THE
INTEGRATED MANAGEMENT
OF ROOT PESTS OF STRAWBERRY
IN THE PACIFIC NORTHWEST

by

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The Integrated Management of Root Pests of Strawberry in the

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ABSTRACT

The roots of strawberry are highly vulnerable to the activities of a complex of arthropod, nematode, and fungal pests. This complex almost certainly accounts for substantial losses in potential yield and plantation longevity. An integrated program for the management of these pests is therefore being developed by re-examining the problem at the levels of farm economics, soil-ecosystem, and pest biology.

The strawberry growing regions of the PNW in southwestern British Columbia and in western Washington and Oregon represent a coherent agroecosystem. Strawberries are grown in three-or four-year rotations which allow increases in root pest populations and subsequent economic loss. The key pests of strawberry roots, some of which need control in all areas, are as follows: root weevils, strawberry crown moth, red stele disease, verticillium wilt, black root rot, root lesion and dagger nematodes, and weeds. All of these pests are shown to interact in the soil-ecosystem and so increase root injury.

Together, the following measures form an IPM program which should economically control root pests, and increase plant health:

1. Restricting the lands used for strawberry production to those with suitable soils and topography.

2. The regular monitoring of fields for pests and areas of poor growth.

3. The use of resistant and tolerant varieties, particularly those having field resistance to root rots and high tolerance to viruses.

4. The management of pathogen biotypes and soilborne antagonists through crop rotations.

5. The achievement of the best possible field drainage.

6. Planting the cleanest possible certified stock.

7. Identification and elimination of the most competitive weeds and those that act as reservoirs of pests.

8. Fumigation with a compound having fungicidal and nematocidal properties, to be followed by a directed recolonization of beneficial antagonistic microflora.

9. Limiting the use of post-planting soil drenches to spot treatments, or infrequent remedial applications.

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I. Introduction

The Pacific Northwest (PNW) region, comprising the southern part of the province of British Columbia and the states of Washington and Oregon constitutes a coherent agricultural ecosystem with respect to strawberry cultivation. This is due to a similarity in seasonal mean temperatures, duration of growing season, amount of rainfall, soil types and expected yields. Similar pest problems beset strawberry growers in these areas as well. Plantings of strawberries in the region are normally cropped for a number of years, thus allowing a build up of damaging populations of such root pest organisms as nematodes, insect larvae and disease pathogens. These organisms, along with the roots of strawberry and weeds, and other incidental soil life, all form part of an interlocking soil ecosystem which can be manipulated by the grower to achieve maximum root health. Manipulation of the ecosystem is most successful when each control measure is used so as to have the maximum effect on the whole system. This demands an understanding of the biological interactions between the crop plants, crop pests, control measures and the environment. If it is to be implemented, a management scheme must be economical. A grower needs to know when pests are causing economic injury, the extent of the injury, and how much can reasonably be spent in controlling them.

In this paper, I have identified some of the below-ground agroecosystem interactions important in strawberry pest management. I have tried, through talking with growers, consultants and researchers, to evaluate the root pest situation as to economic importance, present management techniques, and applicability of an integrated management approach. I hope that this overview has provided information needed for a more secure basing of control tactics and that it stimulates further interest in the area of root pest management.

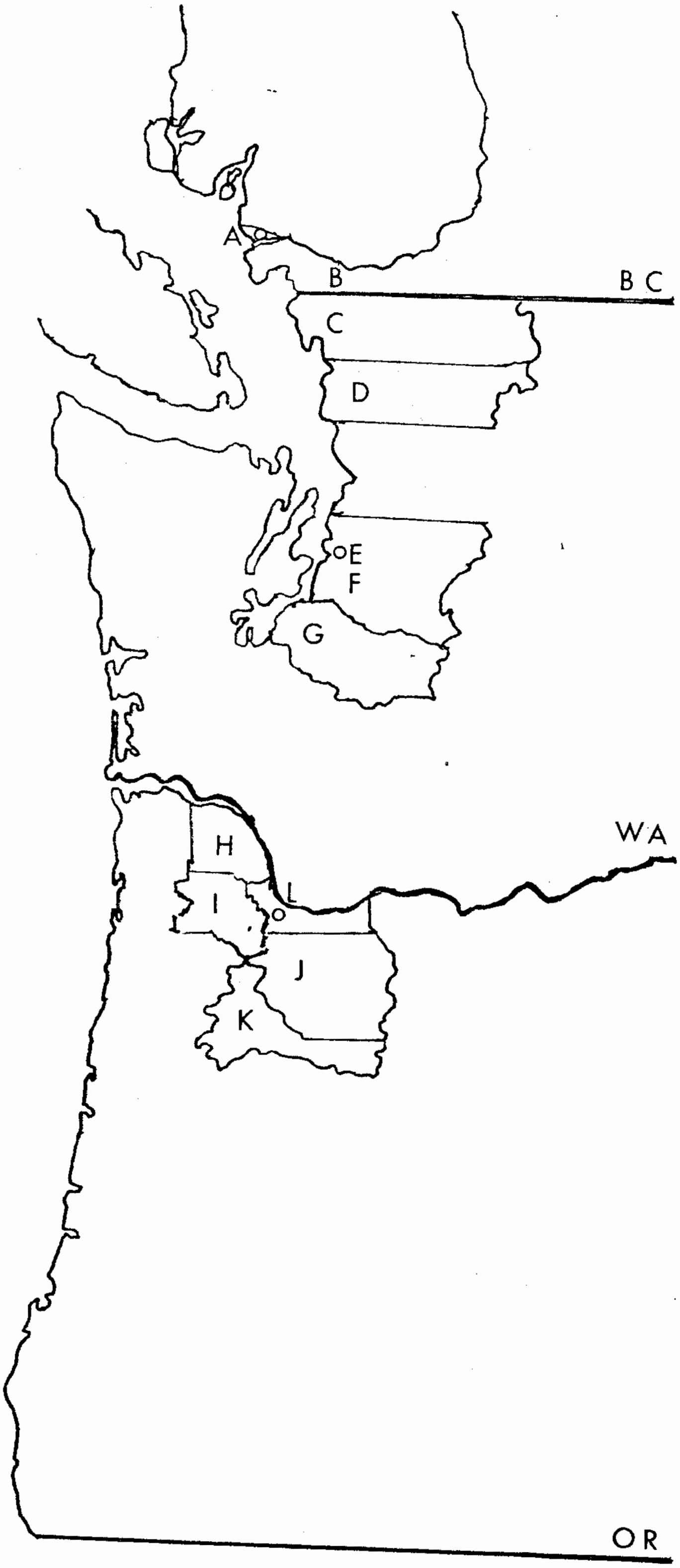
II. An overview of the industry

The primary strawberry growing areas of the PNW are in the well watered valley land between the Cascade range and the coastal mountains. About 93% of B.C. production is in the lower mainland, centered in the Abbotsford area. Most Washington production is in Skagit, Pierce, Whatcom, and King counties; and Oregon production is centered in Marian, Washington, Clackamas, and Columbia counties (Fig. 1). The climate in these areas is excellent for strawberry growth, with 150-180 frost-free days a year and mild winters which allow root growth and limit the frost damage so common in the east. PNW strawberries are recognized for their superior taste and sugar-acid balance, which is why a number of major jam and frozen fruit processors are based there. After California, the PNW supplies the greatest share of strawberries to the processing market in North America. In 1982 87% of the total PNW crop went to processing, with the remainder to the fresh and U-pick markets. Although quite variable, in 1982 there were 10,350 bearing acres in the PNW, which yielded a total of 93,687,000 lbs and grossed $41,514,300. Oregon was the largest producer with 58 million lbs on 5800 ac, Washington produced 18.6 million lbs on 3000 ac, and B.C. produced 17.1 million lbs on 4250 ac. The mean yields in 1982 were respectively: 5, 3.1, and 2.1 ton/ac (OSU Extension Commodity Data Sheet 1984, Washington Agricultural Statistics

1982, and Peters, pers. comm.) For clarity, these and following values are in lbs, tons, acres, and U.S. dollars.

Despite the favorable climate, Oregon and Washington recently have lost much of their market to Californian and Mexican production. In the period from 1969 to 1978, the two states' combined share of of the U.S. market went from 19 to 8% of the total while California increased its share from 55 to 79% (Bringhurst and Voth 1980). As the major strawberry producing region in Canada, B.C. has fared better, increasing its acreage over the period. One reason for the loss of market in Washington and Oregon is that California plantings yield from 5-to 10-fold more than do those in the PNW, and although the California growers have overhead costs as high as $6000/ac before harvest, they are still able to produce for less (Voth 1980). In addition, land prices and labor shortages have tended to harm PNW growers. Most of the prime growing lands in the PNW are near enough to the major cities that land costs, whether as rental fees or mortgages, are prohibitively high.

Figure 1. Strawberry producing areas of the PNW



Key:*

A	Vancouver, B.C.	
B	Fraser Valley	4250 ac
C	Whatcom Co.	550 ac
D	Skagit Co.	600 ac
E	Seattle, WA	
F	King Co.	450 ac
G	Pierce Co.	400 ac
	State total	3000 ac
H	Columbia Co.	400 ac
I	Washington Co.	1800
J	Clackamas Co.	550 ac
K	Marion Co.	1900 ac
L	Portland, OR	
	State total	5800 ac

*1982 figures

The importance of root pests

Pests interfering with the normal development of strawberry roots can cause economic loss to the grower in several ways. Certain pests, most notably root rotting fungi, can severely reduce the suitability of land for strawberry growing, hence limiting production in an area. Heavy, poorly drained soils favor outbreaks of black cortical root rot and red stele disease to the extent that in the PNW, these soils are not now considered for commercial operations. Also affecting the suitability of land for strawberry plantings is the quality of air drainage on the site. In the summer, poor drainage leads to humid conditions which increase mildew and fruit rot problems; in the winter and spring, air drainage is needed to reduce frost damage to the plant crowns. Crown damage by freezing often leads to plant mortality through the later development of black rot of the roots (Plakidas 1964).

Pests of the roots are also instrumental in reducing the useful lifespan of a planting. The strawberry is a perennial plant which can live, reproduce, and bear fruit through its runner plants for many years. Plantings of strawberries are found in Ecuador which have been continuously cropped by Indian growers for 400 years (Darrow 1954). Rotations of eight years or more are not uncommon in temperate regions (Alford 1976). This contrasts with the situation in California where various root pest problems, often verticillium wilt, have necessitated the practice of single year rotations. Obviously, the overhead and labor costs of restocking and replanting a crop are considerably reduced if they can be defrayed over a period of several years. Frost damage, both direct and as a predisposing factor to root disease, is also important in limiting crop life-span (Daubeny 1980). Today, while root pests are an important decline factor, the major limitation to rotation length may be a newly identified complex of strains of crinkle, mottle and mild yellow edge viruses. These can devastate a planting even in the first year (Converse 1978). By shortening rotations from four years to three on the 10,350 ac of strawberries in the PNW, root pests and viruses cost the industry approximately $2,033,800 each year in establishment costs (this and further figures are based on the 1982 Washington State Enterprise Budget, Carkner et al.).

Undoubtedly, the most important result of root pest activity in strawberries is a direct reduction in yield. This may vary from a hidden loss of potential yield from low endemic levels of nematodes, to a total loss if the populations increase out of control or if tall weeds are allowed to overgrow the crop. Very little work has been done which assigns yield loss to the presence of various strawberry pests; an exception is a study by Cram and Andison (1959). They found that 11.6 black vine weevil larvae per plant resulted in a 1.9 ton, or a 44% yield loss. The best way of assessing yield loss due to root pests is soil fumigation with broad spectrum volatiles such as methyl bromide with chloropicrin. A combined application of these compounds kills most of the soil populations of pathogenic fungi, nematodes, root feeding larvae and weeds. The results of fumigation on yields can be spectacular. When chloropicrin and methyl bromide fumigation was introduced in California about 1960, yields skyrocketed from 5 tons/ac to 25 tons or more (Wilhelm 1965). These increases were partly due to new high-yielding cultivars and improved cultural techniques, but control of the root problems was necessary to realize the benefit of these improvements. Wilhelm (1965), testing only for the depressive effect of _Pythium ultimum_ in strawberry, found weight increases over the _Pythium_ infested controls of 50% and 59% (5-week and 20-week old plants) after fumigation with chloropicrin.

Another indication that strawberry yields are not meeting their potential is given by work in Oregon and Washington on the use of new horticultural practices (Norton pers. comm., Martin 1976). Strawberries grown under conditions of optimal root growth such as in raised beds, with black film mulch and drip irrigation, are capable of a doubling or trebling of present yields. Much of this increase might reasonably be ascribed to a larger and more functional root system, and is thus a valid indication of how strawberries might perform in the absence of root limiting parasites.

If root pests account for a 25% loss of yield only, each year approximately 4.27 million lbs are lost in B.C., 4.65

million lbs in Washington, and 14.5 million lbs in Oregon. At the processing price of 43¢/lb, this translates to a loss of about $33 million to the industry.

How important are the effects of strawberry pests on yields as perceived in the industry? Generally, the growers, fieldmen, and researchers I talked with gave conflicting views on the overall importance of the various pests on yields. Taken all together however, fruit rots and aphid borne viruses are seen as the most critical impediments to high yields of fruit. The problems, of course, vary from season to season and place to place. Growers in very isolated places, where no vector aphids are likely to blow in, may be quite free from virus problems, whereas growers in the north Willamette Valley of Oregon consider the crown moth to be their greatest problem. Mites and root weevils are often considered, by entomologists at least, to be next in importance although effective controls do exist. Root rots are always present, but the damage is generally difficult to see and is thus considered negligible, except by plant pathologists. Red stele, although recently reduced in importance by the use of light soils and resistant varieties, may appear when winters are very wet, and was common in 1984. Nematodes, although acknowledged to be limiting when untreated, are not thought to affect yields if the soil is fumigated prior to planting.

It should be stressed that fungal root rots and nematodes probably cause more damage to roots than most growers realize.

Nematode populations are known to begin building up in the first year of a planting, so that they must inevitably account for some lost growth potential by the end of the rotation. Many cosmopolitan fungi have been implicated in strawberry root decline and disease, including the genera: *Rhizoctonia*, *Cylindrocarpon*, *Fusarium*, and *Pythium*, as well as the more familiar *Phytophthora* (red stele) and *Verticillium* (wilt). *Pythium* especially appears to play a major role in root inhibition (Wilhelm 1965, Wilhelm and Paulus 1980 , Maas 1984). Under present cultivation practices, the strawberry plants reach a uniform plateau of root growth and productivity that might be stepped to a much higher level if the inhibitory actions of parasitic microorganisms on the roots could be reduced. The convincing evidence for this lies in the very beneficial effect of broad-spectrum fumigation on strawberry growth.

In addition to the problems of unsuitable land, shortened rotations, and yield loss, root pests of strawberry may indirectly reduce profitability by restricting the use of certain desirable varieties. Such is the case today in the PNW, where the high quality berry producer, cv Hood, cannot be grown in some places because of its susceptibilty to viruses. Similar situations have existed in the past with red stele disease. As pointed out by Wilhelm (1980), resistance to disease in new strawberry cultivars is an overriding consideration, often reducing the possibility of increased yield in a new variety. The use in California of regular fumigation has freed the industry there from the need for high levels of disease resistance in its plants, thus allowing the maximum use of high yielding varieties.

Finally, economic loss may be incurred through the overhead expenses of pest management. The cost of purchasing clean planting stock is a major expense to the grower, a large part of which results from the need to eliminate pathogenic nematodes and fungi from the roots. Cultural and chemical pest control costs can also be substantial. Practices such as pipe drainage, subsoiling, and handweeding all require a certain outlay in materials, labor or both. Fumigation and repeated sprays run into hundreds of dollars per acre per season. Using the Washington State enterprise budget once again, the expenditures on pest management can be roughly calculated. Without considering strawberry crown moth control, the variable costs directly linked to root pests are weevil and weed control, soil sampling, fumigation, and fall subsoiling ($25/ac) (Table 4). Assuming a three year cropping period, these costs add up to $342/ac/yr, which, when multiplied by the total PNW acreage in 1982, gives $3,540,000 as the approximate sum spent on the management of root pests in one year.

In summary then, root pests reduce profitability by making certain lands unusable, by shortening the useful bearing age of the plantings, by reducing yields, by precluding the use of desirable varieties, and by generating high overhead costs.

III. The key pests of roots

Key pests are defined as those with the potential to seriously limit production and thus force the use of pest control activities. The following discussion is a brief review of the key pests of strawberry roots and crowns. It will touch upon their distribution and host range within the PNW, review their life histories and phenologies, and describe the damage caused, as well as the usual means of detection and traditional measures used for control. More thoroughgoing reviews of all of these pests may be found in the literature.

Root weevils

Importance

In the PNW as a whole, various root weevils are the greatest insect problem of strawberry roots, and have been so for many years. As noted by one B.C. entomologist long ago, "this weevil (strawberry root weevil) has shown itself quite capable of wiping out the whole industry or rendering it profitless" (Treherne 1914). At that time only cultural controls and arsenical baits existed for use against root weevils; now, however, the insects can be effectively controlled with the carbamate compound, carbofuran (Furadan). Root weevils are ubiquitous and prolific, with potential for explosive increase, and capable of migrating into plantings and reducing both yield and longevity. If weevil resistance to carbofuran was to develop, or if the compound's registration was for some reason revoked, then root weevils could very shortly become a critical problem to the industry. Even in the face of carbofuran treatment, root weevils may be increasing their populations (Shanks pers. comm.). This is due to the gradual decline in the soil of toxic organochlorine residues from such pesticides as aldrin and dieldrin. Dieldrin, with a half-life of about nine years (Woolson 1967), and several other persistent organochorine insecticides, were much used up to 1969 and 1975 in B.C. and the U.S. respectively, as larvicides for root weevils, and gave some residual control for a number of years after their use was discontinued (Shanks 1976).

Distribution and host range

There have been at least 17 species of root weevils identified as capable of attacking the roots of strawberry in the PNW (Wilcox _et al_. 1934). Only four species, however, are of major importance today (Cram, Shanks pers. comm.). These are: the strawberry root weevil, _Otiorhynchus ovatus_; the black vine root weevil, _O. sulcatus_; the rough strawberry root weevil, _O. rugosostriatus_; and the obscure strawberry root weevil, _Sciopithes obscurus_. These four weevils are found throughout the PNW and with the exception of the black vine weevil from Europe, are North American natives. Distribution within a township or farm is likely to be patchy, with certain species infesting individual fields or parts of fields. This often depends upon the vegetation types growing on the headlands. Rhododendrons, for example, are usually infested by obscure strawberry root weevils, (Bell and Clarke 1980), which may then spread to nearby strawberry fields. In addition to their cosmopolitan distribution, these genera of weevils appear to eat any kind in vegetation. Fruit trees, cole crops, grasses, caneberries, legumes, cucurbits and woody and herbaceous ornamentals are just some of the groups attacked. Black vine weevils even thrive on English laurel leaves which are otherwise used in entomologists' killing jars as a potent source of cyanide gas.

Biology

Since the life history of these four species is very similar, that of the black vine weevil will serve as an example, with some important differences to follow. Of fundamental importance is the fact that all of these weevils reproduce parthenogenetically, and that all are female. Thus, reproductive potential is extremely high, with the possibility of an infestation building from a single egg, larva or adult. Many eggs are produced as well, from 800-1000 eggs were laid in 189 days by individual black vine weevils fed on leaves of the Totem variety (Shanks pers. comm.). In the field, however, a more usual number is about 200 eggs per season (Wilcox _et al_. 1934, Garth and Shanks 1982). Due to the mild winters in the PNW, root weevils are able to overwinter as either larvae or adults, up to 50% of which may survive the winter. The overwintered larvae pupate in May and emerge to feed on foliage in the first three weeks of June. The overwintered adults appear in late April and begin oviposition then, laying at a moderate rate until the first week of August. At this time the new adults also begin laying eggs and both they and the second-year adults lay heavily for several weeks, to halt abruptly by the third week of August. The eggs are laid in soil crevices to 5cm deep and they hatch in three weeks. Upon hatching, the young larvae burrow down to the roots and begin to feed on small rootlets. Wet weather in July and August is considered favorable to egg hatch and larval survival; conversely, warm dry weather can be harmful due to desiccation of the eggs (Nielson and Cram 1978). Larvae hatching in May or June from eggs laid by overwintered adults have the advantage of moist spring conditions and thus may have greater chances of survival.

It is important that the identity and phenology of invading weevils be known since the timing of sprays is crucial to successful control (Schaefers 1981). Following are several variations in life histories between the species of which a grower should be aware. The strawberry root weevil, which is about half the size of the black vine weevil, tends to emerge a week or so earlier, which means it is ready to oviposit during the picking season. No spray can be used against the beetles while harvesting, thus it is critical to know if the strawberry root weevil is causing the trouble. If so, an adulticidal spray must be applied and the infested plants sacrificed to prevent further damage. The rough strawberry root weevil is often associated with sod and so may be a problem in newly broken fields. It emerges a week or more after the black vine weevil and is therefore usually too late to interfere with the harvest. The obscure strawberry root weevil emerges at about the same time as the black vine weevil, so its control is similar.

Damage

The damage done to the feeder rootlets by weevil larvae causes loss of vigor and yield in the strawberry plants. As the larvae grow, so do their appetites, until they are devouring even the large supporting roots and crowns of the plants. In extreme cases, whole fields can be made useless and must be plowed under after the first year of production. All the weevils are flightless, so that severe damage in a field is usually characterized by patches of stunted or dying plants which spread yearly as the beetles migrate.

Detection and control

The presence of root weevils can easily be detected by notches eaten around the edges of the leaflets. When this is noticed, a control must be used before the adults have a chance to lay their eggs. Today, in both countries, carbofuran is being used as a coarse top spray against the larvae and adults. In B.C., carbofuran can be used both in pre-bloom and post-harvest, whereas in the U.S., only a post-harvest application is allowed.

One cultural technique that increases the effectiveness of the spray is the practice of topping the plants after harvest. This destroys hiding places for the adults and also allows greater penetration of spray to the roots where the beetles and larvae are lurking. Mowing and spraying of the headlands around strawberry fields are also helpful since these operations limit the number of weevils ovipositing here and reduce subsequent migration.

Strawberry crown moth

Importance

The strawberry crown moth, *Synanthedon bibionipennis*, or SCM, is an unusual insect pest of strawberry in that it has a curiously limited distribution. Although a native of the PNW, the SCM infests strawberry only in the northern part of the Willamette valley in Oregon. In my talks with growers in Washington and British Columbia, most had not heard of the insect and expressed surprise upon hearing of the damage it does. In the Willamette valley, however, the SCM is considered to be a major limiting factor in strawberry production. Further, despite research activity and operative management programs, the problem seems to be getting worse. Fisher (1982), put a conservative estimate of 1981 losses to the SCM in the Willamette valley at $1.5 million.

Distribution and host range

The SCM has been important in the past in Lane, Linn, Benton, Marion, Polk, Yamhill, Clackamas, Columbia, and Washington counties (Wilcox _et al_. 1932). It also has been noted in Colorado, Utah, Idaho, California, and Washington, but economic infestations in strawberries have not occurred in these states (Fisher pers. comm.).

The SCM also has a very limited host range. It has been reported attacking red and black raspberry, blackberry, and other cane berries as well as wild strawberry. Wilcox _et al_ (1932), stated that it was an economic pest only on strawberry and black raspberry. Its native host is probably a wild strawberry, such as the coast strawberry, _Fragaria chiloensis_.

Biology

The crown moth is a member of the clearwing moth family,the Sesiidae (syn. Aegeridae). The highly damaging peach tree borer is another member of this group. The SCM is a strong, wasplike flier, with two yellow abdominal bands and clear wings, which gives it a superficial resemblance to a yellow-jacket wasp.

There is but one generation per year. Overwintering occurs as diapausing larvae in the plant crown; pupation runs from May to June. Emergence follows in three or four weeks with the first adults emerging about June 1, but most of them later in the month. The ovipositing females are flying, in the daytime, by the last week of June; their flight generally ceases by the first week of August. Each female lays an average of 400 eggs, several to a plant, on the underside of leaves near the crowns. Of these, 58% may be viable (Wilcox *et al*. 1932). The eggs hatch in about ten days and by mid-July half of the new generation of larvae have bored into the crowns of the strawberries; by July 31 90% have done so (Wilmot 1978). A number of larvae will inhabit a crown, 20 or 30 may be average, with 60 or more possible (Wilcox *et al*. 1932).

Damage

Most of the damage caused by the species occurs in early summer when full-grown, overwintered larvae, which are 2 cm long, end their diapause and begin feeding. Up to this time few infested plants will be killed, but after the resumption of feeding much of the plants' vascular system may be consumed with a commensurate loss in plant health. Newly infested plants may take on a noticeable red hue in late summer.

Detection and control

Detection of a crown moth infestation should be done while the adults are flying. Close observation of fields in the daytime in June and July may reveal the presence of the swiftly flying adults, which fly 8 to 10 inches off the ground. A pheromone for SCM has been developed which is being used to attract the males to sticky traps. Control measures can then be based on the number of males present in a field. These traps are being extensively used in commercial pest management programs in Washington County (LaLone pers. comm.). They are placed at one per five acres of berries and an insecticidal spray is applied when between two and six males are caught per day.

Control of the SCM is difficult since oviposition occurs at the time of harvest and at other times the larvae are invulnerable inside the plant crown. A spray of Lorsban is currently being used by growers as directed by the catches in the pheromone traps. Fisher and Weinzien (1981) and Fisher (1982) list several effective cultural controls of the SCM:

1. Culling: Remove individual infested plants and destroy.

2. Trap planting: After harvest, leave several rows of plants unmowed to attract ovipositing females. These rows are later sacrificed by discing or tilling in the fall.

3. Discing infested fields: If a field is to be plowed under after harvest, wait until mid-August to attract the maximum number of ovipositing moths. Spring discing will be less

effective since some moths will complete their development even in dead or dying plants.

4. Avoidance: Do not plant a new field where infestation can occur from a infested adjacent one.

5. Barriers: Moths fly very close to the ground, so barriers such as wind breaks, woods or tall grains may restrict their dispersion.

6. Alternative host destruction: Cane berries in nearby fields should be given a soil drench of Guthion or Diazinon in the fall or spring. This will kill the larvae of the SCM and prevent spread into strawberry plantings.

Incidental arthropods

There are two other soil arthropods that occasionally infest strawberry fields severely enough to cause economic damage. One of these is the garden symphylan, *Scutigerella immaculata* . This is a small centipede-like animal from 6-8 mm in length. It seems to occur mainly in the Willamette Valley and Southern Washington, where it will occasionally devastate first year fields of strawberries by feeding on the rootlets. Infestations are erratic and unpredictable, varying in intensity within a field and from year-to-year (Shanks pers. comm.). Fumigation with dichloropropene or with dyfonate is recommended if a symphylan problem is predicted (PNW Insect Control Handbook 1981).

The larvae of June beetles have occasionally been damaging in newly broken grassland planted to strawberries. These plump, 2cm larvae, commonly called white grubs, are each capable of devouring the roots of several plants in a season. They are most likely to be a problem in a sandy soil. The western ten-lined June beetle, *Polyphylla perversa*, caused serious loss in strawberry fields on Vancouver Island before it was controlled with organochlorine insecticides (Cram pers.comm.).

Verticillium wilt

Importance

Verticillium wilt, caused by *Verticillium dahliae*, has been an important disease of strawberry on the North American west coast, particularly in California. The incidence of wilt there was partly responsible for the change, in the 1960s, to the practices of annual cropping and soil fumigation. In the PNW, wilt has not been so critical, and although most Washington and Oregon growers see it occasionally, it is not often considered to interfere with overall high yields. In the Fraser Valley of British Columbia, wilt is seen rarely (Pepin pers. comm.). Outbreaks may nevertheless occur in strawberries wherever wilt inoculum is allowed to increase through growing susceptible crops.

Distribution and host range

The list of plants attacked by *Verticillim* is very extensive, including deciduous trees, herbaceous annuals and perennials of the Compositae, Rosaceae, Leguminaceae, and Solanaceae. Tomatoes, potatoes, peppers and eggplants are especially good hosts for the fungus and may be expected to increase inoculum where they are grown. Wilhelm and Nelson (1980) mention four common genera of weeds as notably efficient wilt carriers: *Xanthium* (cocklebur), *Senecio* (groundsel), *Solanum* (nightshade), and *Physalis* (groundcherry). Most caneberries are also highly susceptible to wilt and so should not be rotated with strawberries when possible. Grass cover crops are often resistant to *V. albo-atrum* but not *V. dahliae*, the causal agent of strawberry wilt, and so inoculum will not be reduced when they are used in rotation (Sewell and Wilson 1966).

Biology

The species of *Verticillium* attacking strawberry was long thought to be *V. albo-atrum* Rke. and Berth., but a number of taxonomists now consider the pathogen to be a separate species, *V. dahliae* Kleb. The two species are genetically so similar that not all verticillium specialists agree that certain morphological differences are sufficient grounds on which to base a speciation. The two forms differ mainly in the type of resting structure they produce: *V. dahliae* forms small, several-celled sclerotia termed microsclerotia (MS), whereas *V. albo-atrum* forms a darkened, dried, resting mycelium but no sclerotia. Isaac (1967), observed hundreds of isolates of both forms, and never saw the MS type forming resting mycelia or *vice* *versa.* He thus considered the two forms to be discrete species. Nevertheless, the two forms are able to undergo hyphal fusion and genetic recombination, which suggests a very recent and incomplete speciation (Fordyce and Green 1964). The two forms are known to respond differently to temperature. The MS form is capable of growth at temperatures of 30 C whereas the resting mycelial form is not, and this may be a factor in their varying distributions. (Isaac 1967).

V. dahliae is known to differentiate into biotypes of varying pathogenicity to strawberries (Bringhurst *et al.* 1961), tomatoes (Griffiths and Isaac 1966), and nightshade (Wilhelm 1961). The potential for the evolution of host-specific races, or *formae specialis*, in the *fungi imperfecti* has been well documented by studies of *Fusarium*. Despite the fact that few *formae specialis* have been named in *Verticillium*, there is little doubt that it behaves like *Fusarium*. This implies that certain crops used in rotation with strawberries might be expected not only to increase verticillium inoculum, but also to foster biotypes highly pathogenic to strawberry.

Taxonomically, *Verticillium* is a member of the *Fungi imperfecti* because it lacks a sexual stage. Reproduction is by production of conidia which are the primary infective units of the fungus and account for its spread from plant to plant. Although lacking the ability to sexually combine chromosomes, abundant genetic recombination occurs in *Verticillium* through the processes of parasexuality and heterokaryosis (Isaac 1967, Hastie 1970, Day 1974). These phenomena allow the fungus adequate genetic variation to meet the demands of changing hosts and environments. A *Verticillium* heterokaryon may contain two or more nuclei per cell, one of which contains genetic information for a parasitic mode of activity and another for a saprophytic mode (Hastie 1970). Depending on conditions, new hyphal cells with one or the other of these sets of information will be favored to grow and reproduce. Thus, the fungus is allowed a bi-modal existence and tremendously increased adaptability.

V. dahliae overwinters as thick-walled, microsclerotia which are produced in abundance within infected plant tissue. After the breakdown of the tissue of the invaded plant, these are released into the soil where they are very persistent, so that inoculum builds up year after year where wilt is present. Infection occurs when a rootlet comes into contact with a microsclerotium, thus stimulating conidiogenesis and penetration of the rootlet. A systemic infection of the plant's xylem vessels follows, spreading from the roots to the tops. The greater the initial inoculum source, the earlier the symptoms develop, the more severe they are, and the more yields are affected (Powelson 1970). Sewell (1960) found the mycelia of *V. dahliae* to be almost incapable of growth through the soil, so that secondary spread of the pathogen must be either by conidia dispersed by water or cultivation or by contact with the roots of an infected plant. Since lightly infected plants do not allow the fungus to sporulate, there may be little secondary spread of the disease until the inoculum builds to a critical level. Where susceptible hosts and symptomless carriers are present, inoculum can accumlate over a period of many years. The microsclerotia of V. dahliae are extremely long-lived; they are known to remain viable in the soil for eight to ten years (Wilhem 1961).

Damage

Verticillium causes a characteristic wilting and death of strawberry plants but without the vascular streaking often seen in other crop plants. Wilt is usually most severe in the crop's first year of growth with the symptoms starting in the warm weather of June and continuing through the summer (Wilhelm and Nelson 1980). The outer leaves are affected first, with drying of the margins and interveinal areas and then total collapse. This progresses, with few new leaves appearing until the plant finally succumbs. Verticillium wilt can be distinguished from red stele by the way in which the central leaves and crowns remain green up to the death of the plant (Wilhelm 1980).

Detection and control

Verticillium wilt can be spotted in early summer when the symptoms first appear. The first symptoms are brownish or blackish streaks on the upper side of the petioles, soon to be followed by the reddening and wilting of the outer leaves (Wilhelm 1961); infection can then be readily verified by microscopic examination of isolations from the crown and older leaves (Plakidas 1964). Predictive propagule counts can be taken from rhizosphere samples, but this method is of doubtful value. Since from 10 to 200 propagules of V. dahliae/g of soil are capable of causing severe disease (Powelson 1970), the predictive value of a count is low. In addition, many biotypes low pathogenicity exist, and when these are found in soil samples they will confound disease assessment (McElroy pers. comm.). Bio-assays, done by infecting and observing growing plants, are accurate indicators, but time-consuming and expensive. Consequently, outbreaks of wilt are not easily predicted and once discovered much damage may already be done.

Where it is allowed to become a problem, verticillium is difficult to control. None of the currently grown strawberry varieties has adequate resistance to the disease and cvs Benton, Olympus, Shuksan, and Totem are all highly susceptible (Wilhelm and Nelson 1981). Verticillium can be controlled by fumigating with chloropicrin and tarping of the field as is done effectively in California. However, the cost of the operation has been thought too high for use in the PNW. Up until 1983, an alternative source of chloropicrin was available to growers in Washington and Oregon in the form of Terr-o-cide. This fumigant contains 54% ethylene dibromide and 44% chloropicrin, and was used for disease, nematode, and weed control in strawberries. Ethylene dibromide (EDB), however, was recently de-registered by the EPA so Terr-o-cide has now been removed from the market.

The most effective way to deal with wilt in the PNW remains a well-thought-out rotation. Since microsclerotia of V. dahliae are so long-lived, a field may essentially be ruined for strawberry cultivation by a rotation that includes wilt carrying crops, and so non-susceptible crops must be used. Also important is the removal and destruction of any infected plants seen during the season. Since these contain enormous amounts of stable inoculum, care should be taken to remove them from the field regularly, and never to plow them under.

Red stele

Importance

Red stele is the best known and most damaging disease of strawberry roots in the PNW. It has been known since the 1920s and it occurs widely in North America and Europe, but is most damaging in areas with cool climates. In the PNW, red stele has been a major limitation to the use of certain susceptible varieties. In 1962, Daubeny and Pepin surveyed the lower mainland of B.C. for red stele and found it to be causing moderate to severe damage in 71% of 80 sampled fields. At present, strongly resistant varieties, such as Totem and Benton, are the most widely grown. Even with resistant stock, red stele can be a problem in heavy or poorly drained soils and in winters of continuous rainfall. Lands in Washington and Oregon favoring development of red stele have largely been dropped from production and replaced by those with lighter soils. All of the growers I interviewed regularly find red stele in their strawberries, but the reduction in yield from it is unknown.

Distribution and host range

Red stele is found throughout the strawberry growing regions of the PNW. However, the causal agent, *Phytophthora fragariae*, has formed ten or more physiologic races, only certain of which may be found in any given locality. The importance of this is in its effect on the usefulness of resistance to specific races of the fungus.

The host range of *P. fragariae* is narrow but not restricted to strawberry. Races have been found to successfully attack raspberry (Pepin 1967), loganberry (McKeen 1958), and *Potentilla glandulosa*, or sticky cinquefoil (Converse and Moore 1965), a common weed in growing areas. These plants may provide an inoculum reservoir for the pathogen.

Biology

Red stele is caused by the Oomycete, *Phytophthora fragariae* Hickman. In many ways this fungus is similar to the better known *P. infestans*, the pathogen of potato late blight. Both fungi are favored by cool, semi-aerobic conditions, and tend to differentiate into races to overcome specific resistance in their hosts. Both are strongly parasitic, weakly saprophytic, and very host specific. In contrast to *P. infestans*, which does not produce oospores, *P. fragariae* is able to produce these, despite being homothallic (Converse and Shiroishi 1962). The ability to reproduce sexually gives *P. fragariae* substantially more genetic variation and adaptability than if meiotic recombination were not present (Day 1974). The oospores thus formed by the fungus act as long-lived resting propagules. Infection occurs through root contact by swimming zoospores released from sporangia. These sporangia may arise from mycelia, or may be produced on germinating oospores, which apparently do not infect the roots directly (Duncan 1980). Infection usually occurs at the root tips with subsequent colonization and discoloration of the stele, or central tissues of the root. The disease is favored by cool, wet weather, and so infection proceeds in the fall, winter and spring. In the summer, those infected plants that have survived the disease will regrow their roots and not express symptoms, thus masking the presence of the disease. The pathogen is spread through the movement of oospores and zoospores in soil, diseased plant roots, or water. The oospores are very durable with a viability of at least three years in moist conditions at 3 C (Duncan and Cowan 1980). Infested lands must, therefore, either be taken out of production or another and more resistant cultivar planted.

Damage

P. fragariae starts its attack at the feeder roots, destroys these, and then moves to the larger secondary and primary roots. Eventually, all laterals will be rotted off the primary roots and a withered 'rat-tail' effect will occur (Plakidas 1964). The central tissues of the root will turn a reddish brown, which makes for easy diagnosis of the disease. Generally, the disease will take out patches of plants within a field, often in low lying places where water has accumulated in the winter.

Control

The most effective measures against red stele are the use of resistant varieties grown in light, well-drained soils. Breeding resistance to red stele into strawberry has been difficult because of the genetic flexibility of the fungus. A discussion of this will be saved for chapter III. Several of the recent cultivar releases are field resistant to red stele, and up to this point, have been holding their own against the fungus. Thorough drainage of fields by tile, open ditch, and subsoiling are crucial to successful control of red stele. In the PNW, chemical control has not been effective. Broad-spectrum fumigation, as practiced in California, has not been considered practical due to its high cost. Post-plant, fungicidal drenches have been tested with some successes, but a compound has yet to be registered for this application (Montgomerie and Kennedy

1979, MacSwan 1979, Bristow 1980 and 1981). Despite this, the systemic metalaxyl (Ridomil), is being used by some growers against red stele, and is reported to be very effective.

Black cortical root rot

Importance

The black cortical root rot of strawberries is a state of deteriorating root health caused by the actions of certain soil microflora under environmental conditions unfavorable to root growth. Although it is still present in many areas, black root rot is less important now than it was 20 years ago. The impact of the disease has been lessened by confining the strawberry acreage to areas with light soils, by growing new and more frost hardy varieties, and by improved methods of culture.

Distribution

Black root rot occurs wherever strawberries are grown but is most likely to be a problem in areas where they are subject to frost damage while incompletly dormant. This is because freezing of unhardened roots and crowns impairs the integrity and function of protective tissues, allowing increased entry and colonization by opportunistic soil microflora. The areas of the PNW subject to sub-freezing, east winds in the winter, are at higher risk than are more sheltered locations. The upper Fraser

Valley in B.C., Multnomah county in Oregon, and parts of Washington's Clark county are three such areas.

Biology

The pathogenic agents involved in the black root rot complex are indigenous soil fungi, nematodes, and bacteria. Researchers have isolated many species of fungi from strawberries with black root rot, but some are more often involved than others. *Rhizoctonia solani, R. fragariae, Pythium ultimum, Cylindrocarpon radicicola,* and *Fusarium spp.* are all isolated frequently, often in various combinations (Plakidas 1964, Wilhelm 1961). Wilhelm (1961, 1981), and Wilhelm and Nelson (1980), authorities on the subject, stated their belief that *R. fragariae* or its perfect stage, *Ceratobasidium*, and *P. ultimum* were "the primary factors responsible" for black root rot. Most of the fungi involved in black root rot are weak parasites, living saprophytically in the soil and becoming pathogenic only when the strawberry roots are stressed by conditions of waterlogging, low oxygen, or root injury.

An important element of the black root rot complex is the root lesion nematode, *Pratylenchus penetrans*. This ubiquitous nematode is almost always found with rotting strawberry roots and appears to induce onset of the disease. Feeding by the nematode causes necrotic lesions on the roots (Townshend 1962b), which then become infection courts for opportunistic fungi and bacteria. This was illustrated by tests in which the nematocide, dichloropropane-dichloropropene, (D-D), reduced black root rot, whereas applications of a fungicidal compound, formaldehyde, did not (Klinkenburg 1955). High concentrations of *P. penetrans* in the soil thus appear to increase the incidence of black root rot.

Control

Black root rot is favored by poorly drained soils, frost damage prior to hardening off, severe winter freezes, and high concentrations of *P. penetrans*. Reducing the rot is therefore dependent on changing these factors. Where possible, strawberries are grown only in fields having a sloping topography to avoid settling frost, and having light, sandy soils. These are often drained by tile, PVC pipe or open ditches and subsoiling done in the fall before heavy rains. Frost hardy strawberry varieties are used when possible, especially in frost pockets and areas subject to east winds in the winter. Nematodes are controlled prior to planting, by nematocidal fumigation.

Root lesion nematode

Importance

A number of nematodes are commonly associated with the roots of strawberries in the PNW, but apparently only the dagger, needle, and lesion nematodes cause noticeable damage.

The lesion nematode, *Pratylenchus penetrans* Cobb, is much the most damaging of these because it is polyphagous, has large populations, is widely distributed, and is highly pathogenic to strawberry roots. In addition, it is known to interact synergistically with opportunistic soil fungi to cause black root rot, and with *V. dahliae* to increase the incidence of wilt. The lesion nematode is endemic in most cultivated areas in the PNW and if uncontrolled, builds to great numbers in strawberry plantings. Townshend (1962a) found about 87% of Ontario plantings to be infested by the lesion nematode, and McElroy (1977) isolated it from 89% of 287 samples from seven strawberry fields in B.C. McElroy's survey also revealed that there were substantial numbers of the following nematodes in strawberry fields: *Aphelenchoides, Aphelenchus, Heterodera, Paratylenchus,* and *Tylenchus,* but none of these was related to plant damage.

Most growers in the PNW are aware of the damage potential of the lesion nematode, but they consider that fumigating prior to planting will reduce the damage to an insigificant amount. This may be too optimistic, for *P. penetrans* populations can already be rebounding only 36 weeks after fumigation with D-D (Alphey 1981). Cooper and Thomas (1971), working with *Trichodorus sp.* in potato, estimated that with two generations per year, and a doubling of population, it would take only three years for the nematode to reach its former level following a 98% reduction. The lesion nematode has a life cycle of 35 to 85 days, so if we assume a resident population of 2000/1

(1000/pint) of soil, three generations per year, and a 2% survival rate after fumigation, the original level would be reached in two years; with four generations per year, only a year and a half would be needed. _P. penetrans_ may be able to complete its life-cycle in 3-4 weeks, so four generations/year is not unrealisic (McElroy pers. comm.). These rough projections do not take natural mortality into account, but they indicate nevertheless, that given ineffective fumigation, nematodes may easily reach damaging levels within the life of a strawberry crop.

Distribution and host range

In the PNW, the lesion nematode is found wherever strawberries are grown. Unhappily, it is favored by the coarse, sandy soils in which strawberries are often grown to avoid root rots (Haglund pers. comm.). Fine textured, clay soils inhibit movement and population increase of the needle, dagger and lesion nematodes (Townshend and Weber 1971, McElroy 1977). The lesion nematode is securely established in most areas because it is able to parasitize a great range of plants. A total of 232 plant species in 51 families have been reported as hosts of _P. penetrans_, and there are undoubtedly more (Jensen 1953, Townshend and Davidson 1960). Many legumes and a number of other hosts favor rapid increase of the lesion nematode, while showing little damage or loss of yield (MacDonald and Mai 1963). Certain other plants are unfavorable hosts for the nematode, but are nevertheless badly damaged by its activities. Strawberry is considered one of the latter by Oostenbrink (1972), but even so, *P. penetrans* finds strawberry roots favorable enough to become the most numerous and widely distributed nematode in strawberry plantings (McElroy 1977, Townshend 1962a). Favorable crop hosts for increase of the lesion nematode are the legumes: white sweet clover, hairy vetch, black medic, and soybeans; and the grasses: timothy, oats, and corn (Ferris and Bernard 1963, MacDonald and Mai 1963 , Thorne 1961, Townshend and Davidson 1960). Some of the crop and weed species that Townshend and Davidson (1960) found to support the highest populations of the lesion nematode are shown in Table 1.

Table 1. Root lesion nematode counts on weed roots*

Host:	Average number of *P. penetrans* per gram of root:
Creeping Yellow Cress *Rorippa sylvestris*	27,680
Mouse-ear chickweed *Cerastium vulgatum*	23,607
Yellow hawkweed *Hieracium pratense*	18,100
Annual daisy fleabane *Erigeron annuous*	13,637
Timothy *Phleum pratense*	11,556
White sweet clover *Melilotus alba*	9,655
Prickly lettuce *Lactuca scariola*	8,404
Common groundsel *Senecio vulgaris*	7,225
Common dandelion *Taraxacum officinale*	7,225
Field peppergrass *Lepidium campestre*	6,947
Mayweed *Anthemis cotula*	6,804
Black medic *Medicago lupulina*	6,349

*from Townshend and Davidson 1960.

Biology

P. penetrans is a migratory endoparasite of about 0.5mm in length. The nematode overwinters within the cortex of secondary and feeder roots as eggs, larvae or adults. Here it incites the formation of dark brown lesions which are often invaded by fungi and bacteria. The adult and juvenile forms are motile within or without the roots and frequently leave the lesions in search of fresh hosts. Both sexes are present in the population, which implies a heterogeneous gene pool, but the females are able to reproduce without fertilization.. The eggs are laid singly or in small clutches within the plant roots and these may hatch there or remain dormant through the death and deterioration of the root. The nematodes undergo their first molt inside the egg and the second stage larvae break out and migrate to new roots. The reproductive potential of *P. penetrans* is rather low; each female lays one egg per day (Thorne 1961). The full life cycle takes between 35 and 85 days depending on host type, soil temperature, and other factors (Norton 1978). The larvae and adults are persistent in the soil, surviving best when the oxygen supply is adequate but temperature and moisture are low. In one experiment, lesion nematodes without host roots declined by roughly 50 to 60% in 24 weeks, surviving longest at temperatures below 12C (Townshend 1971). They were predictably killed by freezing temperatures, which may account for low spring soil counts in areas of cold winters.

Damage

A lesion nematode infestation will usually appear as patches of chlorotic and stunted plants in a field, but in some cases it will show nothing more than areas of indifferent growth. These expand slowly, at several feet per year, most often along the rows where the roots are interlocking. In strawberries, lesion nematode damage is often associated with low grade fungal pathogens but serious root injury occurs even if only bacteria are present (Townshend 1962b). *P. penetrans* mainly attack the small feeder roots and cause the formation of lesions which may eventually coalesce and girdle the root. In a severe infestation, most roots are girdled and a much diminished, stubby root system is all that remains.

Detection and control

Monitoring for potential nematode damage is done by soil sampling. At present in the PNW, there are several university and private laboratories which perform this service. Samples are taken after the pre-plant fumigation or, preferably, both before and after. If more than 200 root lesion nematodes/l of soil are found, fumigation is recommended (McElroy pers. comm.). Oostenbrink's (1972) estimates of threshold populations vary from 50 to 1000/l, depending upon the soil type. Thresholds are lower in sandy soils because of the nematodes' greater reproductive potential there.

Control of the root lesion nematode consists of a pre-plant fumigation with D-D. This is done either in the spring or the fall but fall fumigation is the more effective because the soil is warmer at that time, which increases the diffusion of the fumigant. Fumigation with methyl-bromide is very effective against all nematode pests. Ethelene dibromide was used as a pre-plant fumigant for nematode control until the fall of 1983 when it was removed from the market because of suspected carcinogenicity.

Needle and dagger nematodes

Three species of nematodes other than the lesion nematode are potentially important in strawberries in the PNW. These are the needle nematode, *Longidorus elongatus* de Man, and the closely related dagger nematodes, *Xiphinema bakeri* Williams and *X. americanum* Cobb. All are native to the region and have spotty distributions. These nematodes are large, from 2 to 7mm long, and so need coarse soils with large pore spaces in order to function. They are not likely to be present in soils containing more than 25% clay (McElroy 1977). Their reproductive cycle is generally slow, often taking a year or more per generation. Reproduction of *X. americanum*, for example, is seasonal in cold climates so that there is but a single generation per year (Thorne 1961). However, under uniform greenhouse conditions, and with a strawberry host, X. bakeri multiplied rapidly, increasing 4.2 times more than in the fallow control in 12 weeks (McElroy 1972). This led McElroy to postulate an eight-week life cycle for the nematode under ideal conditions. Yassin (1969) demonstrated a 19-week cycle for L. elongatus in greenhouse tests. Since PNW winters are usually mild enough to allow root growth of strawberries, it follows that root feeding nematodes would remain active and reproductive, although not at the rates observed under experimental conditions. In strawberry fields, concentrations of the needle and dagger nematodes often reach 2000-2500/l of soil (Moore 1977, McElroy 1972).

Nematodes of this group are free-living ecto-parasites which feed on small lateral roots of plants through a hollow stylet. Lacking the protection of a root, they are vulnerable to nematocidal compounds used as dips or drenches. They are not, however, susceptible to drying or starvation. X. americanum, for example, has been observed to survive for 49 months without a host (Dropkin 1980).

Distribution and host range

Both the needle and dagger nematodes are polyphagous with many crop and weed hosts in strawberry growing areas. For the dagger nematode, tomato, potato, ryegrass, orchard grass, and strawberry are excellent crop hosts, and mouse-ear chickweed, common chickweed, lambsquarters, and barnyard grass are good weed hosts (McElroy 1972). X. americanum has an equally wide host range and occurs widely in North America. In B.C., however, it is largely isolated in areas in the upper Fraser Valley (McElroy 1977). The needle nematode is increased by the presence of tomato, ryegrass, white and red clovers, and strawberry; and by shepherds purse, common chickweed, annual bluegrass, and common speedwell (Thomas 1969, Taylor 1967). Non-hosts or poor hosts of *X. bakeri* are turnip, corn, bean, cucumber, and the cole crops, *Brassica oleracea* (McElroy 1972). For the needle nematode, onion, beet, crucifers, mint and raspberry are poor hosts (Thomas 1969).

Damage

The needle and dagger nematodes are capable of causing direct injury to roots and, perhaps more importantly, can act as vectors for viruses. Nematode transmitted viruses, or nepoviruses, are destructive in European and British strawberry plantations (Lister 1960, Trudgill 1982, Moore 1977). In Britain, the needle nematode transmits the tomato black ring virus and raspberry ringspot viruses. Another cosmopolitan species of *Xiphinema*, *X. diversicaudatum*, transmits arabis mosaic virus to strawberries. These viruses are not present in the PNW, but considering the similarity of climates between the region and Great Britain, and the presence of capable vectors, it is plain that these viruses pose a continuing threat. The only nepovirus that is a present problem in the PNW is tomato ringspot, or TomRSV (Mellor and Stace-Smith 1963, Converse 1981, 1982). The extent of TomRSV injury is unknown but the potential of the virus to cause disease is not in question. Dr. Richard Converse (Oregon State University) has observed a field where the strawberries had collapsed from TomRSV, and 8000 dagger nematodes/l soil were found. (Converse pers. comm.). Significantly, *X. americanum* may not be the sole vector of TomRSV; *X. rivesi* may play a part or the nematodes involved may comprise a heterogeneous 'species swarm'. In addition, TomRSV is possibly vectored by *Tetranychus* mites or by weed seed (Converse pers. comm.). Where dagger nematodes are found, the possibility exists that TomRSV is present, with effects, to some degree, on plant wellbeing. Since the symptoms may appear similar to those caused by other viruses and root rots, they may easily be ascribed to these agents. TomRSV is harbored in caneberries, wild strawberries, and many weeds, and may be spread by weed seeds (Converse 1982).

In addition to TomRSV, the closely related yellow bud virus of peach is vectored by the dagger nematode and has been isolated from the wild strawberry, *F. chiloensis*, on the coast of California (Frazier *et al*. 1961). It is not known if this virus is ever transmitted to cultivated strawberries.

Apart from the disease potential of vectored viruses, the needle and dagger nematodes cause severe direct injury to strawberry roots by their feeding. The damage done by these nematodes is often comparatively greater than that of the lesion nematode. On raspberry, only 200 *X. bakeri*/l of soil reduced top growth by 40 to 50% (McElroy 1972). *L. elongatus* is also very pathogenic, with 130/l of soil causing severe root injury (Szczygiel and Dauek 1974). The small feeder roots are first attacked by both species and are killed. The tips of larger primary and secondary roots are then fed upon, causing a thickening or galling, and eventually only a few, thickened, "fish hooked" primary roots will be left to the plant.

Detection and control

The monitoring and control of these three nematodes is the same as for the lesion nematode. On farms with heavy soils they are not often a problem, but on others they require monitoring along with the lesion nematode. Economic injury levels of 500/l have been proposed for the needle nematode (Seinhorst 1966), and, because of its virus vectoring potential, zero for the dagger (Converse 1980). *X. bakeri* is not thought to vector viruses, but some diagnostic labs may not differentiate it from *X. americanum*.

Fumigation with D-D is used to control all nematode species prior to planting. Since the needle and dagger nematodes do not enter the roots, they are much less likely to be imported with planting stock than are root lesion nematodes.

Weeds

Importance

In horticultural crops, the importance of weeds in limiting yield potential is often underestimated or overlooked. Weeds are considered root pests in this paper because of the many harmful indirect effects they have on strawberry roots (Fig. 2). Strawberries are particularly susceptible to interference from weeds because of their low profile and often shallow, fibrous root system. They can thus easily be overgrown by tall weeds, and their roots are so situated that weeds compete directly with them for moisture and nutrients. Furthermore, both the PNW climate and the cultural systems used there, favor weed growth and interference. The winters are generally mild enough to allow a number of annual weeds such as chickweed, groundsel, and annual bluegrass, to grow through the fall and winter. After a winter of vegetative growth, many winter annuals will flower and seed early, and since their growth is by no means restricted to the winter, will be in a position to carpet the field come spring. The control of winter weeds is sometimes hampered by the incomplete dormancy of strawberries in the PNW in the winter. Some useful herbicides, such as dinoseb, can be phytotoxic when the plants are incompletely dormant (Freeman 1964). The use of matted rows, the predominant spacing system in the PNW, also confounds weed control. Matted rows are about 14in. wide and consist of mother plants that have runnered to form solid mats of strawberries. Once the runners start to cover the rows, mechanical tillage cannot be used, and the use of herbicides which inhibit the rooting of daughter plants is also ruled out.

Biology and damage

Weeds are classed according to their life cycles as annual, biennial, or perennial. In the PNW, the term 'winter annual' often replaces biennial, since many normally biennial weeds complete their rosette stage in the mild winters. In a spreading, perennial crop such as strawberry, the most serious weeds are those perennials that have a rapid vegetative spread. Once established in strawberry fields, weeds such as horsetail, yellow nutsedge, quackgrass, and Canada thistle cannot be controlled by either mechanical or chemical means. These weeds tends to be highly aggressive, competing with the strawberry plants for water, mineral nutrients, and space. In addition, a number of perennial weeds are able to inhibit the growth of crop plants by releasing allelopathic chemicals into the soil. Yellow nutsedge, quackgrass, and certain clovers are all suspected of this ability (Rice 1974, Datta and Bandyopadhyay 1981) Quack grass appears to be especially allelopathic, although how so is not clear. The growth of alfalfa, flax, wheat, oats, and barley can be reduced where quack grass has previously been grown (Kommendahl and Berardini 1959).

Where good farming is practiced, annual weeds are often more of a problem than perennials. In a clean operation, perennial weeds are eliminated from a field prior to planting, whereas annuals are often better adapted for wind distribution of their seed. Most are well suited to the full sun and the irrigated conditions found in strawberries, and may produce seed continuously during the growing season. Groundsel, creeping yellow cress, the chickweeds, and many other winter annuals, are excellent hosts for the root lesion nematode, and so may help to maintain high populations of it through the winter. Many weeds are symptomless carriers of Verticillium as well, and if uncontrolled, can increase wilt inoculum. Red-root pigweed, groundsel, and Solanum spp., are all symptomless carriers (Ndubizu 1976, Wilhelm and Nelson 1980).

Annual weeds are also capable of allelopathic activity. Certain Polygonum, Amaranthus, and Crucifer spp. possess some degree of allelopathy (Kloot and Boyce 1982, Rice 1974). Finally, the annual chickweeds, corn spurry, and lambsquarters have been implicated as reservoirs of nepoviruses (Converse 1982, Fryer and Evans 1968).

Control

For all the reasons mentioned, weeds are generally kept at the lowest possible levels in strawberries; a good management program will identify and target those weeds that are the greatest threat to the crop. The injury potentials of some common PNW weeds are presented in Table 2. Control is started in the year prior to planting with clean cultivation supplemented by a contact herbicide. A plowing, followed by repeated cultivations in the dry months of July to September, kills or weakens most perennial weeds by depleting their food reserves. In the fall, a clean-up spray of amitrole, or glyphosate, is applied. After planting the strawberries in the spring, a pre-emergent chemical is used, usually simizine, chloroxuron, or napropamide. Simizine and napropamide are long residual chemicals and so are aplied but once a year; chloroxuron can be applied several times per season, as necessary.

A satisfactory pre-plant clean-up and competent use of pre-emergent herbicides should result in effective weed management. Certain weed species, however, are tolerant of these herbicides and will continue to be a problem. Shepherds purse, red-root pigweed, lady's thumb, groundsel, and the mustards show some tolerance to napropamide (Freeman 1982). Barnyard grass and groundsel are tolerant of simizine, and many grasses are not controlled by chloroxuron (B.C. Berry Production Guide 1983).

Table 2. Pest status of certain common weeds

Weed	Life-cycle	Vegetative spread	Allelopathic	Root lesion nematode	Needle and dagger nematodes	Verticillium wilt	Herbicide resistant
barnyard grass	*	-			*		*
common chickweed	**	*		*	**		-
clover	***	*	*	**	*		*
dandelion	***	-		**	-	*	-
groundsel	**	-		**	*	*	*
horsetail	***	**		*			*
smartweed	*	*	*	*			*
lambsquarters	*	-	-	*	**		-
mouse-ear chick weed	**	*		**	**		-
mustard	**	-	*	-	-		*
plantain	***	-		**	*		-
quackgrass	***	**	*				*
red-root pigweed	*	-	*	*		*	*
blackberry	***	*	*	*	*	*	*
shepherds purse	*	-		*	*		*
nightshade	***	-	*	*	*	**	-
yellow nutsedge	***	**	*				*

* indicates the presence of, or positive host capability

- indicates the absence of, or negative host capability

** indicates extreme presence of, or excellent host capability

life-cycle: *=annual, **=winter annual, ***=perennial

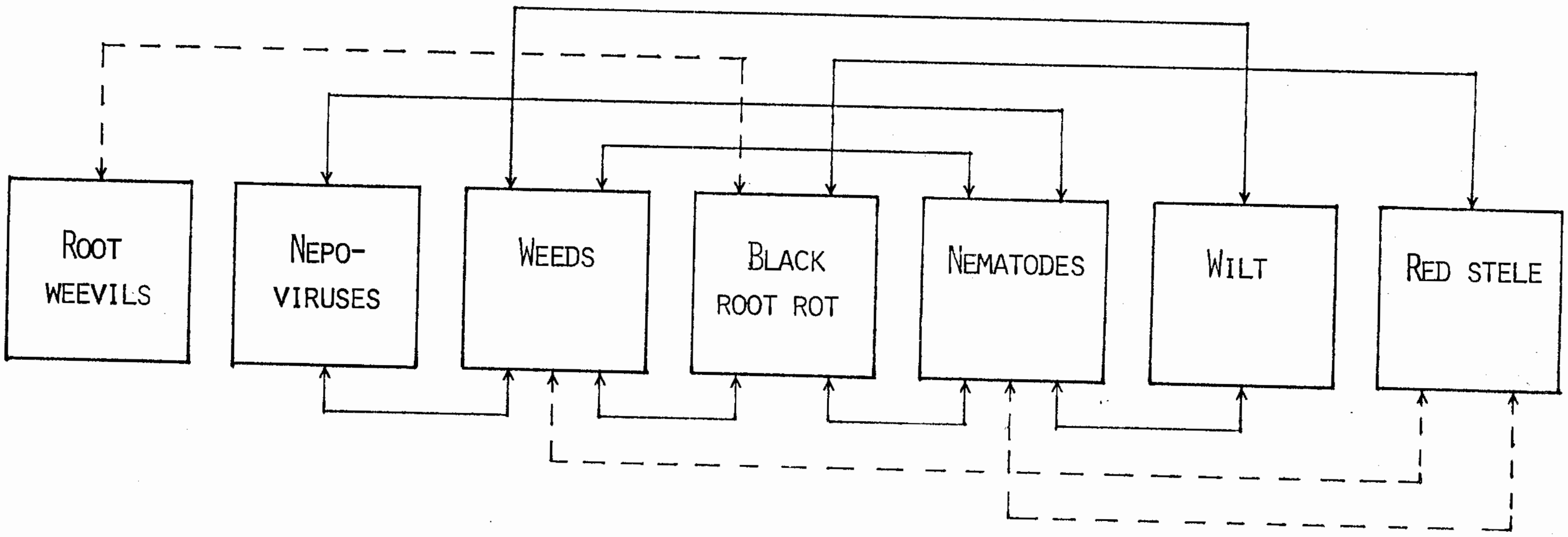
herbicide resistance: to either simizine or napropamide

blank space: unknown

Root pest interactions

The harmful microbes, nematodes, and arthropods of the strawberry root ecosystem often form interrelationships which favor their growth. This produces a 'pest complex', where the fate of each pest affects, to some extent, the fate of all the others. In order to manage this pest complex efficiently, it is necessary to understand these interactions and how changes to the ecosystem affect them. The pest interactions occurring in the strawberry root environment are illustrated in Fig. 2. These occur in the form of the following four mechanisms: disease vectors, inoculum reservoirs, mechanical wounding agents, and modifiers of substrate.

FIGURE 2. ROOT PEST INTERACTIONS*



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* Dotted line represents interactions of minor importance or suspected interactions.

Disease vectors

Two interactions of this type are well known in strawberries; the aphid and nematode transmitted viruses. Although the aphid-borne viruses are presently of the greater importance, nepoviruses are capable of becoming an economic problem. Important in the management of nepoviruses are thorough control of the nematode vectors and of the weed reservoirs of the viruses. Since only one nematode-root contact is needed to transmit a virus, the threshold for the nematode vector is zero. Weed reservoirs of the viruses should be identified and care taken to remove them from fields and headlands.

Inoculum reservoirs

This function is primarily performed by weeds, which are hosts to nepoviruses, nematodes, verticillium wilt, and red stele. The suitability of weeds as hosts for the several nematodes varies from poor to excellent. The progress of verticillium wilt through a field can often be directly related to the presence of *Verticillium* carrying weeds or crop plants. Red stele inoculum may be supplied by rosaceous weeds such as the cinquefoils and brambles. In addition to favoring populations of nematodes and *Verticillium*, weeds may also change the spectrum of low grade soil pathogens and saprobes to one more or less inimical to strawberry roots. The experiments of

Hildebrand and West (1941) showed the power that plant roots and foliage residues have to selectively favor certain soil fungi and bacteria. Thus, the growth of certain species of weeds may lead to proliferation of the nematode or the fungal and bacterial components of black root rot.

Mechanical wounding agents

Nematodes are the important wounding agents in the strawberry root system. The lesions produced by *P. penetrans* are well-known to act as infection courts for the many fungi and bacteria of the black root rot complex. The lesion nematode also plays an important role in increasing verticillium wilt, and this is at least partially due to mechanical wounding by their stylets. Experimentally, *P. pentrans* introduced with *V. dahliae* increases the incidence and severity of wilt, decreases plant dry weights, and decreases the incubation period of the disease (Abu-Gharbieh *et al*. 1962, Faulkner and Skotland 1964, Ndubizu 1976). In some situations, the simultaneous presence of the two organisms results in synergism of disease. In mint, dry weights were reduced 22% by *P. penetrans* or *V. dahliae* but up to 68% when both were present (Faulkner and Skotland 1964).

Modifiers of substrate

Agents such as viruses, fungi, and nematodes are capable of changing the biochemical balance of their hosts, resulting in greater host susceptibility to these or other pathogens. For instance, the presence of *V. dahliae* infection in mint results in substantially greater reproduction of the lesion nematode than occurs in healthy plants (Faulkner and Skotland 1964). Conversely, in a number of cases, nematodes are able to increase the reproductive potential of disease agents in some way other than mechanical wounding (Powell 1963). This is demonstrated when the two similar nematodes, *P. penetrans* and *P. minyus*, which produce identical wounding, cause greatly differing levels of disease in their hosts (Pitcher 1965). In research with strawberries, *P. penetrans* secreted seven times more cellulase, and 50% more pectinase than *Heterodera trifolii*, a nematode ineffective as an incitant of black root rot. The injection of these hydrolytic enzymes into the roots appeared to strongly predispose strawberry to the root rot (Morgan and McAllan 1962).

Weeds may also play a role in altering the host substrate for attack by soil microflora. Allelopathic compounds, which may be washed from the foliage, exuded from the roots, or leached from decomposing residues, may directly condition the roots of plants for an increased incidence of disease (Rice 1974). The mechanisms behind this are unclear, but may often involve inhibition of mitosis and elongation of the root cells, or reductions in nutrient uptake (Fisher 1979). When applied as aqueous solutions to the roots, extracts of plant residues have greatly increased root rots of tobacco, bean, lettuce, and spinach (Patrick *et al*. 1963, 1964).

IV. The integrated pest management approach

The definition and philosophy of IPM has been thoroughly explored by numerous writers in the last decade or so. For my purposes IPM is simply defined as the directed management of the agroecosystem with control measures based on economic, ecological, and sociological consequences (Bottrell 1979). This implies that before the implemetation of any program, enough knowledge has been amassed in these areas to make reasonable, informed decisions. One objective of this paper is to make a start at collating such information as it applies to the pests of strawberry roots.

The advantages of IPM in control of above-ground arthropods have become clear. Based on thorough knowledge of pest biologies, sprays are precisely timed and are thus effective at minimum cost. The natural enemy complex, which may well account for most of pest mortality, is preserved through the use of selective pesticides and timed sprays. Cost-effective cultural controls, such as strip-cropping, sanitation practices, and timed seedings, are integrated with chemical controls. The upshot is, that through understanding and working with an agroecosystem pests are often naturally controlled and money saved.

Managed alteration of a soil ecosystem is complex and poorly understood. The pest complex is likely to include not only arthropods, but important fungal and nematode elements as well. Pest populations and economic damage are difficult to monitor in soil and so the economic threshold levels of most pests are unknown. Accurate predictions of the effects of control measures are often impossible because of the many interactions which occur among the pest complex and among the thousands of species of beneficial or incidental organisms. Moreover, the soil environment is in a dynamic equilibrium so that changes induced by the addition of chemical controls are often slight and short-lived. Certain cultural practices, such as field drainage and crop rotation, are potent modifiers of the strawberry root environment. The strawberry plant itself, through its susceptibility to pathogens, is a major factor in determining the make-up of the pest complex.

All of these factors must be acknowledged when designing a program for reducing the populations of key pests. Following, therefore, is a multi-disciplinary examination of the natural and imposed variables affecting strawberry root pests, and a mention of the value of ecosystem monitoring.

Natural controls

In planning an IPM program, an investigation should be made of the natural controls that are already working to regulate pest populations. Pest organisms are controlled largely by climatic conditions such as extremes of temperature and moisture, by competition for food and space, and by predation, parasitism, and disease. In an agroecosystem, the climatic and biotic factors will account for the principal mortality of arthropods, while shortages of food, space, or mates, and pesticide use are less important. Control of pests by climatic factors to levels below economic injury can rarely be relied upon, but if left in place, the natural enemy complex often keeps pests in balance, if not at sub-injury levels. Insect predators, for example, cause greater mortality in alfalfa weevils than "the combined effect of weather, hyperparasites, diseases, and insecticide usage" (Ambrust 1978). Commenting on the obvious importance of natural enemies, Whitcomb (1974), has reported finding more than 1000 species of insect predators and numerous parasites in soybean fields in Florida.

Because the soilborne pests are protected from extremes of temperature and moisture, natural enemies and diseases may be especially important in their regulation. Adult root weevils, for instance, protect themselves against the heat of summer by estivating in earthen cells (Edwards 1979), and from winter cold by hibernating among the roots of the strawberry plants (Garth and Shanks 1978).

Control measures, therefore, should be chosen with the goal of limiting disruption of the community of beneficial organisms. A few notes on natural enemies of strawberry root pests follow.

Root weevils either have very few arthropod enemies or few are known. The rove (Staphylinid) and the ground (Carabid) beetles will attack both the eggs and larvae (Shanks pers. comm., Wilcox *et al*. 1934). The active Carabid larvae, when plentiful, may be efficient enough to account for the spotty distribution of weevils that is often seen in plantings (Whitcomb 1974). Other important predators of weevils are spiders, toads, frogs, moles, and a number of species of birds. Wilcox *et al*. (1934) mentioned several reports of parasitization of the black vine weevil that came out of Europe about the turn of the century, but up to the present, no effective parasites of this weevil have been found in the PNW. A recent study of the native obscure root weevil, recorded parasitism by a Tachinid fly, *Dolichotarus*, in up to 32% of the adults (Bell and Clarke 1980). Weevils may also be parasitized by Neoaplectanid and Heterorhabditid nematodes, which occur widely in agricultural soils. A Heterorhabditid species was recently isolated from naturally infected black vine weevil larvae in Holland, and it proved to be very pathogenic in pot trials (Simons 1981).

As with root weevils, natural enemies do not appear to be of great importance in regulating the strawberry crown moth. The adults escape predation by their swift flight, while the larvae live safely inside the strawberry stems. A Braconid, *Micorbracon nevadensis*, and a Tachinid, *Parafischeria venatoris*, were reported as parasites by Wilcox *et al*. (1932), and these were found to parasitize between 20 and 35% of SCM in certain fields. A 1982 survey, however, of several hundred larvae from an unsprayed field in Oregon, yielded only two that were parasitized (Fisher pers. comm.).

Symphylans are true soil denizens, with a surprisingly full lifespan of 10 to 12 years (Edwards 1979). They are subject, nevertheless, to a virulent fungal disease, caused by *Entomophthora coronata*. The inoculum remains viable for 30 days or more and will infect and kill up to 95% of the symphylans exposed to it (Stimmann 1968).

The fungal diseases verticillium wilt and red stele are regulated in the soil by a large complex of antagonistic fungi, bacteria, and actinomycetes. Antagonism takes the form of competition for substrate, antibiosis, and mycoparasitism. Soils containing many antagonists having these characteristics are said to be disease suppressive. One important fungus that is an antagonist of Imperfect fungi such as *Verticillium* is *Trichoderma* (*T. harzianum* and other species). *Trichoderma* is not only an overbearing competitor but it also secretes a potent antibiotic, gliotoxin, and is a mycoparasite as well. In dual cultures with *Verticillium*, *Alternaria*, and *Pythium*, I have easily observed the slender hyphae of *Trichoderma* coiling about and evidently penetrating the larger hyphae of these pathogens. *T. harzianum*, when applied to unsterilized soil, gave better suppression of *V. dahliae* on peanut than did fumigating the soil with methyl bromide (Elad *et al*. 1982).

Bacteria are also important antibiotic producers and mycoparasites, and probably are the most important soil antagonists overall. Baker and Cook (1982) suggest that bacteria, because they are spread throughout the topsoil in great numbers, may be particularly effective antagonists of pathogens such as Fusarium, which attack through multiple infections caused by germ tubes. A common, antibiotic-producing bacterium that has proved to be a potent antagonist against the imperfect fungus, Sclerotium cepivorum, is Bacillus subtilis, (Utkehede and Rahe 1980). B. subtilis is also very antagonistic to Rhizoctonia and may be particularly important after fumigation or heat treatments due to its ubiquity, heat resistance, and ability to form resistant spores (Olsen and Baker 1967).

Parasitism of the fungi is not limited to the hyphae; resting structures are also destroyed. Sneh et al. (1977) found that oospores of Phytophthora megasperma and Pythium spp. were attacked by bacteria, actinomycetes, and by fungi from four taxonomic classes. In dry soils, actinomycetes, and hyphomycetes were most effective, whereas in wet conditions, Oomycetes and Chytridiomycetes were the dominant parasites. Up to 89% of the oospores found in the soil were parasitized by these organisms.

In a study of bacterial inhibition of Phytophthora cinnamomi, the genera Bacillus, Streptomyces, and Pseudomonas were commonly seen attacking hyphae and sporophores. Bacteria were considered to have a "profound effect" on the survival of Phytophthora in the soil (Malazczuk et al. 1977). It would appear from the data of these researchers that parasitism accounts for a substantial reduction in both the resting inoculum and the hyphae of the damaging Oomycetes.

Although not natural controls, genetically engineered bacteria capable of selective antibiosis or even the production of plant-systemic insecticides are a real possibility within the next decade or two (Schneiderman 1984).

The soil nematodes are parasitized and preyed upon by many microflora, sometimes in surprising ways. For instance, a bacterial parasite of _P. penetrans_, _Bacillus penetrans_, characteristically penetrates nematodes after attaching to their cuticle (Dropkin 1980). Nematode trapping, and nematovorous fungi are to be found wherever nematodes are populous. Predatory nematodes, like _Mononchus spp._. may be important in regulating the plant-parasitic forms. In samples of nematodes from strawberry fields, Di Edwardo (1961) found _Mononchus_ to comprise up to 31% of the nematodes in some samples. Certain soil mites, tardigrades, ameobae, and collembola all prey on nematodes as well (Norton 1978).

Monitoring

In reviewing case histories of successful pest management programs, it is evident that development of insightful and effective policy stems from biological information aquired through monitoring. A typical agroecosystem of hosts, pests, and beneficials, is both complex and dynamic, and each control measure used affects numerous components of the whole system.

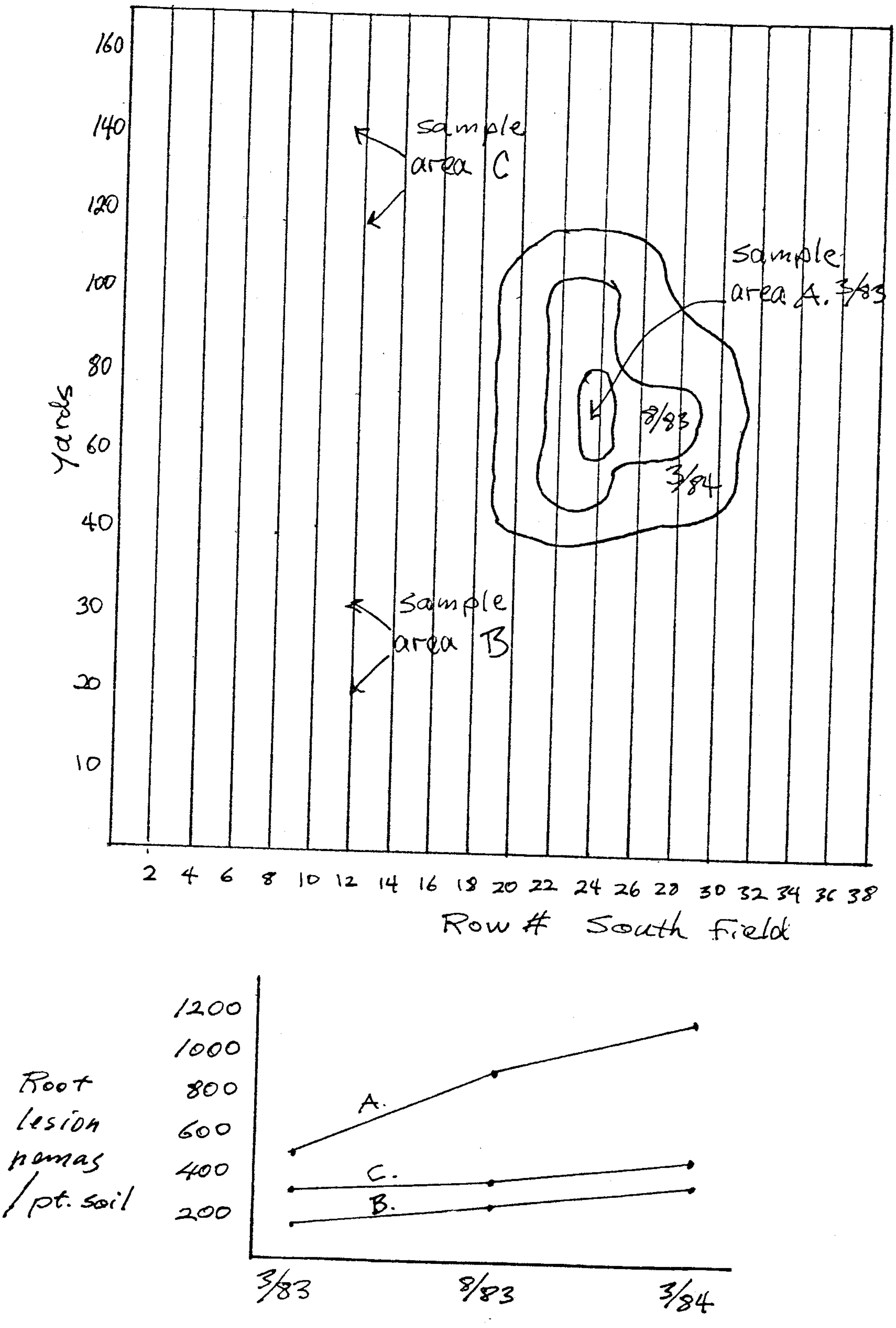
The importance of these side-effects, and the cost-efficiency of the controls used, can only be measured through monitoring. A well implemented monitoring program will give these benefits: a) identification of the key pests and beneficials and measurements of their population changes; b) prediction of pest outbreaks; c) assessment of expected loss.

Monitoring can be either environmental or biological. The recording and collating of weather data is practical in such areas as tree fruit pest management for predicting life-cycle events of certain arthropod and fungal pests. In the management of soilborne pests however, environmental monitoring has not yet found application. This is not to say that weather does not affect the dynamics of root pests, only that not enough is known to make use of existing weather data. The emergence of root weevils and the SCM, for example, are probably tied to the soil temperature (Garth and Shanks 1978), and the survival of active adult weevils, symphylans, and nematodes, may be substantially reduced in those winters when the soil freezes. Populations of root lesion nematodes fluctuate markedly with the seasons. In eastern North America, numbers are lowest in January, begin increasing in April, and peak in July (Di Edwardo 1961). The amount and duration of rainfall may also affect the activity of root pests. The oospores of _P. fragariae_, for example, are thought to need 48 hours of saturated conditions for germination (McElroy pers. comm.).

More useful in strawberry growing than the monitoring of weather are direct population counts of pest organisms. Several samplings in a season will show changes of pest populations and distributions, allow estimates of loss, and planning of control measures. Sampling for soilborne pests usually involves taking soil samples and sending them to a diagnostic laboratory. In the case of root weevils, SCM, and red stele, identification is done on the spot. Root weevils are easily detected by watching for leaf notching with the limitations that the species involved are not identified, and that no counts can be made. While disease symptomology can be used in monitoring programs, the actual casual agents can be quantified only by microscopic examination. This incurs problems of expense, time-lag for processing, and often inconsistent sampling technique. At present, for these and other reasons, most key pests of strawberry are not being sampled commensurate with their injury potential. A systematic sampling scheme for root weevils, symphylans, root rot pathogens, and nematodes, would discover pockets of these pests before damaging levels and spreading occurred.

Comprehensive monitoring demands a recording system that is clear and easy to use; I propose the following. Since root pest populations usually are clumped within a field, a chart as shown in Fig. 3 might be appropriate to show their distribution.

FIGURE 3. FIELD SAMPLING RECORD SHEET



Areas of poor growth are marked as shown and the numbers of sampled pests recorded on a standard line graph. All key and incidental pests should be thoroughly sampled twice each season, and in areas of poor growth, further samplings may be called for. The samples from areas of poor growth can then be compared with those from healthy areas. In this way, the following information is processed: a) identification of the pests; b) the distribution of pests through time; c) changes in populations; d) the presence of areas subject to specific problems; e) the actions of beneficial organisms and climatic factors. This system is ideally suited to programming into a micro-computer, which could conveniently file these data from year-to-year and help reveal trends. I visualize a sequence of overlays which could be run on the screen to show incipient problem areas, and changes in their size as the season progresses.

What advantages accrue from this monitoring activity? A graphic representation of problem areas and the pests or practices involved would be helpful in grasping the problem and working out solutions. The system lends itself to a selective, or a spot, application program, which reduces application costs and damaging interference with beneficials. Areas prone to pest damage would be identified so that action could planned.

The decision to apply a control to an area is properly based upon an economic threshold (ET), which is defined as the pest density at which a control must be applied to prevent the population from reaching the economic injury level. In turn, ETs are based on an assessment of yield loss from pest activities, which in the case of strawberry root pests has seldom been done. Thus ETs are at present either not used, or are worked out by trial and error. A threshold of this sort has been called an action threshold, and while adequate in some cases, may not lead to the optimal use of controls (Thompson and White 1979). In the strawberry root pest complex, action thresholds are being used for nematodes and the SCM. Red stele and wilt are not often sampled quantitatively, and there is no real threshold for the root weevils; treatment is usually recommended at first sign of leaf-notching. As Wiese (1983) points out, competent loss assessments are rare and those performed often focus only on a single pest or physical factor in a complex system. In the light of the root pest interactions illustrated in Fig. 2, it would appear that to achieve useful ETs a multifactorial study of each pest's contribution to the total loss must be undertaken.

An important, and underused management tool is the post-treatment evaluation. A control of 100% is seldom attained and should not be assumed. Many root pests, such as nematodes, will soon multiply back to their original levels if only a small number are left uncontrolled. Post-treatment sampling is the only way to evaluate the effectivness and cost-efficiency of a control, and hence is the major tool available for fine tuning the design of an IPM program.

Resistant varieties

In an agroecosystem the crop host plant is the dominant life form, and affects in some degree all other forms present. Genetically altering the crop, is therefore a potent means of bringing about favorable change in the agroecosystem. The vigor and the susceptibility, tolerance, or attractiveness of a cultivar has a direct effect on the dynamics of pest populations. As well, the quality and quantity of root exudates of each cultivar may effect the microfloral balance in the soil. According to Baker and Cook (1982), root exudation and the resulting rhizosphere changes, are "the factors of greatest significance in root disease initiation". Variations in the quality of root exudates are known to foster changes in the relative proportions of bacteria, actinomycetes, and fungi in the soil (Schroth and Hildebrand 1964). In some cases these changes may result in increased pathogenesis either by favoring the germination of propagules, or by decreasing the inhibition of disease agents through competition and antagonism. The classical example of this is a study of the flax rhizosphere by Lochhead *et al*. (1959). Although Schroth and Hildebrand cautioned about drawing conclusions in regards to these findings, the field resistance of certain flax varieties appeared to stem from their favoring rhizosphere growth of *Mucor*, *Penicillium*, and *Trichoderma*, whereas susceptible varieties favored *Alternaria* and *Fusarium*.

Small fruit breeders in the PNW must consider a formidable number of factors while selecting cultivars for commercial use. These include resistance to pests of course, but often of primary importance are horticultural characteristics which are necessary for commercial success, including fruit quality, yield, ease of capping, winterhardiness, etc. When a pest becomes a serious limiting factor, however, resistance to it may be sought. Such is the case with the aphid-borne viruses; once infected, today's popular varieties are not tolerant enough of this evolving complex to maintain economic yields for long. Other pest problems which are being bred against in the PNW include fruit rots, two-spotted spider mites, red stele, and powdery mildew. In the future, resistance to nematodes, root weevils, and aphids may be considered (Daubeny pers. comm.). These priorities are liable to change as new pest problems, weather patterns, and cultural practices evolve. Since it takes at least 15 years of crossing and testing, and much expense to produce a new variety, only those pest problems of high injury potential, and those which cannot be adequately controlled by other means are candidates for resistance.

In the PNW, 20 or more factors are considered in strawberry breeding, each additional one therefore complicates the task immensely. In selecting for so many characteristics, achievement of less than optimal potential may have to be accepted in some. In contrast, strawberry breeding in southern California is more straightforward. There, the fields are fumigated and re-planted yearly, so that resistance to arthropods and diseases is no longer a consideration. The breeder is thus free to select largely for high yield and fruit of good shipping qualities. These varieties give the California grower a large advantage in yield but they are useless in the PNW where the plants must survive for several years unprotected from pests.

Resistance to pests in strawberries falls into the areas of field resistance, race-specific resistance and tolerance. The varying ability of strawberry varieties to prosper after infection by the aphid-borne viruses is related to their tolerance. Often tolerance takes the form of increased vigor, an ability to outgrow the pest infection. Adventitious regrowth of strawberry roots destroyed by red stele is an example of tolerance, although it is sometimes considered to be field resistance (Gooding 1972). Tolerance is also found against root weevils (Cram 1978).

Tolerant varieties are able to grow and produce profitable crops in the presence of a parasite, even though they do not limit its population. In contrast, resistant varieties have physical or physiological characteristics that inhibit growth and reproduction of the pest. Not all types of resistance are equally useful against strawberry pests. Specific, or vertical resistance, has been exploited extensively against red stele with disappointing results. Specific resistance is determined by the actions of genes for resistance (R-genes) in the host, which impart a near immunity to specific races of the pathogen. In response many pathogens are able to evolve genes which key for the specific processes needed to overcome the host R-genes. A strain of the pathogen with this newly acquired complementarity quickly overcomes the host's specific resistance, which is then said to break down. This process was clearly demonstrated by Gallegly and Niederhauser (1959) working with late blight of potato; that a very similar situation existed in red stele of strawberry was noted by Converse (1967). The evolution of new races of both late blight and red stele was seen as a direct result of the selection pressure applied to the pathogen by the inclusion of strong R-genes in new varieties. Converse (1967) supported this with evidence that the incidence of new races of *Phytophthora fragariae* in Oregon fields was related to the former presence of varieties having strong R-genes. *P. fragariae* rapidly overcomes the incorporation of simple R-genes into the host by its high rates of sexual and asexual recombinations. Specific resistance is thus useful against red stele for a limited timespan only and this is confirmed in the literature. In 1949, when Scott *et al.* discovered the second race of red stele in Maryland, they commented prophetically: "Breeding for resistance to red stele in strawberries appears more involved than was originally believed to be the case since at present no variety is known to be resistant to both of the strains now recognized". Since then 10 or more races have appeared worldwide and many resistant cultivars have been released which had short-lived specific resistance.

The presence of specific resistance in strawberries such as that to red stele, is rather anomalous. Generally, disease resistance is inherited quantitatively, is additive, and is moderately to highly heritable (Galleta 1980). This points to a polygenic inheritance of most traits, which is to be expected with the strawberry's octoploid nature and high heterogeneity. Implicit is the polygenic quality expected in field, or horizontal resistance. These terms are best used in an epidemiological sense to describe simply that degree to which a clone prospers in the presence of pests in the field. This encompasses tolerance of pests, drought tolerance, frost-hardiness, inoculum reduction, non-attractiveness, escape, undetected specific resistance, and overall vigor. A cultivar with high field resistance has accumulated many beneficial genes which act independently on the plant to impart resistance. This type of resistance operates in all plants at some level. Field resistance is stable because simple, Mendelian changes in the pathogen are usually insufficient to overcome the combined effects of many genes. The pathogen is thus not confronted with a surmountable environmental pressure which causes it to evolve new races.

All resistance noted so far to verticillium wilt has been field resistance. (Varney _et al_. 1959, Bringhurst _et al_. 1967). High resistance to wilt may, however, be correlated with low yield, and this is possibly one reason why there are so few wilt resistant varieties available (Bringhurst _et al_. 1967).

Resistance to red stele is not limited to that of a specific nature. Breeders at the Horticulture Station at Auchincruive, Scotland, began selecting for field resistant varieties in the 1950s and the work culminated in the release of a number of cultivars highly field resistant to red stele, several of which are widely grown in Great Britain (Gooding 1972, 1973). The two most successful and vigorous cultivars in the PNW today, Totem and Benton, both possess some field resistance to red stele (Daubeny, Lawrence pers. comm.), although even this may be losing its effectiveness (Peters pers. comm.).

There is also interest in the PNW in breeding cultivars resistant or tolerant to nematodes and root weevils (Daubeny pers. comm.). The findings of Cram (1978, 1980, Cram and Daubeny 1982) and Shanks (1982) appear to point to the feasibility of resistance to weevils. In one test, cv Totem was the best of five in regrowing roots eaten by root weevils. In addition, weevils fed on the leaves of cv Tyee were significantly less fertile and the viability of their eggs was reduced relative to those fed other varieties. Several nematodes, including the root lesion, have been more injurious to certain strawberry varieties than to others, showing that some level of resistance is possible (Szczygiel and Danek 1974).

Cultural controls

Many farming practices used in strawberry production have a definitive effect on pest problems. When these practices are manipulated so as to depress pest populations, they become cultural, or managerial controls. Cultural controls often work by increasing the health of crop plants, rather than by directly attacking the pests, and consequently have little negative effect on ecosystem diversity or the beneficial organisms therein. Cultural controls serve a long-term, guiding function in agroecosystems, and are integrated with other agronomic practices.

Selection of land

No measure will affect the development of pest problems to a greater extent than the selection of crop land. Strawberries will grow in many soils and microclimates, but to produce consistently high yields and long rotations, specific conditions must be met. Strawberries thrive in a perfectly drained, deep, sandy loam soil. A high organic matter content is very beneficial but if absent can be compensated for by a fertilization program. This is the case in parts of California, where the soils are largely sand. The soils used for strawberry production in the PNW are of three types (Frenkel 1979). Those in B.C. and most of Washington are young, well-drained inceptisols of alluvial origin. They have high organic matter, weakly differentiated horizons, and little clay deposition in the sub-strata. In the Tualatin and west Willamette Valleys of Oregon are rich and friable mollisols, usually well drained but with clay-rich sub-strata which may hold water. Further east in the Willamette Valley are heavily weathered and leached ultisols, very well drained but less fertile. The soils of the PNW are young, often only 1000 years old, and have not yet developed a hardpan layer. This, however, cannot be counted on; the Puyallup soils of the Skagit Valley have enough hardpan formation to trap standing water in the winter (Hallock 1979). In addition to good drainage, soil depth is important for the best root development. Under ideal conditions, strawberry roots can grow to depths of 10 feet (Wilhelm and Nelson 1980), and so a shallow soil may limit root and plant growth.

The topography of a prospective site should meet several criteria. An ideal site is a gentle slope for surface water and air drainage, facing south for maximum sun and soil warmth in the spring. Good air drainage is especially important to avoid frost damage to the crowns and flowers in the spring, and problems with mildew and fruit rot in the summer.

Lastly, the cropping history of the land should be known. *Verticillium*, red stele, nematodes, and other root pests may infest the soil and remain a problem for years.

Very few lands can be expected to meet all of these criteria, and economic factors, such as the proximity to markets, housing starts, labor supply, and land costs will dictate the availability of land. Nevertheless, for the establishment of a serious, long-term strawberry operation, a site meeting most of these criteria should be sought.

Crop rotation

Crop rotation is a powerful agronomic tool for use against the pests of roots, but due to economic pressures and the availability of cheap chemical fertilizers and pesticides, it has not been resolutely applied in many crops in North America in the last several decades. This situation may change, however, and as overhead costs increase, rotation may again be considered. At present, many growers in the PNW take their lands out of strawberries for several years between plantings, and some use cover crops, but few use a structured rotation designed expressly for gains in control of soilborne pests and root health. The benefits of rotation are increased soil fertility, organic matter, and structure, and some control of weed, arthropod, and disease pests. Rotation increases the heterogeneity of the ecosystem; this leads to a better biological balance (Cook 1982), and thus certain pests may be naturally controlled. The practices of cover cropping and strip cropping often have these effects as well. Some of the effects that rotation has on the soil ecosystem are illustrated in Fig. 4. This and Figs. 6-9 were designed to be graphic and accessible displays of the effects of control measures on the important soil lifeforms. By necessity, many effects have been generalized, and not a few are best guesses. All are assumed to occur within 1/2 year of application, and the chemicals to be applied at standard rates.

FIGURE 4. [illegible]SYSTEM EFFECTS OF CROP ROTATION

	SUPPRESSIVE EFFECT				SUPPORTIVE EFFECT			
	STRONG	MODERATE	WEAK	NO EFFECT	WEAK	MODERATE	STRONG	
WEEDS		■						PEST COMPONENTS
ROOT WEEVILS			■					
PARASITIC NEMATODES			■					
NEPOVIRUSES		■						
VERTICILLIUM WILT		■						
RED STELE				■				
BLACK ROOT ROT			■					
* S.B. ROOTS, DIRECT							■	BENEFICIAL COMPONENTS
* S.B. ROOTS, INDIRECT							■	
BENEFICIAL INSECTS				■				
BENEFICIAL NEMATODES						■		
ANTAGONISTIC FUNGI							■	
ANTAGONISTIC BACTERIA							■	

*Direct and indirect effects on strawberry roots.

Rotations, as practiced generally, include a legume to maintain soil nitrogen levels, and a sod crop to increase soil organic matter and tilth. Deep-rooted crops of either type are capable of beneficial penetrating and loosening of the sub-soil. An inter-tilled cash crop allows mechanical or herbicidal clean-up of weeds. Noxious perennial weeds can be eliminated through the use of smother crops. In some cases, insects and nematodes are controlled by structured rotations.

Control of root diseases is one of the greatest benefits of rotation. The processes of disease suppression are complex, but they fall into four general areas:

1) Decreases in pathogen inoculum. Oospores, chlamydospores, and other propagules die off in the absence of a host. Much mortality is from predation and parasitism, but spores are also subject to starvation and desiccation.

2) Displacement of pathogenic strains by those less so. Monocropping favors the evolution and proliferation of pathogens especially adapted to the host. When the host roots are removed by rotation, these specialized pathogens are soon displaced by less pathogenic strains more adapted to handle a variety of carbon sources. This is especially true of damaging facultative parasites such as Pythium, which exists as a number of species of varying capabilities in wheat (Cook pers. comm.), and strawberries (Maas 1984). Nematodes are also known to form biotypes of greatly varying pathogenicity and specificity (Thorne 1961). In some cases, antagonism causes displacement. In

Fusarium, strains of low pathogenicity may fill the root niches that more aggressive strains would claim if they were not inhibited by soil antagonists (Rovira 1982).

3) Increases in antagonistic microflora. Each crop plant causes proliferation of a unique microflora at its roots and beyond. Bacteria, principally non-sporing pseudomonads, sheath the roots with up to a billion cells per gram (Alexander 1961). Also present, but less numerous, are actinomycetes, and an assortment of fungi including mycorrhizae, *Mucor*, *Penicillium*, *Fusarium*, and *Rhizoctonia* (Alexander 1961). By competing for niches on the roots, much of this microflora is antagonistic and thus changes in it can affect the fortunes of pathogens. Qualitative differences in the rhizosphere flora can be brought about by changes of temperature, moisture, host plant, soil amendments, and rotations (Garrett 1956). In a classic work which, however, would have benefited from further replications, Hildebrand and West (1941) showed that repeatedly incorporating various cover crops into soil resulted in differences in strawberry plant weights. This was related to the development of a unique microflora by each treatment. The soybean soil, although favoring high counts of the pathogen, *Thielaviopsis basicola*, produced plants with healthy roots and high dry weights. *T. basicola* is not pathogenic to strawberry and thus, in this case, may have been acting as a beneficial antagonist. The types of bacteria found in the rhizosphere also appeared, in this work as well as in that of West and Lochhead (1940) and

Rouatt and Atkinson (1950) to be related to the damage from root rot. Rapidly multiplying, amino-acid auxotrophs were present in large numbers on roots where disease was suppressed, but where heterotrophic bacteria were prevalent, root rot was much worse. Supporting these results, Cook (1982) found that fluorescent pseudomonads from the rhizosphere of wheat carry over from year to year and are important antagonists of Gaeumannomyces graminis, the agent in take-all of wheat. Interestingly, in this case, antagonism is favored not by rotation, but by the monocropping of wheat for six or more years.

4) Fungistasis. Fungistasis is an undefined factor in the soil which inhibits fungal spores from germinating, thus reducing pathogenesis. The mechanism behind this is thought to be an insufficiency of nutrients, but antibiosis may also play a part (Baker and Cook 1982). Crop rotation may increase fungistasis by increasing the richness of microflora in the ecosystem. Legumes in particular, are a fertile source of nitrogen and carbon compounds, and produce a complex, bacteria-rich microflora of increased fungistatic capability (Alexander 1961, Baker and Cook 1982).

A potentially important aspect of green manuring is phytotoxin build-ups from incorporated crop residues (Patrick et al. 1963, 1964). In cool, waterlogged soils, plant material may break down to toxic organic compounds such as methane, acetic, lactic and formic acids. Anaerobic decomposition products of quack grass, for example, are "extremely toxic to test plants", and extracts of red clover can be toxic to strawberries. The stress that compounds such as these place on plant roots has been related to root disease etiology in a number of lab tests (Cochrane 1948). The generation of phytotoxins is much reduced in well aerated soils, and little activity is noticed after 40 days (Patrick *et al*. 1963).

In designing a rotation, the first step is to study the host-ranges of the key pests. The suitability of various alternative crops is shown in Table 3.

Table 3. Crop suitability for rotation with strawberry

Root pest:	Host status:			Reference:
	Poor	Moderate	Good	
root lesion nematode		strawberry alsike clover red clover beans "grains"	timothy	Morgan and Collins 1963
root lesion nematode	Sudan grass marigold	ryegrass sweet clover brome grass	vetch rape oats soybeans	MacDonald and Mai 1963
root lesion nematode		wheat oats	corn soybeans	Ferris and Bernard 1963
root lesion nematode	mustard	wheat cabbage red clover alsike clover	timothy white sweet clover black medic	Townshend and Davidson 1960
root lesion nematode	beet strawberry daffodil	potato oats rye wheat tomato onion carrot barley	peas red clover	Oostenbrink 1960, 1972
dagger nematode	crucifers cucumber corn white clover	peas tomato blueberry	strawberry rye potato raspberry orchard grass	McElroy 1972
needle nematode	onion beet crucifers raspberry potato mint		ryegrass red clover white clover	Thomas 1969

Table 3. Continued

Root pest:	Host status:			Reference:
	Poor	Moderate	Good	
verticillium wilt	celery asparagus carrot cereals lettuce beans peas	caneberries cabbage brussel sprouts cucumber pumpkin strawberry radish spinach	peppers tomato eggplant potato	Wilhelm *et al*. 1970

Root lesion nematodes and root weevils cannot be completely controlled by rotation because of their broad host-range, but, as noted by Oostenbrink (1960), a year or two of a non-susceptible crop can have a pronounced effect on other pests. Fumigation, which is never 100% effective, can be greatly complemented by suitable rotations. Ultimately, due to slower rebuilding of pests, fewer treatments may be necessary and the life-span of the strawberry crop increased. Many years ago, strawberries were rigorously rotated with clover and potatoes (Treherne 1914, Wilcox *et al*. 1934), but it is now known that these crops increase root lesion nematodes and wilt. Legumes are such good hosts for the root lesion nematode, that even after fumigation, their populations may reach higher levels at the end of the season than existed before, making them poor break crops with strawberries (Oostenbrink 1960). Overlooking economic considerations, a rotation program favorable to strawberries might be structured like this: (Adapted from Oostenbrink 1972).

1) A pre-planting, broad-spectrum fumigation.

2) Strawberries, for 4-5 years.

3) Grass crop, for 2 years, such as wheat, oats, or rye. These are tolerant of the root lesion nematode and do not favor other root pests. Soil organic matter and structure are increased.

4) Row crop, for 2 years, such as a crucifer, bulb, or root crop. Not potato. These are poor hosts for the root lesion nematode, and allow clean cultivation between rows.

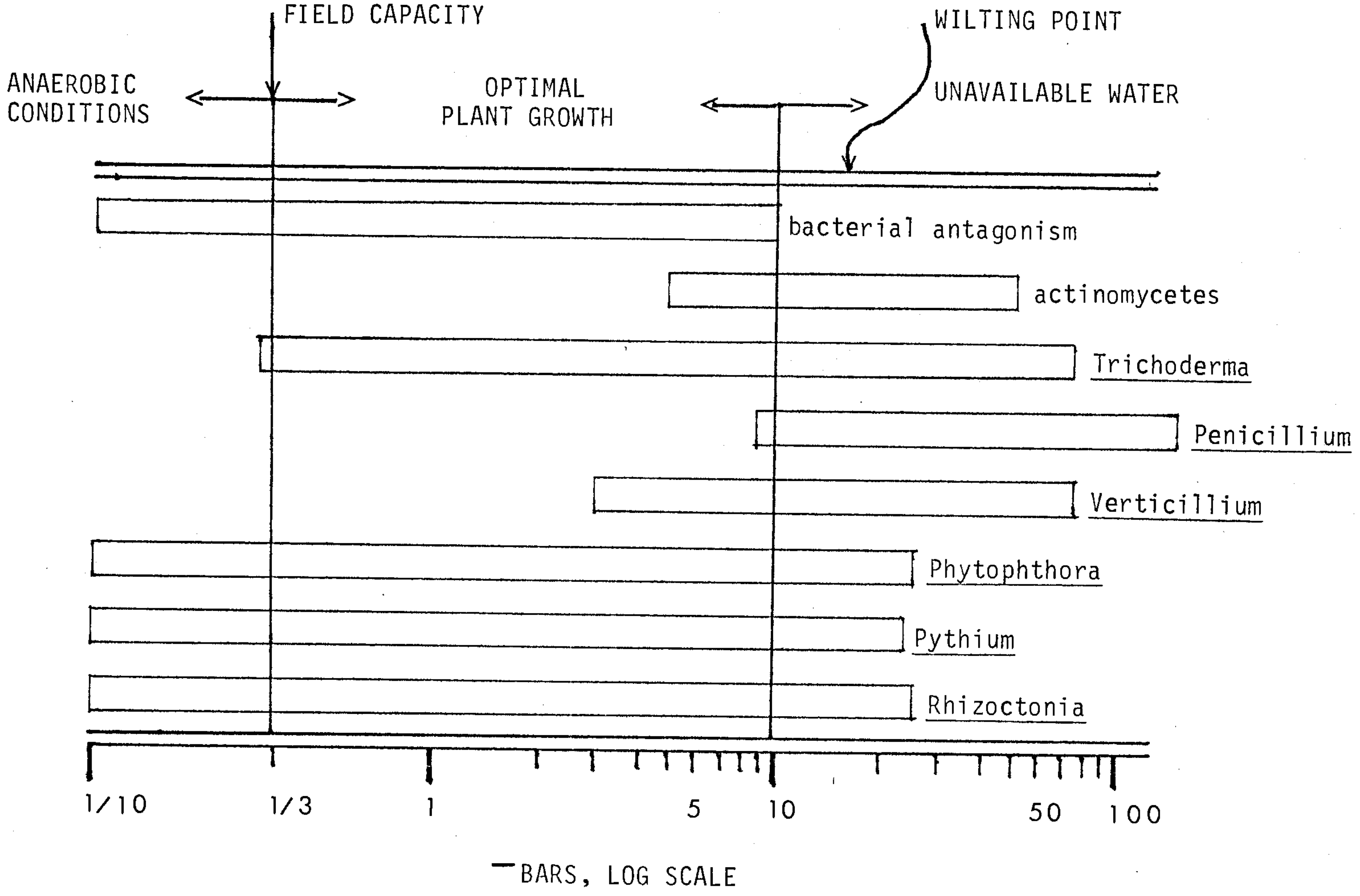
5) Soil tested for nematodes. Fumigation. Recolonization with antagonists. Replant strawberries.

Drainage

The amount of moisture in the soil has a major influence on disease organisms. Any pathogen exhibits optimal growth at some level of moisture, and this is related either to its biology or to changes in soil microflora by which it is favored. The roots of plants are also strongly affected by moisture; stress and vulnerability occur in soils either too wet or too dry. Since oxygen is excluded as water fills the soil pore spaces, water levels above field capacity quickly lead to anaerobic conditions, and this change leads to a qualitative turnover of microflora. None of the fungal pathogens is a strict anaerobe, but Oomycetes such as *Pythium* thrive in waterlogged soils. Their growth is aided by the stressed condition of oxygen-starved roots as well as by diminished antagonism from the actinomycetes and Imperfect fungi. When the soil is dry, verticillium wilt may be a problem, for although its growth is not favored by dry substrates, it is able to grow and cause disease at moisture levels below those tolerated by antagonistic bacteria (Cook and

Papendick 1972). The moisture levels favoring the antagonistic microflora are generally the same as those most suitable for growth of crop plants (Fig. 5).

Figure 5. Optimum moisture ranges for some microflora



* From Buckman and Brady 1969, Baker and Cook 1982, and Cook and Papandick 1972.

Techniques available to aid drainage include land smoothing to eliminate puddling, cover-cropping to loosen the soil and prevent surface sealing by rain, and reducing tillage with heavy machinery (Hallock 1979, Easter 1979). Plastic tubing has replaced tile for field drainage, and its installation, with laser leveling and one-pass backfilling, has become very efficient (Easter 1979). While not prevalent in B.C. or Washington, many fields in Oregon have been drained with plastic pipe 50ft on centers. This might well be a factor in the somewhat higher yields regularly seen there. Open ditch drainage is a good alternative to plastic tubing where the soil type leads to constant silting up problems. Finally, subsoiling between the rows in the fall may be of great benefit in reducing winter rots such as red stele. The effects of drainage on the strawberry root system are illustrated in Fig. 6.

FIGURE 6. ECOSYSTEM EFFECTS OF DRAINAGE

	SUPPRESSIVE EFFECT				SUPPORTIVE EFFECT			
	STRONG	MODERATE	WEAK	NO EFFECT	WEAK	MODERATE	STRONG	
WEEDS				■				PEST COMPONENTS
ROOT WEEVILS				■				
PARASITIC NEMATODES					■			
NEPOVIRUSES					■			
VERTICILLIUM WILT					■			
RED STELE	■							
BLACK ROOT ROT	■							
* S.B. ROOTS, DIRECT							■	BENEFICIAL COMPONENTS
* S.B. ROOTS, INDIRECT							■	
BENEFICIAL INSECTS				■				
BENEFICIAL NEMATODES					■			
ANTAGONISTIC FUNGI						■		
ANTAGONISTIC BACTERIA				■				

*Direct and indirect effects on strawberry roots.

Certified stock

The use of pest-free planting stock is of major importance in strawberry production. In past years, in the PNW, no useful certification program existed, and growers took their chances. Recently, a privately run program was begun to monitor for red stele and the root lesion nematode. To assist in producing clean stock, the several producers now use broad-spectrum fumigation and their plants are regularly checked for root pest infestation (McElroy pers. comm.). The quality of planting stock available to the PNW grower has since improved noticeably, although it is not yet pest-free (Daubeny pers. com.).

Four factors are of importance in judging planting stock:

1) Digging date. Plants dug too late in the spring may have already broken dormancy, which can result in a weakened plant, and poor establishment percentages.

2) Root rots. The presence of black root rot, or other rots on the stored plants will reduce success in establishment.

3) Red stele. Red stele imported on planting stock not only favors an outbreak in that field, but may result in the transport of new and aggressive strains of the fungus.

4) Nematodes. Nematodes on the roots of planting stock will provide the population base needed to substantially shorten the life-span of the planting.

Clean planting stock is particularly important in fields partially sterilized by fumigation, as is proposed in this paper. If saprophytic soil fungi such as *Trichoderma* are not re-established before planting, root rotting pathogens brought in on the roots will have a free run. Nematodes are particularly dangerous since their predators will have been eliminated from the soil.

Mowing

The mowing or topping of strawberry plants after harvest is an established and beneficial practice which helps to reduce foliar pests by breaking their life-cycles, and root weevils by removing their hiding places. It also aids in hand-cleaning the fields of weeds. It is well to be aware however, that mowing may have undesired results with respect to nematode dynamics. MacDonald and Mai (1963) and others have noted that severe pruning of the foliage increases the suitability of many plants for reproduction of root lesion nematodes. In a 2 1/2 month period, populations of this nematode increased by 3-to 20-fold over the controls in grasses and legumes repeatedly pruned. Experiments have not been done, to my knowledge, on this effect in strawberries, but if it should occur, mowing might hasten the re-establishment of this nematode after fumigation.

Solarization

The intentional pasteurization of soils by the sun's radiation is a very recent development but it shows promise for reducing soilborne pathogens such as *Pythium*, *Fusarium*, and *Verticillium*. The practice, as instituted by Katan *et al.* (1976,1983), consists of covering tilled and irrigated soil with a thin polyethelene film for a month or so in the summer. This heats the soil to temperatures of around 50C, which is high enough to kill or weaken most pathogens. In addition to a direct reduction of inoculum, microbial populations are shifted towards heat resistant and non-pathogenic saprobes (Katan *et al.* 1976). This shift involves displacement of pathogenic by saprophytic fusaria (Katan *et al.* 1983), heat sensitive *Pythium spp.* by those heat tolerant (Pullman *et al.* 1981), and increases in *Trichoderma spp.* (Elad *et al.* 1980). The microbial changes resulting from solarization are long-lasting. Heating the soil increased *Trichoderma* from a base of 10-15 propagules/g to 350/g after 135 days (Elad *et al.* 1980).

Solarization has thus far given 83-100% control of *Pythium*, *Rhizoctonia*, and *V. dahliae* (Pullman *et al.* 1981), and 70-95% control of *Fusarium* in the second season (Katan *et al.* 1983). However, charcoal rot of bean (*Macrophomina phaseolina*) was not controlled by solarization in Arizona (Mihail and Alcorn 1984). Besides root diseases, solarization may also control weeds and nematodes.

Combining solarization and inoculations with antagonists appears to be particularly promising. *Trichoderma* inoculations combined with either methyl bromide fumigation or solarization reduced root disease of potato significantly more than did either treatment alone (Elad *et al.* 1980). This is because these treatments leave a partial biological vacuum in the soil that is filled securely by the beneficial *Trichoderma* when it is purposefully re-inoculated.

The benefits of solarization for strawberry production are its simplicity, environmental soundness, and smaller cost compared with broad-spectrum fumigation. In the PNW, however, research to prove its value has not been undertaken, that I'm aware. All the work so far has been in intensely hot places like Arizona and Israel, and it is not known whether the soil would warm enough in the PNW to precipitate the needed effects. Also deficient is research into the effects of solarization on the root lesion nematode, red stele, and other key and incidental pests of strawberry roots.

Neoaplectanid nematodes

On account of their high pathogenicity and wide host-range against insects, several species of Neoaplectanid nematodes are being examined by researchers for their potential as bio-control agents. Most work is being done with *Neoaplectana carpocapsae*, which attacts the root weevil pests of strawberry (Rutherford pers. comm.). Neoaplectanids attack slow-moving larvae as 3rd stage juveniles, and pursue their prey in response to chemical stimuli (Gaugler 1980). Having penetrated the insect, the nematode releases a bacterium which multiplies rapidly and kills the host in about 48 hrs through septicemia of the hemocael. The nematodes are most effective in moist, protected environments, such as the soil, where desiccation is not a problem. Thus, an application of Neoaplectanids is expected to last in the soil up to 16 months before dying off (Rutherford pers. comm.). Because the nematodes move slowly, they are unable to catch active, predator larvae, so a beneficial selectivity is built-in.

Work is underway on the use of Neoaplectanids in several places worldwide. In Australia, they are being investigated for control of a number of insects, including the lilac borer, a _Synanthedon sp._ similar to the strawberry crown moth (Bedding and Miller 1981). At Simon Fraser University in B.C., a research group headed by Dr. John Webster (1984) is working on Neoaplectanid taxonomy, pathology, and even practical applications in horticulture. A new firm in California has recently succeeded in getting the nematode exempted from EPA registration requirements, and now produces them for sale (B.R. Supply).

Neoaplectanids are inexpensive to mass produce and so may become an economical alternative to insecticides in the near future. Moreover, recent work suggests that they are compatable with chemical controls since they are not adversly affected by chemically killed insect hosts (Hara and Kaya 1983). The dosage rate is approximately 2 billion/ha, which is about the number that can be produced in a cubic foot of growth medium. They can be applied through standard spray equipment, and are not pathogenic to mammals.

Chemical controls

Many pesticides are potentially useful against the root pests of strawberries but few of these are registered for use. Because of increasingly rigorous toxicological testing, the registrations of some chemicals now used are unsure, and registrations for new pesticides are uncommon. A number of familiar chemicals, such as captan, glyphosate, Meta-systox R, and carbofuran were registered with now discredited IBT toxicological data so the future availability of these is not certain (Maxwell 1981). The sudden de-registrations of EDB and Nemagon point out that no chemical now used can be taken for granted. In addition, the strawberry industry in the PNW is comparatively small, so that it is often uneconomical for chemical companies to pursue the costly registration of a pesticide used only on this crop. It is therefore important that chemicals now available be used so as not to endanger their efficacy or their registrations.

In this discussion several chemicals not yet registered for use on strawberries, but nevertheless of potential benefit, will be considered.

Soil fumigation

Soil fumigation in PNW strawberries is limited at present to the use of D-D (dichloropropane-dichloropropene), which gives excellent control of the nematode pests of strawberries but has little effect on pathogenic fungi or weeds. With the recent loss of EDB, the three broad-spectrum fumigants available to growers are methyl bromide (MB), chloropicrin (C), and metham (Vapam). These have not traditionally been used in strawberry production in the PNW because of their high cost or unavailability, but as a result of the increasing cost of D-D, and of losses of market to the higher yielding California industry, a re-examination of their potential is called for.

Fumigation of the soil with a general biocide at relatively low rates results in a partial sterilization only. Fortuitously, most root pathogens are more vulnerable to these toxicants than are saprophytic fungi and bacteria (Altman 1970). Thus, at the right dosage, the soil may be relieved of *Pythium*, *Rhizoctonia*, *Phytophthora*, *Verticillium*, and other root limiting fungi, while at the same time, a biological balance of saprophytes is maintained in the soil. This balance, however, is artificially shifted to one more favorable to the strawberry plants. For example, the total numbers of soil bacteria, including many antagonists, are elevated for up to 1/2 year after fumigating with MB+C (Mulder 1979), and the beneficial Trichoderma usually shows a long-lasting increase as well (Vaartaja 1966). A great benefit of fumigation with MB+C or metham is that along with fungi, the nematodes, arthropods, weeds, and weed seeds are eliminated. The negative aspects of broad-spectrum fumigation are the resultant mortality of the predators and parasites of nematodes and arthropods, and of earthworms and other beneficial invertebrates. Also eliminated are the mycorrhizae which normally live symbiotically with strawberry roots. These were once thought to be detrimental, but are now considered to have a neutral effect on growth in soils of adequate fertility (Wilhelm and Nelson 1980). The effects of fumigation with D-D and MB+C can be compared in Figs. 7 and 8.

Figure 7. Ecosystem effects of D-D

	Suppressive effect				Supportive effect			
	Strong	Moderate	Weak	No effect	Weak	Moderate	Strong	
Weeds				■				Pest components
Root weevils				■				
Parasitic nematodes	■							
Nepoviruses	■							
Verticillium wilt			■					
Red stele				■				
Black root rot			■					
* S.B. roots, direct			■					Beneficial components
* S.B. roots, indirect							■	
Beneficial insects				■				
Beneficial nematodes	■							
Antagonistic fungi			■					
Antagonistic bacteria				■				

*Direct and indirect effects on strawberry roots.

FIGURE 8. ECOSYSTEM EFFECTS OF BROAD-SPECTRUM FUMIGATION

	SUPPRESSIVE EFFECT				SUPPORTIVE EFFECT			
	STRONG	MODERATE	WEAK	NO EFFECT	WEAK	MODERATE	STRONG	
WEEDS	■							PEST COMPONENTS
ROOT WEEVILS	■							
PARASITIC NEMATODES	■							
NEPOVIRUSES	■							
VERTICILLIUM WILT	■							
RED STELE	■							
BLACK ROOT ROT		■						
* S.B. ROOTS, DIRECT			■					BENEFICIAL COMPONENTS
* S.B. ROOTS, INDIRECT							■	
BENEFICIAL INSECTS	■							
BENEFICIAL NEMATODES	■							
ANTAGONISTIC FUNGI					■			
ANTAGONISTIC BACTERIA						■		

*Direct and indirect effects on strawberry roots.

The use of a mixture of MB and C for land preparation in strawberries was pioneered in large part by Dr. Stephen Wilhelm at the University of California, Berkeley. After careful study of many factors involved in yield loss to root diseases, he concluded that strawberry root health is limited, not only by the major fungal and nematode diseases, but by a "phytostasis" factor in the soil, probably due to _Pythium_ and _Ceratobasidium_ (Wilhelm 1965, 1966, Wilhelm and Nelson 1980, Wilhelm and Paulus 1980). To overcome these root limiting agents in California production, MB and C are used in combined applications which exploit their complementary properties to the best effect. MB has a very high vapor pressure and so diffuses rapidly and thoroughly in the soil and buried plant debris. It is the only fumigant which dependably kills pathogens at depths of 4ft (Grimm and Alexander 1971). While MB is extremely effective against arthropods, nematodes, and weeds, it is less so against many of the fungi (Domsch _et al._ 1983). Thus C with its wide fungicidal activity and slower diffusion rate is added to MB in a 1:1 or 1:2 ratio for better action against _Verticillium_ and other resistant pathogens. The result is synergism, where the combined effects of a given weight of the two fumigants is better than the same weight of either one alone (Wilhelm and Paulus 1980, Lembright 1980).

MB+C fumigation has now been used, with no apparent ill effects to the soil, for the last twenty years in central and southern California, and yields there average about 30 tons/acre. It is hard to escape the conclusion that PNW strawberries would benefit from a similar release from the soil phytostasis.

Metham sodium or Vapam is a broad-spectrum fumigant of good fungus killing ability which might be used as a less expensive alternative to MB+C. It has recently been found to be practical applied as a liquid in irrigation water for control of verticillium wilt in peanuts (Krikun and Frank 1982), and white rot of onions (Adams and Johnson 1983). At the low (1/2 the recommmended) rates used in these crops, metham costs about 1/4 as much as MB+C, making it competitive with D-D. (This applies only in the U.S., metham is more costly in Canada). Moreover, metham kills weeds, arthropods and fungal pathogens as well as nematodes. Metham is being used commercially in Belgium to control the root lesion nematode and _Phytophthora_ in chicory fields (Mulder 1979). Sinha _et al._ (1978) noted a reduction in most fungi for 45 days at both low and high rates of metham, but an early rebounding of _Trichoderma_. This, they thought, may contribute to the "excellent season-long control associated with the use of metham".

Metham appears to have great potential for control of root pests in annual crops; however, in perennials its effects may not last long enough to make it useful. Metham disperses in the soil water, making it theoretically possible to place it where desired through the use of irrigation. In tests, however, metham was not successful in killing sclerotia of _Sclerotium cepivorum_ deeper than 15-20cm, or shallower than 2cm (Adams and Johnson 1983). If this limitation is general, recolonization by harmful fungi might be expected in strawberries even before the crop begins to bear fruit. Buczacki and White (1977) found that metham gave neither complete nor lasting control of crucifer clubroot in the field.

Currently, there is interest by PNW strawberry growers in injecting metham through the irrigation system, as is done profitably in potato crops in eastern Washington. For the reasons just noted, and the additional problem of areas missed by the sprinklers, this procedure will probably not be successful.

Taken altogether, the mixture of MB+C appears to be the most beneficial of the available fumigants for use in strawberries. There remain questions as to its effectiveness in perennially grown strawberries, and to its cost. Little work has been done on the effects of broad-spectrum fumigation in crops grown more than one year, but the procedure has been used in forest tree nurseries for some years. Approximately one year after fumigation with Trizone (a mixture of MB+C and propargyl bromide) inocula of _Trichoderma_ and bacteria were significantly higher, and _Pythium, Rhizoctonia_, and _Fusarium_ significantly lower than in the nonfumigated beds (Vaartaja 1966). The 2-3 year effectiveness of solar pasteurization of soil is also evidence that fumigation effects on fungal pathogens may be long-lasting (Katan _et al._ 1983). These studies point to the nature of the fungal elements which first recolonize fumigated or heat treated soil as the key to a favorable long-lasting balance. I propose, therefore, that a directed recolonization of beneficial fungal saprophytes follow MB+C fumigation. This is done in four ways:

1) Partial sterilization. The key factor. Many variables, such as soil temperature, moisture, porosity, and organic matter content are involved in diffusion rates and efficacy of fumigants (Goring 1970). Taking these into account, the dosage is adjusted to a rate which eliminates nearly 100% of pathogens, nematodes, and weeds, but which leaves enough saprophytes, ammonifiying bacteria and other beneficials that these quickly rebound and establish a beneficial balance.

2) Exclusion. MB+C fumigation must be done in the late summer or early fall when the soil is warm. After fumigation a field should be quarantined to keep out infested soil on machinery and workers' boots (McElroy pers. comm.). Water should not be allowed to drain in from other fields. Vaartaja (1966) found that dust is a carrier of Pythium and other pathogens but this is perhaps unimportant in PNW winters.

3) Food base. A carbohydrate source added to the soil after fumigating may favor recolonization with saprophytic antagonists (Cook and Baker 1983). For example, Trichoderma grows well on high cellulose substrates such as wheat bran, whereas bacteria and actinomycetes are favored by manure and legume foliage (Rouatt and Atkinson 1950). By manipulating the timing and type

of cover crops preceding fumigation, a favorable recolonization might be stimulated; however, much work needs to be done in this area before specific recommendations can be made. The fumigants may not thoroughly penetrate all green stems and roots, so the cover crops should be plowed down early enough to allow for some decomposition.

4) Inoculations. Re-inoculating fumigated soil with antagonists may prove practical in the near future. Elad *et al.* (1980, 1982), found that *Verticillium* and *Sclerotium rolfsii* were controlled best if MB fumigation was followed by inoculations with *Trichoderma*. The combination gave 93% control of the diseases of tomato, and yield increases of 160%; this was substantially better than MB fumigation alone. Inoculations with *Trichoderma* have also proven successful in reducing *Rhizoctonia* damage to field grown strawberries (Elad *et al*. 1981). This inoculation procedure is now being developed for commercial use in Israel, and should be practical in a high-value crop such as strawberries, at least in nursery operations (Cook and Baker 1983). Optimally, antagonists should be isolated from a field prior to fumigating, grown in some quantity, and returned to the field as soon as the fumigant has dissipated sufficiently. The inoculum may be applied either as an amendment or as a root dip prior to planting.

Due to the need for special application equipment and plastic covers, the cost of MB+C fumigation is high; about $1100/ac if done commercially. Even at this cost, however, when all factors are considered, the total yearly costs of pest management in strawberries are only about $162/ac more with MB+C fumigation than with D-D (Table 4.).[1] This is because treatment costs for root weevil and weed problems will be reduced by the MB+C treatment. At the 1982 price of 43¢/lb for processed berries, and assuming a harvesting cost of 30¢/lb, it means that an additional 640 pounds/ac must be harvested to pay the extra cost of fumigation. Assuming a 5-ton average yield, this additional harvest translates to an increase of only 6.4%. MB+C fumigation should result in yield increases of substantially greater than 6.4% due to its superior control of weeds, low grade pathogens, and other pests not controlled by D-D.

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[1] The Washington State Strawberry Enterprise Budget (Carkner _et al_. 1982) was used for purposes of illustration and standardization. Some of the estimates of pest control costs included in it, including those for fruit rots, aphids, and handweeding, are probably low.

Table 4. Comparison of the costs of fumigation with methyl bromide+chloropicrin (MB+C) and D-D*

Establishment costs	D-D	MB+C
soil sample	2.50	2.50
glyphosate spray	73.52	.00
fumigation	325.00	1100.00
Tenoran	60.28	60.28
hand weeding	27.00	.00
Meta-systox	68.74	68.74
Devrinol	78.28	78.28
Total(rounded)	642.00	1314.00
Continuing production costs		
Tenoran	42.13	42.13
hand weeding	27.00	00
Guthion	29.93	29.93
Ronilan/Meta-systox two appls.	129.87	129.87
mow berries	9.98	9.98
Furadan	104.18	00
Devrinol	60.13	60.13
Total (rounded)		
year 1	404.00	272.00
year 2	404.00	272.00
year 3	404.00	**404.00
Establish. costs ammortized at 12%	240.00	490.00
Total yearly cost	644.00	806.00

*adapted from Strawberry Enterprise Budget, Western Washington, Carkner et al. 1982

**includes cost of hand weeding and Furadan drench.

Post-planting chemicals

The soil applied chemicals other than herbicides of most interest to PNW strawberry growers today are carbofuran for weevil control, metalaxyl for red stele, benomyl for verticillium, and fenamiphos for nematodes. These pesticides can be very effective when integrated with other measures, but if relied on solely they may become ineffective due to problems of resistance or microbial imbalance.

Carbofuran (Furadan) is the only post-planting chemical available with the 3-month life-span, and high soil activity needed to kill the larvae of root weevils. However, the prevalent mode of application, a calender based, broadcast treatment has two faults: First, if detected early, weevil infestations will be localized, so that a field-wide spray is costly and unnecessary, and beneficials such as the larvae of predacious beetles are best left undisturbed (Fig. 9); Second, evidence is accumulating that soil microflora, especially the actinomycetes, become adapted to carbofuran treatments and degrade it with increasing efficiency (Williams *et al.* 1976, Getzin pers. comm.). In soils treated with carbofuran for several years, measured doses were degraded more than twice as fast as those from virgin soils (Felsot *et al.* 1982). Hence, the the efficacy of carbofuran should be protected by using spot applications only where infestations are known. This is the approach recommended by Dr. Tom Cram, a long-time weevil expert at the Vancouver Research Station (Cram pers. comm.).

FIGURE 9. ECOSYSTEM EFFECTS OF CARBOFURAN

	SUPPRESSIVE EFFECT				SUPPORTIVE EFFECT			
	STRONG	MODERATE	WEAK	NO EFFECT	WEAK	MODERATE	STRONG	
WEEDS				■				PEST COMPONENTS
ROOT WEEVILS	■							
PARASITIC NEMATODES		■						
NEPOVIRUSES			■					
VERTICILLIUM WILT			■					
RED STELE				■				
BLACK ROOT ROT			■					
* S.B. ROOTS, DIRECT				■				BENEFICIAL COMPONENTS
* S.B. ROOTS, INDIRECT							■	
BENEFICIAL INSECTS	■							
BENEFICIAL NEMATODES		■						
ANTAGONISTIC FUNGI				■				
ANTAGONISTIC BACTERIA				■				

*Direct and indirect effects on strawberry roots.

The systemic fungicide metalaxyl (Ridomil) has recently generated much interest because of its excellent suppression of Oomycete pathogens. It appears to be the most effective of the latest releases of systemic fungicides for the control of red stele (Montgomerie and Kennedy 1979, Bristow 1981, McIntyre and Walton 1981). When applied at the time of transplanting, fall, and early spring, up to 3-fold increases in plant weight may be obtained. Metalaxyl will soon be registered in B.C. for use in strawberries, and its use is fast increasing in the PNW as a whole; nevertheless, I believe a cautious approach to the compound will lengthen its useful life.

It is doubtful whether *P. fragariae* will remain sensitive to metalaxyl for long if a yearly regime of two or three applications of the fungicide is begun. In only a few years of use, tolerance to the chemical has already been noted in *Pythium, Phytophthora*, and a number of other pathogens as well (Bruin and Edgington 1981). Metalaxyl, like benomyl and most other new systemics, affects a specific enzyme system of a fungus. Given sufficient exposure, most fungi are able to circumvent this action by using another system not affected by the chemical (Dekker 1977). Doing so sometimes reduces the pathogen's general fitness and pathogenicity. In the case of *Monilinia laxa*, the cause of brown rot on apricots, strains resistant to benomyl were both less pathogenic and less able to survive in competition with the wild type (Ogawa *et al.* 1984). However, this is not axiomatic; Talboys and Davies (1975) isolated strains of *V. dahliae* which were both strongly pathogenic to strawberry and capable of growing in high concentrations (10ppm) of benomyl. Another reason for caution in the use of metalaxyl comes from the work of Cohen and Samoucha (1984), in which they investigated pathogen cross-resistance to several systemic fungicides. They found that strains of *P. infestans* resistant to metalaxyl were also resistant to propanocarb, cyprofuram + folpet, SAN 371F, and phosethyl Al (Aliette). Thus the use of a fungicide regime to manage Oomycete resistance does not look promising. These results are especially interesting with respect to Aliette, an unusual fungicide which has been highly effective against red stele in field trials (MacSwan 1979). Aliette exhibits low toxicity to pathogens outside the host plant (Cohen and Samoucha 1984) and so apparently functions by increasing plant resistance. Because this mode of action appears so different from that of other systemics, the cross-resistance comes as a surprise.

Multiple yearly treatments of metalaxyl might have the same effect on *P. fragariae* as does specific resistance, namely the fostering of races of the pathogen able to overcome a specific inhibitory mechanism and then cause disease. In addition, because the chemical suppresses red stele but does not kill the pathogen, use in propagation nurseries could create a situation where infested but apparently clean stock is shipped out and planted. For these reasons, metalaxyl, if registered, should be used sparingly. In this proposed management scheme, it is used at the end of the rotation, after harmful watermolds have recolonized in order to extend the crop into a profitable 3rd or 4th year.

Benomyl (Benlate) and similar compounds have been proposed for use as controls for verticillium wilt in strawberries. Tests have shown conclusively that benomyl is a potent inhibitor of *Verticillium*. As little as one soil drench in September, for example, subdued wilt into the following spring (Talboys and Davies 1975). Benomyl and thiophanate methyl (Fungo) prevented spread of *V. dahliae* through stolons to the runners if applied in two 0.1% drenches (Jordan 1975). Benomyl has thus been recommended as a preventive measure to be applied at high rates before any wilt is evident (Talboys and Frick 1974).

Despite these results, benomyl and related benzimidazole compounds are probably undesirable for use against root rots of strawberry. As well as their propensity for selecting resistant races of the pathogen, they have the drawback of being especially toxic to some of the antagonists in the Imperfect fungi while having little or no effect on the Oomycetes. Soil applications of benomyl have also been noted to allow the root pathogen *Armillaria* to prosper while reducing *Trichoderma* (Baker and Cook 1982).

The use of benomyl and other selective fungicides in the soil may lead to 'disease trading'. This has been documented with the unrelated fungicide, PCNB (Terrachlor), as when it favors *Pythium* after controlling *Rhizoctonia* (Haglund pers.

comm.). In a particularly interesting case, PCNB applied to the soil acted so as to inhibit the natural controls of the root lesion nematode on strawberry roots. The greater populations of nematodes then caused an increase in verticillium wilt (Rich and Miller 1964).

In the integrated program I am proposing, verticillium wilt should be adequately controlled through rotations and MB+C fumigation, making the use of benomyl unnecessary.

There are at present no chemicals registered for post-planting nematode control in strawberries; however the organo-phosphate fenamiphos (Nemacur) might be registered if enough demand was present. The compound is very effective against the root lesion nematode in raspberries when applied as a winter drench (Haglund 1980, 1981). It is an extremely toxic chemical and may have some negative effects on soil arthropod predators, although the December application time should limit these. Broadcast and calender applications of fenamiphos are unnecessary; instead, limited spot treatments based on soil samples might be beneficial in the last year or two of a crop.

Carbofuran is used as a nematocide in crops such as bananas, however, the rates needed for a nematocidal effect are 4 or more lbs of active ingredient/ac while the registration for strawberries limits the maximum to 2 lbs AI/ac or 2.3L/ha. Because carbofuran is long-lived in the soil and can build up from year to year, the berries are monitored for the parent material and five breakdown products. The fruit processing firms are therefore very concerned that carbofuran residue not enter the fruit as a result of nematocidal use at high rates (LaLone pers. comm.).

V. Conclusion

The many pests which reduce the health of strawberry roots cost the industry a great deal of money and lost yield. Little measurement of these losses has been done, but at averages of 2-5 tons/ac, PNW strawberries are clearly not yielding up to their genetic potential. As things now stand, most management of pests is directed at those seen above ground, with remedial controls used on soilborne pests only when their effects become obvious. While the aphid-virus complex may now be the chief limitation on strawberry health, the depressive effects of endemic root pests should not be underestimated.

An integrated program for the management of root pests, although initially costly, might result in greatly increased yields and a more competitive industry. The main points of the IPM program I am proposing are reviewed below.

1) Choose a suitable site for strawberry production. Strawberries will grow in many environments but the problems associated with heavy soils, hard freezes, and poor air drainage may preclude a profitable operation. There are no control measures available today, nor are there ever likely to be, which can ameliorate the problems caused by a poor site. Because of the increasingly intense competition from California and Mexico in the processing market, marginal operations in the PNW have little future.

2) Sample the fields to know what pests are present and the extent of the damage they have caused. Regular sampling for nematodes, weevils, and diseases allows not only timely treatments, but evaluation of results and redesign of the control program for the best, economical control.

3) Use the varieties with the best record against the specific pest problems of the area. In fields prone to red stele, varieties with high field resistance may outperform those resistant to only certain races of the fungus. High tolerance to viruses is mandatory in many areas today. In the future, nematode-and weevil-tolerant varieties may become available.

4) Use crop rotations to limit the development of aggressive pathogens especially adapted to strawberry. Rotations also reduce pathogen inoculum, promote beneficial antagonists, help control certain weeds, and improve the structure and fertility of the soil.

5) Drain the fields by the most effective means possible. This is usually through buried plastic pipe, but open ditches are a reasonable alternative. Fall subsoiling between the rows is highly beneficial, and should be done wherever red stele is a problem. Water standing for more than two days may lead to outbreaks of root rot.

6) Plant the cleanest, highest quality stock available. Nematodes and fungi imported on plant roots provide for imminent failure of the crop by re-inoculating soil which may be low in natural enemies and antagonists. Infested stock also may import

new, more pathogenic biotypes of pests into an area.

7) Keep fields as close to weed-free as possible. When hand weeding, workers should be able to identify the most harmful species so they can be removed preferentially. Especially harmful weeds are those that are competitive, spreading, and difficult to extricate from matted rows; those that act as reservoirs for viruses, nematodes, and disease pathogens; and those that are allelopathic.

8) Fumigate with a tarped application of methyl bromide and chloropicrin in place of D-D. This gives far superior control of most root pests, and yet, if done properly, maintains a healthy microflora which is more favorable to strawberry growth. The recolonization sequence of fungi after broad-spectrum fumigation is critical for a long-lasting effect. This is therefore directed through careful manipulation of the fumigation process, quarantine of the field in winter, maintaining a suitable food source for recolonizers, and in the future, inoculations with desirable antagonists.

9) Limit the use of post-planting soil drenches to times when they will have the maximum beneficial effect. In an integrated program with rotations and fumigation, additional control of weevils, nematodes, and red stele should not be needed for the first several years. As these pests recolonize, remedial applications of specific chemicals may be of great value, even adding an additional year onto the rotation. If these compounds are thus used, problems of resistance, rapid

degradation, and residues in fruit should not develop.

The goal of this program is to increase the health of strawberry roots by depressing the activities of pests to a level lower than would occur naturally. To do this, energy in the form of chemical and cultural controls is applied to the ecosystem so that a temporary and favorable stasis is created, in which plants thrive. Broad-spectrum fumigation alone may produce the desired ecosystem changes, but only for a limited period, perhaps a year or two. In the case of multicropped strawberries, this stasis must last four to five years, so management should focus on prolonging the effects of the fumigation treatment. It must therefore be combined with the proposed measures which act to exclude and reduce pest populations, reduce pest competence by altering the physical and biological environments, and manage the selection of pest biotypes to favor those not injurious to strawberries.

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