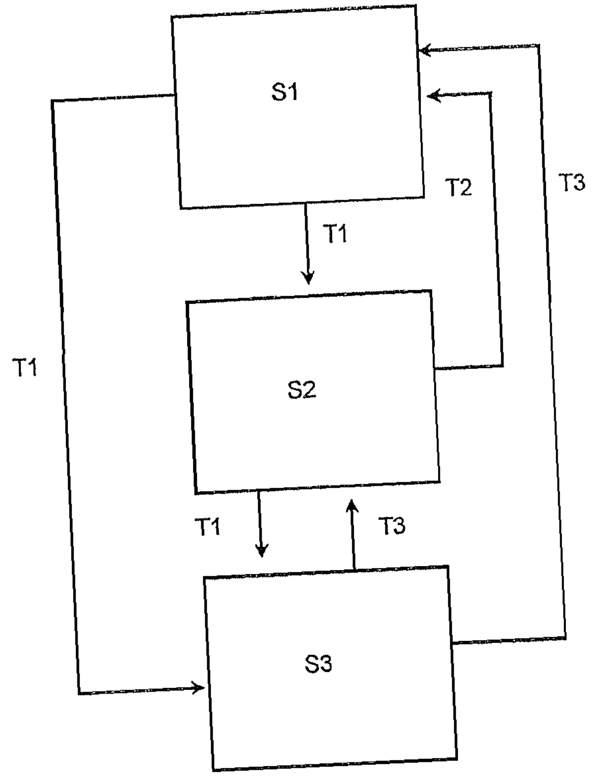

Figure 7. State-Transition model for riparian communities in relation to fennel invasion on Santa Cruz Island, California. **S1:** State 1. Closed-canopy community consisting predominantly of live oaks, cottonwoods, and willows with patches of mulefat and coyote brush in the understory. Fennel is not present. **S2:** State 2. Open-canopy community consisting of mulefat and coyote brush that forms a continuous shrub layer. Fennel is present but not abundant and is patchily distributed. **S3:** State 3. Open-canopy community consisting of discontinuous patches of mulefat and coyote brush. Fennel is abundant and distributed among and within the patches of mulefat and coyote brush. **T1:** Transition 1. Canopy is opened by natural processes (fire, flooding, local environmental conditions, disease) or grazers. **T2:** Transition 2. No natural disturbance over a relatively long period of time or grazing is removed. **T3:** Transition 3. Fennel control actions are implemented, including cutting, chemical, fire, or biological methods, or a combination of the methods.

by natural processes such as disease, fire, and flooding, or by grazing.

State 2 (S2) is an open canopy riparian area but has a continuous vegetation structure dominated by mulefat (*Baccharis glutinosa*), coyote brush (*Baccharis pilularis*), and willows. It is a naturally occurring riparian type, but it could also be converted from S1 under a T1 process. Fennel may be present, but at low densities and cannot become established because of the continuous nature of the vegetation cover.

State 3 (S3) is a riparian area with an open canopy, in which the vegetation is patchy and allows fennel to become established around the edges and within the patches themselves. S3 can either occur naturally or result from a T1 process and can come from either an S1 or S2 condition.

Transition 2 (T2) is hypothetical and driven by the absence of disturbance, and it allows S2 areas to convert back to S1 conditions. S3 areas will not revert to S1 or S2 conditions in the absence of disturbance because when fennel is present it inhibits the establishment and growth of native riparian species. Transition 4 (T4) is driven by management processes employing cutting, digging, spot herbicide application, biological control, or any combination of the above methods. Because of the interspersion of fennel with native species, control methods will be labor-intensive, applied in relatively small local areas, and will need to be carried out consistently over a number of years.

Discussion

The main concern of any habitat restoration program is the effect of the program on the ecosystem, and nonnative plant management must be conducted within this ecosystem context. Although the primary focus of most nonnative plant control programs will be a single species, the removal of the species will have at least as profound an influence on the system as the original invasion of the species did. Therefore, in virtually all nonnative plant management programs, 3 fundamental processes should be studied:

1. The reasons underlying the successful establishment of the nonnative species;
2. The effects of the nonnative species on the communities in which it occurs;
3. The probable effects of removing the nonnative species on the communities it has invaded.

Determining answers to what will happen when the nonnative species is removed is the most important of the 3 processes for long-term planning and management programs. In many cases, it will not be known exactly how a community will respond to the removal of a nonnative, so it will be best to start with small-scale experiments and then increase the scale as information is collected. This increases the efficiency of management programs and reduces the likelihood of pushing the system in an undesirable direction.

Our preliminary field experiments indicate that Garlon4® effectively controlled fennel, and although we have not enhanced the habitat for native herbaceous species we have no evidence indicating that they have been harmed by herbicide use. Narrow spectrum herbicides can be an important part of an integrated nonnative plant management program as they allow for the control of certain species and the release of others. We wanted to release grasses so that they would inhibit future germination by fennel and to stabilize the soil to prevent erosion. Because broadleaves are often the first plants to reinhabit an area (Aldrich 1985), fennel probably would have reinvaded the test sites if we had simply used mechanical control 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

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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 graz-