EXOTIC PESTS and DISEASES

Biology and Economics for BIOSECURITY

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Risk Assessment of Plant-Parasitic Nematodes

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Introduction

In this chapter, we consider plant-parasitic nematodes as exotic pests and as representatives of other exotic soilborne pests and diseases. The species in this study are selected for current policy and trade barrier implications and for biological significance.

The process of invasion of an exotic nematode species has four phases: arrival, establishment, integration, and spread. Arrival is the introduction of a new population into a community of established species, typically by some factor other than individual locomotion. Associations of plant-parasitic nematodes with imported agricultural commodities suggest that the probability of arrival is high. The fact that nematodes are small, spatially aggregated, and difficult to identify increases the probability of their arrival. Establishment occurs when the newly arrived species maintains a population through local reproduction, not continuous immigration. Nematode species with a broader geographic range are more likely to become established once they have been introduced. However, the introduced species may not reach economically damaging levels; that depends on conditions at the invasion site. Integration may require ecological and evolutionary changes in both the invading population and the resident community. Integration is not a rapid process; it may proceed over a long period. Spread is the movement and redistribution of a species by active or passive means. Active dispersal of plant-parasitic nematodes through locomotion is most important at the scale of individual fields. Passive means of movement, including wind, water, contaminated equipment, or transportation of infested commodities, are important at the field, regional, and national scales.

Understanding of the phases of invasion allows assessment of the threat that exotic plant-parasitic nematodes might pose to California agriculture. The fact that a nematode species is a serious pest elsewhere does not mean that it would be equally damaging in California. The challenge is to determine the probability that the nematodes could arrive, become established, and cause significant economic, ecological, or societal damage. These risks must be weighed against the cost, and probability of success, of intervention.

All the nematode representatives selected are A-rated pests and either do not occur in California or have established limited infestations. They represent different life history strategies, host ranges, and modes of dispersal. The question is not whether these A-rated nematodes will be introduced into the state, but whether they can be eradicated, contained, or will become established after introduction.

Despite quarantine and containment programs, plant-feeding nematodes spread to new countries and new locations. Many important exotic nematode pests play major roles in California agriculture and urban landscapes. Introduced nematodes of economic importance include the dagger nematode (*Xiphinema index*), the sugarbeet-cyst nematode (*Heterodera schachtii*), and the citrus nematode (*Tylenchulus semipenetrans*). They were probably introduced and spread with planting material or equipment. Most seem distributed with their primary agricultural hosts and are not prevalent or even present in natural habitats (although we have not surveyed exhaustively).

The representative nematode exotic pests considered in this chapter, with rationale for their selection, follow.

Burrowing nematode (*Radopholus similis*), Thorne, 1949: The burrowing nematode is a migratory endoparasite of roots of over 200 woody and herbaceous perennials, including important commercial crops such as citrus. All life stages are readily transported within plant tissues and associated soil. Due to its wide host range, it is one of the most economically important plant-parasitic nematodes in tropical and subtropical regions of the world. Burrowing nematodes have been found in soil and plant materials destined for California during border inspections, and an eradication program was completed for an isolated urban infestation in 1996. The establishment of burrowing nematodes would result in quarantines by importing countries.

Reniform nematode (*Rotylenchulus reniformis*), Linford and Oliviera, 1940: The reniform nematode is a sedentary semiendoparasite in the adult female stage of over 200 tropical plants, including commercial crops such as cotton, grapes, and citrus. It is readily transported in roots and associated soil. In 1960, reniform nematodes were eradicated from an isolated San Diego infestation after a quarantine shipment of ornamental date palms tested positive. Due to the widespread establishment of reniform nematodes, importing countries would not impose quarantines.

Rice foliar nematode (*Aphelenchoides besseyi*), Christie, 1942: The rice foliar nematode is a migratory endoparasite of leaf tissue and also feeds ectoparasitically in buds and seed coats. It tolerates desiccation and is readily transported with unhulled grain. Feeding by the nematode causes white tip disease of rice. The rice foliar nematode has been detected in rice destined for export from California in recent surveys. Unmilled rice would be subject to quarantines by importing countries.

Sting nematode (*Belonolaimus longicaudatus*) Rau, 1958: The sting nematode is a migratory ectoparasite of roots of a large number of plants. It has rather specific environmental requirements. It feeds on turf grasses in sandy soil and high-value commercial crops including cotton. The sting nematode is established in several golf courses in southern California, and an internal quarantine has been imposed to minimize the probability of its spread.

Golden nematode (*Globodera rostochiensis*), Behrens, 1975: The golden nematode is a sedentary semiendoparasite with restricted host range. Its eggs are contained and protected in a hardened cyst and may survive for up to 30 years (Spears 1968; Winslow and Willis 1972). The golden nematode, *G. rostochiensis*, and the related species, *Globodera pallida* (collectively known as potato cyst nematodes), are among the most important pests of potatoes due to the severity of damage and their survival in the absence of a host (Golden and Ellington 1972). The golden nematode is also a pest of other important California commercial crops, including tomatoes. The golden nematode has never been detected in California. Should it enter, it is unlikely that it can be eradicated. If it becomes established, the U.S. Department of Agriculture (USDA) quarantine against infested regions would be extended to California.

Biology and Ecology

Four out of every five multicellular animals on the planet are nematodes (Platt 1994). They exist in almost every conceivable habitat and have a wide range of feeding habits and food sources. They include bacterivores, fungivores, carnivores, omnivores, and plant feeders. Herein we focus primarily on plant feeders of importance as pests in agriculture.

Most, perhaps all, higher plants support the feeding of a range of nematode species. Usually several species can be found feeding on the roots of a single plant. They feed on the outside of plants as ectoparasites of roots or of bud tissues, or within tissues as endoparasites of roots, stems, leaves, or seeds. In some cases, they remain migratory throughout the life cycle; in other cases they become sedentary in some life stages. The diversity of their life history, host ranges, and survival strategies contributes to the difficulty of eliminating them once established.

Burrowing Nematode

The burrowing nematode is found worldwide in tropical and subtropical regions. It occurs wherever bananas are grown, including Africa, parts of Asia, South America, and southern Europe. It also occurs in the southeastern United States and Hawaii (Ferris and Caswell-Chen 1997).

There are more than 350 known hosts of the burrowing nematode. Most banana and plantain cultivars are attacked. Other hosts include citrus, coconut, ginger, palm, avocado, coffee, black pepper, sugarcane, tea, vegetables, ornamentals, trees, grasses, and weeds.

Burrowing nematodes cause spreading decline in citrus. Symptoms usually appear about a year after infection. Infected trees have sparse foliage, retarded terminal growth, poor color, twig dieback, and a general unthriftiness (Christie 1957; DuCharme 1954). Leaves may wilt at midday, but show temporary rejuvenation with rain or irrigation. There may be little new growth during the spring flush. Trees may bloom profusely, but bear only a few small fruit. Trees will appear undernourished without exhibiting specific symptoms of malnutrition. Below ground, dark lesions appear at the site of nematode penetration; the lesions coalesce to form a canker.

In Florida burrowing nematode infestations result in citrus yield losses of 50 to 80 percent for grapefruit and 40 to 70 percent for oranges (DuCharme 1968). Grapefruit trees appear to be more adversely affected than orange trees.

Avocado trees show similar spreading decline symptoms when infested with the burrowing nematode. The nematode can also decimate production of several indoor decorative plant species. It is a severe pest of the parlor palm and may preclude commercial production.

The burrowing nematode feeds in all life stages after hatching from the egg and is able to complete its life cycle within the root cortex. The nematode is also present in rhizosphere soil. Reproduction is sexual but parthenogenesis, the production of viable eggs without fertilization, must be possible because a population can be initiated from a single egg (Orton Williams and Siddiqi 1973).

Reniform Nematode

The reniform nematode is widely distributed in many tropical and subtropical regions of the world. It has been reported in most of Africa, the Caribbean, Japan, the Middle East, South Pacific, Central America, Italy, Spain, Mexico, China, and the Far East. Within the United States, the reniform nematode is established in Alabama, Arkansas, Florida, Georgia, Hawaii, Louisiana, Mississippi, North Carolina, South Carolina, and Texas.

Over 140 plant species in 115 genera representing 46 families are attacked by this nematode (Jatala 1991). Some of the economically important host plants are banana, cabbage, cantaloupe, cassava, citrus, kale, lettuce, mango, okra, pigeon pea, pineapple, sugarcane, pumpkin, coconut, cotton, radish, cowpea, soybean, sweet potato, crimson clover, tobacco, eggplant, tomato, and guava.

Above-ground effects on host plants include dwarfing, shedding of leaves, malformations of fruit and seeds, and general symptoms of an impaired root system. Below ground, roots are discolored and necrotic with areas of decay. Plant death is possible in heavy infestations.

Reproduction and development of the reniform nematode are favored by fine-textured soils with a relatively high content of silt or clay (Koenning et al. 1996; Robinson et al. 1987). The reniform nematode reproduces sexually; however, it may also reproduce by parthenogenesis. Juveniles develop through three molts to the preadult stage without feeding. All juvenile stages and males are found in the soil. Soon after the final molt, the young adult infective stage penetrates host roots and the anterior part of the body becomes embedded within root tissue.

Rice Foliar Nematode

The rice foliar nematode occurs in most rice-growing areas of the world, including Australia, Sri Lanka, Comoro Islands, Cuba, El Salvador, Hungary, Indonesia, Italy, Japan, Madagascar, Mexico, Pakistan, the Philippines, Taiwan, Thailand, the former Soviet Union, and Central and West Africa (Bridge et al. 1990; Ou 1985). It has been reported in the southern U.S. states that produce rice.

Rice is the most important host worldwide for this nematode. The white tip disease caused by the nematode is characterized by whitening of the leaf tips, which later become brownish and tattered. The upper leaves are the most affected; the flag leaf is often twisted, hindering the emergence of the panicle. In the seedbed, emergence of severely infected seedlings is delayed, and germination is low. The most conspicuous symptoms occur early in development. Diseased plants are stunted, lack vigor, There are more than 350 known hosts of the burrowing nematode. Most banana and plantain cultivars are attacked. Other hosts include citrus, coconut, ginger, palm, avocado, coffee, black pepper, sugarcane, tea, vegetables, ornamentals, trees, grasses, and weeds.

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On strawberry, the rice foliar nematode is the causal agent of "summer dwarf" or "crimp" in the United States and Australia. Other host plants include onion, garlic, sweet corn, sweet potato, soybean, Chinese cabbage, sugar cane, horseradish, lettuce, millet, many grasses, orchids, and many ornamental plants (Franklin and Siddiqi 1972; Ferris and Caswell-Chen 1997).

Nematodes become dormant under seed hulls at the end of the growing season (Taylor 1969). They become active and are attracted to the actively growing parts of the plant after infested seed is planted. During early growth, rice foliar nematodes are found in low numbers within folded leaf sheaths, feeding ectoparasitically around the growing point (Todd and Atkins 1958). Although reproduction of this nematode is predominantly sexual, parthenogenesis has been reported (Sudakova and Stoyakov 1967).

Sting Nematode

The sting nematode has been reported from the Bahamas, Bermuda, Brazil, Costa Rica, Mexico, Australia and Puerto Rico. In the United States, the nematode occurs in Florida, South Carolina, North Carolina, Virginia, Alabama, California, Mississippi, Louisiana, Texas, Arkansas, Kansas, Oklahoma, New Jersey, and Nebraska.

Sting nematodes are the most destructive nematodes in turf grass ecosystems in Florida (Busey et al. 1991). In addition to turf and other grasses, these nematodes have a wide host range that includes grapes, citrus, cantaloupes, lettuce, tomatoes, beans, onions, corn, wheat, barley, oats, forage crops, cotton, ornamentals and weeds. Based on differences in host reactions and fitness, there may be several physiological races of sting nematodes (Abu-Gharbieh and Perry 1970; Robbins and Barker 1973).

Affected plants appear stunted, yellow, and exhibit drought and malnutrition symptoms. They fail to respond to water and nutrients. Badly affected plants collapse and die. Small patches (up to several feet in diameter) of diseased turf can be noticed at a distance. Belowground symptoms include a reduced root system with stubby, coarse roots. Above ground, shoots may show stunting, premature wilting, yellowing, and, in some cases, infested plants may die. In fields, the boundary between infested and healthy plants is well-defined.

Soil texture and composition have been identified as major limiting factors for sting nematode reproduction (Perry and Rhoades 1982). The distribution of the nematode is restricted to sandy soils; in Virginia, Miller (1972) found it only in soils with 84 to 94 percent sand. Reproduction and movement are inhibited in heavier, fine-textured soils. Males are required for reproduction, but only one mating is sufficient for sustained egg fertilization (Huang and Becker 1999).

Golden Nematode

The golden nematode was originally discovered in Germany in 1913. By that time, it had spread throughout Europe (Wallace 1964). It probably originates with the potato in South America. During the 1960s and 1970s, Canada was found to have several areas of golden nematode infestation (Mai 1977). Vancouver Island is the area closest to California where the golden nematode is known to be established. In the early 1970s, scientists in Mexico discovered an infestation of golden nematodes in the state of Guanajuato, one of the major potato-producing regions in Mexico (Alvarez 1972). In North America, it was first discovered on Long Island, New York (Nassau County), in 1941 after a potato grower noticed isolated areas of poor plant growth (Mai and Lear 1953).

Approximately 90 species in the family *Solanaceae* are known to be hosts, including potato, tomato, and eggplant (Mai and Lear 1953). In addition, there are numerous weed hosts (Goodey and Franklin 1958, 1959). Of the weed hosts, bitter nightshade, silverleaf nightshade, hairy nightshade, black nightshade, and jimsonweed are all present in California. Hosts are not equally susceptible, and cultivars may differ in their susceptibility to various races of the nematode (Kort et al. 1977).

No distinct host symptoms are associated with low populations, but as populations increase, symptoms appear. A potato crop will show poor growth in small areas that enlarge with continuous cropping. Plants in infested patches exhibit symptoms of water and mineral deficiency, including chlorotic leaves and wilting. The bodies of immature females that have erupted through the root epidermis appear as minute, white specks on the roots. At extremely high nematode densities, tubers may become infected.

Survival, reproduction, and population dynamics of the golden nematode can be greatly influenced by temperature, moisture, day length, and soil factors. In general, golden nematodes will survive in any environment where potatoes can be grown. Eggs remain dormant within the dead female's body (the cyst) until stimulated to hatch by chemical stimuli from host plant roots. The nematode eggs can remain dormant and viable within the cyst for up to 30 years (Winslow and Willis 1972). While dormant in the egg stage, the golden nematode is more resistant to nematicides (Spears 1968).

When soil temperatures are above 10°C and the proper hatching signals are received, second-stage juveniles hatch from the eggs, escape from the cyst, and migrate toward host plant roots (Clark and Hennessy 1984; Ferris 1957). Juveniles penetrate the roots, establish a feeding site, and begin to feed. Those that develop into females become rounded, break through the epidermis, and are exposed on the root surface. Male nematodes develop similarly, but in the final juvenile stage they emerge as a motile worm that leaves the root and is attracted by chemical signals from females (Green et al. 1970). After mating, each female produces approximately 500 eggs, which are retained in the body (Stone 1973). After the female dies, the body cuticle forms a protective cyst.

Introduction and Spread

Factors Influencing the Introduction and Spread of Nematodes

Nematodes are generally excellent invaders of new habitats. They have evolved numerous strategies for exploiting favorable environments and withstanding harsh conditions. Their small size and the difficulty of detecting them in plant and soil material increase the probability that they will be successfully introduced. The feeding relationships of plant-feeding nematodes with host tissues and their survival capabilities contribute to the ease with which they are disseminated with plants. Once introduced, the generally nonspecific nature of symptoms increases the probability that their presence may go undetected or unrecognized for considerable periods. Their dispersal in and around plant tissues and throughout the soil contributes to the difficulty of targeting them in management or eradication programs.

The most important determinant of rate of spread in agriculture is the movement of infested plants and propagative material. Especially important is material that will be propagated and distributed as nursery stock. Sale and movement of infested nursery stock, seed, or turf immediately spreads the nematode pest to uninfested areas and distributes it throughout the planting site. Depending on the area serviced by a nursery, spread from an infested source may be local, statewide, or even across state boundaries.

Significant movement of nematodes is also generated by natural and human forces. Nematodes with stages that are resistant to desiccation, such as the reniform and rice foliar nematodes, may be spread widely and for long distances in blowing dust. Wind spread of cysts of the oat cyst nematode (*Heterodera avenae*) across desert regions between cereal production areas has been detected in Australia (Meagher 1977; Viglierchio 1991).

Many nematodes, particularly endoparasites, are consumed in plant material by birds and other animals (Martin 1969; Thomason and Caswell 1987). They successfully survive passage through the digestive tract and become point-source infestations along migration patterns or within territorial boundaries. Their introduction into the new Polder region of the Netherlands after reclamation of the land from the sea has been associated with migratory birds. Movement from field to field also occurs with contaminated soil adhering to vehicles and farm equipment. Movement of the soybean cyst nematode (*Heterodera glycines*) in the Midwest has been associated with the purchase of used equipment from established soybean areas for use in new areas of production.

Such spread results in single or multiple point-source infestations in a new field, which, left undisturbed, might take several years to become evident. However, tillage and water movement are the norm. Nematodes are readily and rapidly spread throughout a field and among fields by irrigation water, surface runoff, engineered drainage systems, and land leveling (Thomason and Caswell 1987; Waliullah 1984). Such forces generate rapid broadcast distribution of the pests. In the irrigated agriculture of California, up to 11 separate tillage operations may be conducted in a field after harvest in late summer to prepare it for the next crop in the spring. Consequently, enormous movement of soil and its resident organisms occurs within a field in a single year. Spread throughout a field from a point-source infestation will probably occur in one or two years under conventional production practices in annual crops in California.

For some nematode species, a primary constraint in establishment is soil texture; for others, host availability and soil temperature may be more important. Burrowing and sting nematodes prefer coarse, sandy soils. In California, sandy soils are present in the Coachella Valley, the Bard Valley near Blythe, the Edison-Arvin citrus district of Kern County, and in streaks throughout the state. Citrus and date palms in the Coachella Valley are planted in soils subject to temperatures that would favor the development of burrowing nematode populations. Host crops found along the California coast, even when planted in sandy soil, experience temperatures favorable to the development of the burrowing nematode for only a few months of the year. On the other hand, reproduction and development of the reniform nematode is favored by fine-textured soils (Robinson et al. 1987).

The main dissemination risk for the rice foliar nematode is seed (Bridge et al. 1990). On a local scale, this nematode can be dispersed in floodwater, but survival in water decreases as temperature increases from 20° to 30°C (Tamura and Kegasawa 1958). Once introduced into a field, the rice foliar nematode may survive in plant debris (Sivakumar 1987).

In general those environments that favor potatoes and tomatoes also favor the golden nematode. The survival of the golden nematode is completely dependent on the presence of host crops; the nematode and host have coevolved over many thousands of years, resulting in specific recognition signals between host and parasite (Endo 1971).

Introductions of Exotic Nematode Species into California

All the nematodes considered in this study, except the golden nematode, have been introduced into California. Some species have been eradicated, some are of disputed presence, and one is established in limited areas.

The California Department of Food and Agriculture (CDFA) Nematology Laboratory, in collaboration with county agricultural commissioners, has made 70 detections of the burrowing nematode since 1995 in shipments destined for California. It has been discovered and eradicated in commercial nurseries. In 1996 it was discovered in a residential area in Huntington Beach and, due to the early detection and isolated nature of the infestation, eradicated. The source of the infestation was an illegal shipment of banana corms from Louisiana (Chitambar 1997a).

Since 1989 the CDFA Nematology Laboratory has made 64 detections of reniform nematodes in quarantine shipments. A reniform nematode infestation of ornamental date palm plants was detected in San Diego in 1960. The plants were established in a residential property before a confirmed diagnosis of the pest was completed. Subsequently, the plants were removed from the infested site, and all plants and soil were fumigated with a nematicide. As in the case of the 1996 burrowing nematode infestation, an eradication program was biologically feasible due to early detection and the isolation of the infestation.

Infestations of reniform nematodes on established yucca plants were first detected in 13 residential properties in Highland, San Bernardino County, during a residential grid survey in 1967. The infestation was traced to yuccas brought into California from Harlingen, Texas, and planted in the subdivision. The infested areas were treated with dibromochloropropane (DBCP Nemagon). In 1971 the nematode was detected again in the same locality. Despite a second treatment of Nemagon, it was still present in 1973 and 1974. After subsequent treatment, the reniform nematode was declared eradicated from the infested areas on December 31, 1978. In 1980 the nematode was detected again from the same region. The current status of the San Bernardino infestation is not known (Chitambar 1997b).

From 1959 to 1996 the rice foliar nematode was detected only twice in California by the CDFA Nematology Laboratory. The first was in 1959 in strawberries that originated in Oregon; the second was in 1963 in a fungal culture collected from a Butte County field. Attempts to find the nematode from the same field were unsuccessful. In response to Turkish requirements for phytosanitary certification of rice shipments from California, a survey for rice foliar nematodes was initiated in 1997. One confirmed and three suspected detections of rice foliar nematode were made in samples collected from two counties. These locations tested negative when examined a second time. Consequently, the government of Turkey now requires certification of California rice on a per shipment basis; each shipment must be sampled and found free of rice foliar nematode. Three detections have been made since 1998.

The CDFA Nematology Laboratory detected the sting nematode in 1962 on Bermuda grass from Georgia, in 1967 on roses from Texas, and on coconut palm from Mexico, and in 1983 and in 1987 in soil from Florida. The sting nematode was detected 84 times and *Belonolaimus* spp. twice between June 1992 and December 1993. During the last week of May 1992, a sod sample from a Coachella Valley (Riverside County) golf course tested positive for sting nematodes.

Intervention Strategies

The first step in preventing the establishment of exotic nematodes is by excluding their entry into the pest-free regions. Exclusion may be done through cultural methods and quarantines. Should an exotic nematode enter, it may be prevented from establishing through the completion of a successful eradication program. If eradication is not feasible, then containment efforts may be undertaken to prevent further spread. If an exotic nematode becomes established, growers would have a variety of control methods available, including chemical treatments, developing resistant varieties, crop rotations, soil solarization, changing cultural controls, and developing biological control programs.

Exclusion

Cultural Methods Avoiding infestations by exotic nematodes is the highest priority. The use of certified nematode-free planting stock is critical. The movement of soil from infested fields must be avoided.

The most effective means of controlling the rice foliar nematode is through seed treatments. Both chemical and hot water treatment of seed can be used to kill nematodes (Atkins and Todd 1959; Pinherio et al. 1997). Although there is some risk of reduced germination using hot water treatments, careful management of treatment temperatures and immediate planting of treated seed minimize deleterious effects (Taylor 1969).

Quarantines In countries that are free of exotic nematode pests, quarantines can lower the probability of their introduction. In countries where nematodes are localized, quarantines can reduce further spread. Although all the nematodes in these case studies are A-rated pests in California, they are subject to different quarantine regulations on the basis of their biology, sources, and historical factors.

The CDFA has external quarantine programs for the burrowing and reniform nematodes to reduce the probability of their introduction through infested plant and associated materials in shipments to California. It also has an internal quarantine against the sting nematode. Entry is restricted from all areas under quarantine of soil and potting media, plants and plant parts with roots, parts of plants produced below ground or at soil level, and plant cuttings for propagation.

In addition to the CDFA's quarantine programs, the burrowing nematode nursery certification program serves as another means of protection. Certification of nursery stock is mandatory if the stock is being marketed for farm planting. The nursery has the option (voluntary) to sell noncertified stock if it will not be used for farm planting.

Formal quarantine regulations have not been implemented against the rice foliar nematode at the state or federal level. However, federal regulations have prohibited the importation of paddy rice into the United States since November 23, 1933. Shipments of rice from the southern United States to California are not restricted.

The Animal and Plant Health Inspection Service (APHIS) of the USDA enforces a federal quarantine on the golden nematode. Interstate movement of the following materials from New York state is restricted: soil, plants, grass sod, plant crowns, roots for propagation, bulbs, corms, rhizomes, root crops, small grain and soybeans (unless in approved containers), hay and straw (unless in approved containers), plant litter, corn (except shucked corn), used farm materials and equipment (unless free of soil), and seed potatoes. Potatoes for consumption grown in fields certified free of golden nematode (or receiving applications of required soil fumigants) may be transported if free of soil and moved in approved containers.

Eradication

Unless infestations are quickly identified, eradication of nematodes is extremely difficult, if not impossible. For a very small, isolated infestation, excavation of all plant material and soil and their removal to a protected area for treatment have been feasible for nematode eradication in California. Using this method, burrowing and reniform nematode introductions have been declared eradicated.

For larger infestations, soil removal and fumigation for nematode eradication is difficult. An alternative is to remove or destroy all roots and other plant material, treat the soil with nematicides, and maintain it plant free for two to three years. Due to the wide host ranges of most of the plant-feeding nematodes considered in this study, growing a nonhost crop would require elimination of host weeds. This approach was attempted in Florida for eradication of the burrowing nematode; it failed both as an eradication strategy and as a containment strategy (Noling 2001). Eradication of the golden nematode through nonhost rotation is unlikely due to the extreme longevity of eggs protected in cysts.

Containment

The primary focus in containment is to minimize the potential spread of the nematode. Considerations include restricting movement of plant material, soil, and drainage water from the infested area. In established perennials, preventing disruption of root-to-root contact is important. In the Florida program to restrict spreading decline of citrus (caused by burrowing nematode), trees and roots are removed in buffer zones two trees wide around infested sites. The buffer zones are treated with nematicides to reduce the probability of nematode spread. Decontamination of equipment and footwear is essential. Fencing of the area may be necessary to minimize animal and human traffic.

Management of Established Infestations

The use of pesticides, resistant varieties, crop rotation, soil solarization, and other cultural controls is effective to various degrees in controlling infestations and, in some cases, preventing further spread (Evans and Brodie 1980). For greatest effect, they are applied in strategic combinations targeted at the life cycle and biology of the introduced species.

Chemical Control Chemicals used to control nematodes (nematicides) can be classified according to their volatility as either fumigants or nonfumigants. Depending on the concentration used, many fumigant nematicides are general biocides that kill many soil organisms, including nematodes, fungi, bacteria, plants, and insects. In contrast, some nonfumigant nematicides more specifically target nematodes. Some nonfumigant nematicides are nonphytotoxic and can be used to manage nematodes in perennial crops.

Pesticides are subject to review of their registration status. Environmental quality and health concerns have resulted in limits being imposed on some nematicides. Methyl bromide, for example, will not be available after 2005. For 1,3-dichloropropene (Telone II), the amount that may be applied annually per township in California is restricted. In addition, all organophosphate and carbamate pesticides are subject to evaluation under the 1996 Food Quality Protection Act.

Resistance Plant-breeding programs seek to develop crop varieties that are resistant to nematodes. Preferably, the developed cultivar should be resistant to the target nematode and also to other major disease problems; the resistance should be uniformly inherited; and the cultivar should have desirable horticultural characteristics. Resistant planting materials can substantially reduce losses due to nematodes. However, there are several examples of plants selected for resistance to one nematode species that have elevated susceptibility to another species. Broad and durable resistance is a desirable but difficult goal in plant-breeding programs. After a suitable source of resistance is identified, it may take five to seven years to develop a resistant crop variety that is compatible with California production practices and market requirements.

Crop Rotation Crop rotation using poor hosts or nonhosts is useful for nematode control in annual cropping systems. In the absence of their food, nematodes starve and populations decline. Effectiveness of this type of control depends on availability of appropriate nonhosts. Weed hosts must be eliminated during the nonhost rotation.

Soil Solarization In soil solarization, clear plastic film is laid over moist soil during periods of high solar radiation and air temperature. The resulting soil temperature elevation may be sufficient to kill pest species in upper layers of soil (Katan 1984; Stapleton and DeVay 1986). In Egypt, for example, soil solarization reduced population levels of the reniform nematode for 60 days after planting. Soil solarization has been used to reduce population levels of the golden nematode under New York field conditions (LaMondia and Brodie 1984). Since many regions of California have higher air temperatures and more solar radiation during the summer months than New York, control of the golden nematode by soil solarization may be more effective under California conditions (Pullman et al. 1984). However, constraints of solarization include nematode survival below the affected layer and the opportunity cost of removing land from production during the several weeks of the treatment period.

Cultural Control To offset sting nematode damage in turf systems, certain cultural practices, including enhancing soil aeration and moisture and close mowing, are useful (Nutter and Christie 1958; Giblin-Davis et al. 1991). Numbers of sting nematode were reduced in soils amended with alfalfa meal, cottonseed meal, or rice straw (Tomerlin 1969). Soil amendments have also been effective in control of the reniform nematode (Badra et al. 1979; Amin and Youssef 1998).

Biological Control Nematodes have natural enemies that can reduce their ability to survive and reproduce. Several have been studied as potential biological control agents of the sting nematode in turf grass (Grewal et al. 1997; Giblin-Davis 1990; Bekal et al. 1999). Fungi and other organisms have been investigated for their potential to control the golden nematode (Jatala et al. 1979).

Parties Potentially Affected by Nematodes

Agricultural industries, including growers and the marketing sector, consumers and taxpayers may all be affected by exotic nematode infestations. Potential effects include crop loss, increased control costs, change in cultivars grown, change in crop rotations, delay in replanting of perennials, reduced interstate commerce, and trade barriers for exported crops and plant materials, increased consumer prices, and increases in regulatory costs. Such problems already exist in California. For example, in some areas sugar beet growers can only grow sugar beets once every five to seven years due to the sugar beet cyst nematode.

Agricultural Industries

Many of the commodities at risk from at least one of the nematodes under consideration in this chapter are among the highest-grossing agricultural industries in California (Table 8.1) (California Agricultural Statistics Service 2000). Among the top 10 agricultural industries in California, grapes, nursery products, lettuce, citrus, cotton, strawberries, and alfalfa would be affected by at least one of the nematodes in this study. Overall, the annual value of the commodities potentially at risk was $18.3 billion in 2000. This represents 61 percent of the total value of agricultural production in California (Table 8.1).

As the leading agricultural producing region, the absolute value of affected commodities is greatest for the San Joaquin Valley. The affect-

Table 8.1 California commodities most likely to be affected by exotic nematodes by region

Region[a]	Total value of production ($ million)	Number of top 10 commodities affected	Value of affected commodities (in millions)	Percent of total value	Major crops affected
San Joaquin Valley	14,412	6	7,249	50	Grapes, cotton, citrus, alfalfa, tomatoes (proc.), nursery[b]
Central Coast	5,610	8	4,706	84	Lettuce, grapes, nursery[b], broccoli, strawberries, unspecified vegetables, flowers, cauliflower
South Coast	3,675	9	3,137	85	Nursery[b], flowers (foliage and cut)[b], strawberries, citrus, avocados, vegetables—unspecified, broccoli, lettuce, grapes
Desert	2,588	7	1,321	51	Alfalfa, citrus, lettuce, nursery,[b] grapes, carrots, unspecified vegetables
Sacramento Valley	2,294	5	1,409	61	Rice, tomatoes (proc.), grapes, nursery,[b] peaches
Mountains	508	6	231	45	Alfalfa, nursery,[b] pasture, grapes, rice, potatoes
North Coast	256	3	145	57	Grapes (wine), nursery,[b] pasture
Total[c]	30,017	7	18,348	61	Grapes, nursery,[b] lettuce, citrus, cotton, strawberries, alfalfa

[a] Counties in each region are: San Joaquin Valley—Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, Tulare; Central Coast—Alameda, Contra Costa, Lake, Marin, Monterey, Napa, San Benito, San Francisco, San Luis Obispo, San Mateo, Santa Clara, Santa Cruz, Sonoma; South Coast—Los Angeles, Orange, San Diego, Santa Barbara, Ventura; Desert—Imperial, Riverside, San Bernardino; Sacramento Valley—Butte, Colusa, Glenn, Sacramento, Solano, Sutter, Tehama, Yolo, Yuba; Mountains—Amador, Calaveras, El Dorado, Inyo, Lassen, Mariposa, Modoc, Mono, Nevada, Placer, Plumas, Shasta, Sierra, Siskiyou, Trinity, Tuolumne; North Coast—Del Norte, Humboldt, Mendocino.

[b] Includes both host and nonhost commodities.

[c] The total is greater than the sum of counties because the value of production for some commodities was not specified by region.

ed crops in the San Joaquin Valley have a value of $7.25 billion. Even though the value of the affected commodities is less for the central and south coast regions, these regions have the largest percentage of total value of production that is potentially affected by at least one of the nematodes in this case study. The affected commodities account for over 80 percent of the total value of agricultural production in these regions.

Growers Growers are affected through reduction in crop yields and increases in pest management costs needed to prevent crop damage or other degradation in quality. Growers are also indirectly affected by any changes in market prices for widespread establishment of exotic nematodes. With widespread infestations, yield losses or increased costs of production may cause market prices to rise, thereby offsetting the lost revenues or increased costs.

Marketing Sector Restrictions on plant imports from California may be imposed by other states or countries. These may be mitigated by demonstration that the containment is effective and the infestation localized, or by undertaking control measures to ensure that nematodes are not transported into uninfested regions.

The burrowing nematode is a pest of concern and will become an issue in the export commodities to at least Japan, Taiwan, and the European Union. Japan has published a list of the plants reported to be hosts of the burrowing nematode and requires that these plants be accompanied by phytosanitary certification that they are free of the nematode (M. Guidicipietro 2000). Citrus and strawberry nursery stock, carrots, and other root crops could be prohibited for export to these countries, or regulatory treatments could be required. Arizona has already indicated intent to regulate California nursery stock as a response to any modification of California's Burrowing Nematode Exterior Quarantine.

Because the reniform nematode is widespread, no impact to foreign exports has been identified. It is expected, however, that quarantine action would be taken by other states to regulate reniform nematode host material. Should the golden nematode become established, the federal quarantine on this pest would be expanded to include California.

Other Related Agricultural Industries The economic impacts go beyond crop loss and control costs at the farm level. For widespread infestations, market prices may rise and quantities may be reduced. As growers shift out of production of crops susceptible to exotic plant-feeding nematodes, industries supplying inputs (such as labor, seed, etc.) for the production of those crops may also be affected. How they would be affected depends on the inputs required by the replacement crops.

Consumers

Consumers would be affected by higher food costs. Both increased production costs and yield losses put upward pressure on consumer prices. In addition, people purchasing nursery plants for landscaping would face higher prices for those commodities.

Taxpayers

Intervention strategies for exotic nematodes (exclusion, eradication, containment, and suppression) each can be funded and administered by either the private or public sectors or some combination. When public regulatory agencies are involved, issues related to taxes and budget allocations come into play. Taxpayers may fund border control measures to prevent the entry of exotic nematodes. Public programs may be necessary to eradicate small infestations or undertake plant-breeding programs to develop resistant varieties suitable to California. Other, important research areas include developing new nematicides, identifying natural enemies, and decontaminating plants in nurseries.

Policy Scenarios

Once a nematode has entered California, an eradication program through soil removal and nematicide treatment may be attempted if the infestation is small enough. For larger infestations, a chemical eradication program may be attempted. Usually, public agencies will mandate and conduct the eradication program. However, in some instances, such as the chrysanthemum white rust eradication program in California during the late 1990s, growers are required to complete an eradication program themselves. In this section, an analysis of a grower eradication program will be completed for the rice foliar, sting, reniform, and burrowing nematodes. Due to the long survival period of the golden nematode, eradication is not biologically feasible; therefore, only the costs of establishment are calculated for this pest. The pests and crops considered in these analyses are the rice foliar nematode on rice in the Sacramento Valley; the golden nematode on fresh and processed tomatoes in the San Joaquin Valley; the sting and reniform nematodes on cotton in the San Joaquin Valley; the reniform nematode on table, raisin, and wine grapes in the San Joaquin Valley, and wine grapes from Sonoma County; and the burrowing and reniform nematodes on oranges in the San Joaquin Valley, lemons from San Diego County, and grapefruit from Riverside County. The diversity of nematodes, crops, and regions allows us to compare how differences in input costs affect the decision to eradicate or manage an infestation and the optimal management alternatives to use.

If the eradication program fails or if it is not feasible, then the pest is considered to be established. Eradication costs will vary depending upon where the nematode is found. Eradication costs are also influenced by the cropping sequence, soil, and climate of the infested site. Due to the wide disparity in costs of eradication, sample costs per acre are presented for agricultural infestations in rice, tomatoes, cotton, citrus, and grapes.

The costs of eradication will be compared to the expected losses due to establishment. Those losses can vary significantly, depending upon the pest and the area in which it becomes established. For these analyses, the lowest treatment cost alternative for selected commodities will be determined and the costs per acre estimated. The per acre infestation costs will be aggregated over different infestation sizes to reflect the potential increase in grower costs for a specific agricultural industry. Given the number of pests considered in these analyses, market effects are not estimated. Due to the large number of options, depending on farm-specific characteristics, a policy of containment should eradication not be feasible is not pursued in this analysis. If the grower costs of establishment are less than the costs of eradication, then the implications for an eradication program by public regulatory agencies will be discussed.

Economic Analysis

The economic analysis first examines the grower costs of an eradication program, then the grower costs of establishment using the least-cost control method, and then compares the costs of eradication to the costs of establishment. Data on preinfestation levels of grower costs for both the eradication and establishment scenarios are available from University of California Cooperative Extension budgets (1997-2001). Where costs of nematicide treatments are considered, specific chemicals that have been demonstrated to be effective are selected as examples. Their selection for these analyses does not imply endorsement of specific products. The chemicals considered in the analyses include 1,3-dichloropropene (Telone II), metam-sodium (Vapam), aldicarb (Temik), and fenamifos (Nemacur 3).

Eradication

Methodology The same eradication strategy is used for each crop. Eradication takes place over a two-year period. At the start of the period one soil fumigation treatment of Telone II, at 35 gallons per acre, is completed, followed by one treatment of metam-sodium (Vapam) at 25 gallons per acre, not exceeding a concentration of 250 ppm. A second and third treatment of Telone II and Vapam are applied at annual intervals. Both Telone II and Vapam are custom applied, and Vapam is applied with 6 acre-inches of water. For reniform nematodes, an additional pretreatment irrigation of 6 acre-inches is required to bring the nematode out of dormancy prior to soil fumigation. Application and materials for the three Telone II/Vapam treatments cost $3,615. Due to the wide host ranges of the nematodes in this study on both commercial crops and weeds, the land must remain fallow during the two-year eradication program and maintained plant free with herbicides. Herbicide treatments are $39 per acre over the two-year period. Eradication costs to growers also include lost revenues and interest on idle capital. For this study an average value of $500 per acre per year is used for a total loss of $1,000. This cost is invariant to the commodity under consideration because no crops are grown on the land. If an alternative crop is possible, then the cost would be the difference between profits earned with the original crop and profits earned with the replacement crop.

Results The eradication costs per acre range from $4,729 for the sting nematode on cotton produced in the San Joaquin Valley to $6,454 for the reniform nematode on lemons grown in San Diego County (Table 8.2). The differences in costs are due to varying regional water prices and the type of nematode eradicated.

The cost of water in California varies dramatically depending on where crops are grown. In the San Joaquin Valley, different water districts charge different prices, and the cost of water for the crops in this study ranges from $3.14 an acre-inch for raisins to $5.63 an acre-inch for table and wine grapes. In contrast, water costs $13.33 an acre-inch for grapefruit in Riverside County and $50.00 an acre-inch for lemons in San Diego County.

The type of nematode that is being eradicated also influences total eradication costs. Because reniform nematodes require an irrigation treatment before the soil is fumigated with Telone II and Vapam, reniform eradication costs are higher than the costs for the rice foliar, sting, and burrowing nematodes, all other factors being held constant. Application rates of nematicides may differ with soil texture. Lower rates than those used in these analyses may be effective in coarse-textured soils. Always, attention must be paid to soil moisture and temperature conditions, which can significantly influence efficacy of nematicides.

Table 8.2 Total eradication costs per acre[a]

Nematode	Crop	Telone II/Vapam	Herbicides	Water	Income and interest	Total cost
		($)				
	Annual Crops					
Rice foliar	Rice	3,615	39	81	1,000	4,735
Sting	Cotton	3,615	39	75	1,000	4,729
Reniform	Cotton	3,615	39	150	1,000	4,804
	Perennial Crops					
Reniform	Wine grapes, Sonoma	3,615	39	217	1,000	4,871
	Wine grapes, San Joaquin Valley	3,615	39	203	1,000	4,857
	Table grapes	3,615	39	203	1,000	4,857
	Raisin grapes	3,615	39	113	1,000	4,767
	Oranges	3,615	39	191	1,000	4,845
	Lemons	3,615	39	1,800	1,000	6,454
	Grapefruit	3,615	39	480	1,000	5,134
Burrowing	Oranges	3,615	39	96	1,000	4,750
	Lemons	3,615	39	900	1,000	5,554
	Grapefruit	3,615	39	240	1,000	4,894

[a]All costs are for the two-year program.

Management of an Established Infestation

The alternative to eradicating a newly introduced nematode is to allow it to become established and then to manage the population. The establishment scenario estimates the cost of a nematode infestation without any pest control measures adopted and compares that cost with the costs of control using a chemical treatment. When no control measures are used, yields decrease, and the cost per unit of production increases. When chemical controls are used, production costs increase, but yields are maintained, and the costs per unit of production again increase. For each crop, the point at which yield decline would be enough to warrant treatment is estimated to determine if growers should undertake control measures.

Methodology The potential decline in yields and the appropriate nematicide treatment alternative were determined for each crop in this study (Table 8.3). Yield reductions were provided for resistant and nonresistant varieties, when available. While yield reduction figures are given for resistant varieties, many resistant varieties would not be suitable for California. Due to variations in population densities from year to year and agro-climatic differences between regions, a minimum and maximum range of yield decreases is given. For perennial crops, the analysis is completed for the planting of a new orchard or vineyard.

In addition to yield reductions when no treatment is undertaken, we estimate that there will be a delay of one year before perennial crops start producing and that the productive life span of the plants will be reduced to half that without the exotic nematode infestation. The delay in bearing fruit postpones the revenues that a grower receives. We calculate the losses associated with postponed revenues as the discounted difference between what the grower would have received if no nematodes were present and what the grower receives with nematodes.

The costs of a shorter production life span are estimated by amortizing the costs to establish a grove or vineyard over half the original expected life of the vineyard or grove using the formula

$$\text{Annual amortization costs} = \frac{\text{Total Establishment Costs}*r}{(1-(1+r)^{t})}$$

where r is the interest rate and t is the expected life.

If a chemical treatment is used to manage an exotic nematode infestation, the appropriate nematicide treatment depends on whether the crop

Table 8.3 Exotic nematode treatment scenarios

		No treatment reduction in yield		Chemical treatment			
Nematode	Crop affected	Resistant	Nonresistant	Pesticide	Other considerations	Years effective	Other practices
		(%)					
Rice foliar	Rice	24	17–54	Telone II	None	1	Use clean seed
Golden	Fresh and processed tomatoes	N/A	10–30	Telone II	If treat, rotation period is 2–3 years	Pretreat when in rotation	If no treatment, use a long rotation of 5–6 years
	Potatoes	0–100	10–30	Telone II	None	1	
Sting	Turf grass/sod	Some grasses more resistant	0–100	Telone II	None	1	Temik
	Cotton	N/A	60–80	Telone II	None	2	Temik
Reniform	Cotton	N/A	40–60	Telone II			Temik
	Citrus and grapes, before planting	N/A	40–80	Telone II and Vapam	A pretreatment irrigation of 6 acre-inches to bring the nematode out of dormancy	4-5 years, then after plant treatments	
	Grapes, after planting	N/A	40–80	Nemacur 3	None		N/A
Burrowing	Citrus, before planting	N/A	40–80	Telone II and Vapam	None	4–5 years	N/A
Burrowing and reniform	Citrus, after planting	N/A	40–80	Nemacur 3	None	2	N/A

is an annual or perennial (Table 8.3). For annual crops, a preplanting soil fumigation with Telone II is recommended. To reduce surviving nematodes in debris from a previous rice crop, and for reniform nematodes in land used for cotton, the treatments must be done before each planting of the host crop. If rice was not grown the previous year, no soil treatment would be needed before planting with clean rice seed. For sting nematodes on land in a cotton rotation, treatment is every other year. The price for materials and application are given in Table 8.4. Nematode control costs for annual crops are reflected as an annual increase in the costs of production.

Treatments are more aggressive in fields that will be planted with a perennial crop to allow the roots of nursery stock to become well established before nematode populations build up again in the soil. Preplanting treatment of such fields consists of one treatment of Telone II, followed by one treatment of Vapam (Table 8.3). Telone II and Vapam are both custom applied (Table 8.4). After the pest population recovers, biennial treatments of Nemacur 3 are used to manage nematodes.

For perennial crops, the preplant nematode control costs are reflected as increases in the establishment costs of a grove or vineyard and then amortized over its expected productive lifetime using Equation 8.1. Even though Nemacur 3 is applied after the vineyard or grove becomes established, the net present value of the costs to apply it over the productive lifetime is also amortized into an annual expense.

Once the annual increase in costs was determined, the break-even yield loss value was calculated as

$$\text{Break-even yield loss value} = \frac{C_N}{RY}$$

where C_N is the cost per acre of nematode treatments, R is the average annual returns per unit for the crop as given in University of California Cooperative Extension crop budgets, and Y is the yield per acre when nematodes are treated.

The establishment of an exotic nematode may cause additional costs to agricultural industries if quarantines are imposed. The extent to which any industry is affected depends on the type of crop, what percentage of total production originates from the quarantined area, and the availability of markets in regions that will not impose quarantines.

Commodities that are affected by quarantines include those that are sold as root crops or with roots attached or other commodities in which the nematode lives. Examples include potatoes, carrots, sod, nursery plants, bulbs, rhizomes, and unhulled rice. Commodities that would not be affected would be those without direct feeding by nematodes or those that receive additional processing or treatment that eliminates the nematode. Examples include fresh citrus fruit, cotton, milled rice, fresh grapes, raisins, wine grapes, and treated root crops.

The establishment of quarantine does not necessarily result in losses for an industry. If a relatively small percentage is exported to regions protected by the quarantine, or if alterna-

Table 8.4 Nematicide application costs

Nematicide	Unit	Quantity	Price per unit	Application method	Application costs	Other costs
Telone II	Gallon	10	$18.29	Custom applied	Included in per gallon costs	None
Temik	Pound	5	$4.43	Grower applied when seeding	N/A	Only suppresses, grower would need to plant in nonhost crop after 4-5 years
Telone II followed by Vapam 3 weeks later	N/A	Telone II: 35 gpa; Vapam: 250 ppm	Telone: $640; Vapam: $325	Custom applied	Telone: included in materials costs Vapam: $40 per acre-inch of water	Applied with 6 acre-inches of water
Nemacur 3	Gallon	1		Grower applied when irrigating	N/A	None

tive markets are readily available, then no industry-wide effects may occur. When relatively small quantities are affected or alternative markets are available, the costs to move commodities from quarantined markets to other markets are small. In the short run marketing costs will be incurred as product is redirected; however, once new markets are established, these extra costs will disappear. As the percentage affected increases, or if access to alternative markets is limited, marketing costs increase, and quarantines may impose additional costs on an agricultural industry. The effects of any permanent additional marketing costs or changes in demand due to quarantines would be captured at the market level and are beyond the grower level analysis being completed for this study.

Results Treatment costs for annual crops range from a low of $22 per acre to a high of $201 per acre (Table 8.5). Costs are lowest when the nematicide Temik is used; however, nematode populations will build up over time. The costs of population buildup and the need to periodically rotate to a nonhost crop are not included in the cost of using Temik. The costs to treat sting nematodes with Telone II are also lower than the annual cost to treat rice foliar, golden, and reniform nematodes with Telone II because sting nematodes in cotton need to be treated only every other year.

As was the case with the eradication scenarios, differences in the amortized treatment costs for perennial crops are due in part to variations in the cost of water between regions (Table 8.5). In addition, vineyard and grove productive life spans vary. The longer trees or vines are in production, the greater the time over which costs are spread out, and the lower the annual amortized investment cost.

There is no scenario among the nematode pests and crop combinations under analysis in this chapter where it is unequivocally the case that a nematode population should not be subjected to nematicide treatment when the yield reductions are at higher levels (Table 8.5). However, when yield losses caused by the rice foliar nematode on rice and the golden nematode on processed tomatoes are at the lower levels, treatment may cost a grower more than lost revenues. For the rice foliar nematode, if yield losses are expected to be less than 24.9 percent, the grower should not treat. Similarly, if processed tomato yield losses are expected to be lower than 13.7 percent, the grower minimizes losses by not treating. In all other scenarios treatment minimizes losses as the gains in yields, and, consequently, revenues, are greater than the extra cost of nematode control. In general, the yield loss threshold level is lower for perennial crops than for annual crops.

What is not examined in this analysis is whether a grower would stop growing a crop due to yield losses or increases in production costs. Based on currently available crop budgets, costs may increase anywhere from 1.7 percent to 21.9 percent (Table 8.5). In general, the percentage increase in costs is greater for the annual crops treated with Telone II than for the perennial crops (Table 8.5). The greater the percentage increase in costs, the more likely it is that growers would switch to growing other crops. Interviews with county Cooperative Extension personnel indicate that many growers would stop growing cotton if exotic nematodes, such as the sting or reniform, became established in cotton fields.

Cost/Benefit Analysis

The cost/benefit analysis compares the costs and benefits of a grower eradication program for small infestations of exotic nematodes. The costs are for eradication, and the benefits are from avoiding the costs of control.

Methodology Eradication of an exotic nematode will be undertaken if the cost of investing in nematode eradication is less than the benefits of preventing the cost of control. For annual crops, the benefits of the two-year eradication program extend beyond the two-year period; thus, the total benefits are equal to the present value of all future annual benefits. The eradication costs are compared to the present value of the benefits to determine if growers of annual crops will invest in an eradication program.

For perennial crops both the costs and benefits of the eradication program are amortized into an annual value over the productive life of the vineyard or orchard. To determine if growers will invest in an eradication program for perennial crops the annual costs and benefits are compared.

Results For all crops and for all nematodes, the costs of an eradication program are greater

Table 8.5 Annual costs and yield loss threshold levels for treating an exotic nematode infestation

Nematode	Crop	Annual increase in costs for treatment	Minimum yield loss	Maximum yield loss	Yield loss threshold level	Increase in production costs	Treat?
		($)			(%)		
	Annual Crops						
Rice foliar	Rice	201	17	54	–24.9	21.3	Maybe
Golden	Tomatoes (fresh)	201	10	30	–3.5	3.9	Yes
	Tomatoes – (processed)	201	10	30	–10.8	13.7	Maybe
Sting	Cotton (Telone II)	103	60	80	–10.3	11.2	Yes
	Cotton (Temik)	22	60	80	–2.2	2.4	Yes
Reniform	Cotton (Telone II)	201	40	60	–20.2	21.9	Yes
	Cotton (Temik)	22	40	60	–2.2	2.4	Yes
	Perennial Crops						
Reniform	Wine grapes, Sonoma	170	40	60	–1.4	1.9	Yes
	Wine grapes, San Joaquin Valley	167	40	60	–5.1	6.9	Yes
	Table grapes	167	40	60	–2.4	2.5	Yes
	Raisin grapes	167	40	60	–8.1	8.2	Yes
	Oranges	152	40	60	–3.5	2.7	Yes
	Lemons	220	40	60	–1.8	2.0	Yes
	Grapefruit	161	40	60	–4.4	3.2	Yes
Burrowing	Oranges	150	40	80	–3.4	2.6	Yes
	Lemons	192	40	80	–1.6	1.7	Yes
	Grapefruit	155	40	80	–4.2	3.1	Yes

than the benefits (Table 8.6). Costs exceed the benefits by about 50 percent for the rice foliar nematode and the reniform nematode in cotton. Costs are over 1,000 percent higher than the benefits when Temik is used to control the sting and reniform nematodes. In general, though, the costs to a grower to eradicate an exotic nematode infestation are 160 to 180 percent greater than the benefits for both annual and perennial crops. Therefore, growers would not voluntarily invest in eradicating nematodes on their own land under any scenario.

Failure to eradicate a newly introduced nematode in one field, however, will allow the nematode to spread and infest other fields. Costs then increase for other growers.

These negative spillover effects may make it cost effective for a public agency or a grower association to incur or subsidize any eradication efforts on individual farms. By preventing the spread of exotic nematodes, the whole industry benefits. When determining the public costs and benefits of a policy to eradicate, the benefits of protecting the industry need to be weighed against the costs of eradicating discrete, small infestations.

Should an infestation of only one species of nematode become established in California, the costs of production for many agricultural industries increase (Table 8.7). For example, should sting nematodes infest 10,000 acres of land used for cotton production, industry control costs are $1 million. Industry control costs for reniform nematodes would be even greater, $2 million for a 10,000-acre infestation. Costs then rise in proportion to the acreage infested (Table 8.7). However, sting nematodes prefer coarse soils and reniform nematodes prefer fine textured soils. Because these two nematodes infest different soils, if both sting and reniform nematodes become established, costs would be cumulative. For a 10,000-acre infestation each (20,000 acres total) costs are $3 million for the industry.

Costs are not cumulative, however, when nematodes infest the same soil in the same region because control measures are effective against both species. For example, if both golden and burrowing nematodes infest tomato fields, then the cost to the industry of a simultaneous 10,000-acre infestation is only $2 million (Table 8.7). This cost is the same as the cost if either nematode becomes established.

Table 8.6 Grower costs and benefits of eradicating nematodes

Nematode	Crop	Costs	Benefits	Grower eradicates?	Percent costs greater than benefits
		------- ($) -------			
	Annual Crops[a]				
Rice foliar	Rice	4,735	3,203	No	48
Sting	Cotton (Telone II)	4,729	1,634	No	189
	Cotton (Temik)	4,729	353[c]	No	1,240
Reniform	Cotton (Telone II)	4,804	3,203	No	50
	Cotton (Temik)	4,804	353[c]	No	1,261
	Perennial Crops[b]				
Reniform	Wine grapes, Sonoma	465	170	No	174
	Wine grapes, San Joaquin Valley	462	167	No	177
	Table grapes	462	167	No	177
	Raisin grapes	462	167	No	177
	Oranges	401	152	No	164
	Lemons	613	220	No	179
	Grapefruit	427	161	No	165
Burrowing	Oranges	393	150	No	162
	Lemons	528	192	No	175
	Grapefruit	407	155	No	163

[a]Total costs are compared to the present value of benefits over time.
[b]Annual amortization of eradication costs compared to the annual amortization of management costs.
[c]Does not include costs of rotation to nonhost crop every 4–5 years.

As infestations increase, a larger proportion of production is affected. Eventually, the proportion will be large enough to affect market prices and quantities. Increases in costs will raise prices and decrease quantity demanded and quantity supplied. With higher prices and lower quantities, consumers are worse off. The higher prices will mitigate grower losses to some extent. When determining whether a public eradication program should be undertaken, these additional costs and benefits must also be considered.

Table 8.7 Aggregate grower costs of widespread nematode establishment

Nematode		10,000 Acres Infested	
		Each	Simultaneously
		($ million)	
Sting	Cotton	1	N/A
Reniform	Cotton	2	N/A
Total		3	N/A
Golden	Tomatoes	2	2
Burrowing	Tomatoes	2	2
Total		4	2

Conclusions

Nematodes are excellent invaders; they have evolved numerous strategies for exploiting favorable habitats and withstanding harsh conditions. The degree of risk differs with the life history strategy of the nematode species. Often, a lack of basic information impairs our ability to quantitatively assess that risk. In those instances, we rely on qualitative assessment, based on experiences with the pest in other areas of the world to determine whether there is cause for concern. Such assessments include a degree of uncertainty, but provide direction for immediate action and future research.

Although the direct and opportunity costs of establishment may be substantial, eradication is difficult, if not impossible, unless the nematode is detected very early. Significant costs may also accrue from the imposition of quarantine restrictions on exports of California seed, propagative material, and agricultural products. Indeed, Turkey has already imposed restrictions on the importation of unhulled rice from California because several times the rice foliar nematode has been detected.

We began this chapter with the observation that many of the important pests of California agriculture are not native to the region. They have been introduced with plant material, adhering soil, and other means. They have been spread throughout the state by our tillage, propagation, labor, irrigation, and harvesting practices. The same can happen and, indeed, has happened, with the A-rated exotic pest nematodes reviewed in this chapter and with other species that they exemplify. The challenge will continue to be to intercept their introduction, accurately identify them using the best technology available, and to eradicate, contain, or manage them as appropriate.

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