

Strawberry Black Root Rot

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The Disease

Black root, black rot, or strawberry black root rot were the descriptive names first given for a debilitating root cortical disease of uncertain cause. The disease has been a challenge for strawberry growers for at least a century, and probably longer. Early work in 1917 (Fletcher) described root rot or black root of strawberry and stated that the disease was prevalent in Massachusetts, Michigan, and New York in the years 1902 to 1908. Black root rot typically causes little disease in the first year, although it has been implicated in occasional transplant failures. Generally, the loss in plant vigor and elevated plant mortality during harvest, especially under conditions of environmental stress, increases in severity each year, leading to increased yield variability within a field and eventual loss of productivity (Maas, 1998; Strong and Strong, 1931; Zeller, 1932) (Figure 1). Infected roots develop expanding black cortical lesions leading to root girdling, cortical rot, and a resulting loss of root function and loss of root mass responsible for the decline syndrome (Figure 2).

Unraveling the Cause

Heald (1920) may have been the first to assign *Rhizoctonia* as the causal pathogen responsible for “dying out” of strawberry beds in western Washington. Since that time, a fairly large number of pathogens, including *Pythium* spp., *Fusarium* spp., *Cylindrocarpon* spp., *Idriella lunata*, and *Ramularia* spp., as well as environmental

conditions, such as drought, waterlogging, compaction, and winter injury, also have been associated with strawberry black root rot (Maas, 1998; Martin and Bull, 2002; Miller, 1948; Nelson and Wilhelm, 1956; Nemeč and Sanders, 1970; Watanabe *et al.*, 1977, and Wing *et al.*, 1994).



Figure 1. Variable plant growth in a black root rot-affected field.



Figure 2. Cortical root rot symptoms on a strawberry structural root.

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Black root rot generally has been regarded as a complex disease with multiple causes (Maas, 1998; Martin, 1988; Plakidas, 1964). However, *Rhizoctonia* fungi have been most convincingly demonstrated as the primary cause of the disease (Coons, 1924; Husain and McKeen, 1963; Martin, 1988; Molot *et al.*, 1986; Ribeiro and Black, 1971; Wilhelm *et al.*, 1972; and Zeller, 1932). The further identification of specific types of *Rhizoctonia* pathogenic to strawberry has been important in consistently demonstrating pathogenicity and the association of this pathogen with the disease. In 1963, isolates of binucleate *Rhizoctonia* pathogenic to strawberry were differentiated from the multinucleate *R. solani* and described as *R. fragariae* by Husain and McKeen (Figure 3). *Rhizoctonia solani* is not commonly isolated from strawberry roots and is not consistently pathogenic (Martin, 1988). Ogoshi *et al.*, (1979) separated the binucleate *Rhizoctonia* spp. into at least 15 anastomosis groups and identified *R. fragariae* as belonging to one of three of those groups, anastomosis groups (AG) A, G, or I.

Martin (1988) isolated all three anastomosis groups (AG A, G, and I) of *R. fragariae* pathogenic to strawberry from commercial strawberry fields in Connecticut. He determined that isolates of different AG may differ in pathogenicity and could be recovered from roots in different frequencies in spring versus fall seasons.

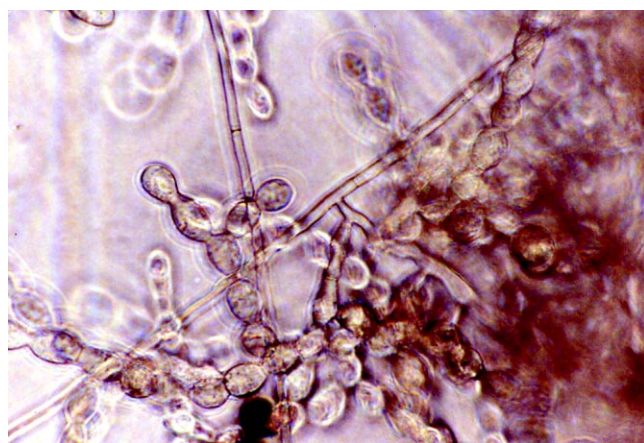


Figure 3. Hyphae and monilioid cells of *Rhizoctonia fragariae*.

Contributing Factors: Lesion Nematodes

The lesion nematode, *Pratylenchus penetrans* (Cobb) Filip & Schur. Stek. (Figure 4), has been variously regarded as a primary cause of black root rot (Goheen and Smith, 1956; Klinkenberg, 1955), as a predisposing factor for disease (Chen and Rich, 1962; Townshend, 1962), or as a component of a disease complex involving more than one pathogen (Chen and Rich, 1962; LaMondia and Martin, 1989; Maas, 1998; Ribeiro and Black, 1971). A number of surveys have associated lesion nematodes with increased severity of black root rot under field conditions (Goheen and Bailey, 1955; Goheen and Smith, 1956;

LaMondia, 1994) and results of controlled experiments have confirmed the role of the nematode in the disease (Chen and Rich, 1962; LaMondia, 2003; LaMondia and Martin, 1989).



Figure 4. The root lesion nematode, *Pratylenchus*.

We conducted experiments in which pure cultures of *R. fragariae* AG A, G, and I were inoculated to strawberry alone or in combination with monoxenically produced lesion nematodes (without contaminant microorganisms) under growth chamber conditions at 10 and 24 °C (LaMondia and Martin, 1989). Our results demonstrated that the presence of *P. penetrans* increased the severity of black root rot caused by all three AG of *R. fragariae* at both 10 and 24 °C. Higher inoculum densities of *P. penetrans* were more effective than low densities in this respect. Both structural and feeder root length were reduced more in the presence of both pathogens than with either one alone. In addition, temperature appears to be a factor in determining whether AG G or AG I predominates. AG I caused more root rot than AG A or AG G at cooler temperatures and may be more active than other AGs in late fall to early spring. AG G was more virulent than AG A or I under warm conditions and may be the more important pathogen over the summer. Survey results from Connecticut have indicated that AG G was the most common AG isolated from strawberry roots in the spring and AG I was most common in the fall (Martin, 1988). The differential survival of roots infected with AG G during the summer or AG I during cool conditions may account for those results as roots infected with those AG will be killed and not recovered compared with roots infected with AGs causing less disease at those temperatures.

The timing of sampling and the type of plant sample collected may have a large influence on the ability to associate lesion nematodes with strawberry black root rot. Plant-parasitic nematodes are obligate parasites and require susceptible living root tissues upon which to feed. Sampling in late stages of the disease after the complete

or nearly complete loss of healthy unsubsized roots due to black root rot may effectively eliminate lesion nematode populations and mask an association of these nematodes with the early stages of the disease.

In addition to the influence of black root rot on strawberry roots and nematode populations, soil and root densities of plant-parasitic lesion nematodes infecting strawberries exhibit seasonal variation (DiEdwardo, 1961; Szczygiel and Hasior, 1972). These variations often make it difficult to interpret the relation between nematode population density and strawberry yield loss from samples taken at different times during the year. While changes in population densities may be dramatic throughout the year, population dynamics tend to be similar and repeatable year after year within areas of similar climate on a single crop, regardless of differences in soil moisture or precipitation (Winslow, 1964). We conducted a series of experiments to investigate the relation between strawberry root type, biomass, and nematode population densities in roots and soil over time (LaMondia, 2002). Nematode population densities are best correlated with perennial strawberry crowns set fruit buds in the fall, which determines yield potential for the next June crop (Maas, 1998). It may not be surprising, then, that the influence of nematode-induced stress may not be reflected in yield until the next year (LaMondia, 1999a).

Contributing Factors: Stress

Environmental stresses, including soil compaction, excess moisture, and winter injury, also may increase the severity of black root rot (Coons, 1924; Maas, 1998; Wing *et al.*, 1994). These stresses may affect root function and the ability of the plant to respond to root infection or quickly produce new roots to replace nonfunctional, diseased roots. The reduction in the size and function of the root system diminishes plant vigor and contributes to the decline syndrome.

Contributing Factors: Root Type

Differences in strawberry root anatomy may significantly add to the variation associated with disease and with sampling for nematodes. Three distinct types of roots, structural, perennial, and feeder, exist on crowns at the same time and the relative abundance of each morphological type varies with time (Wilhelm and Nelson, 1970). All three of these root types have specific functions and are necessary for the growth and survival of the strawberry crown. New structural roots (which eventually become perennial roots) are produced from crowns. Structural roots are the larger, nearly white roots produced by first-year plants (Figure 5). These roots have a well-defined root cortex surrounding a central vascular ring (Figure 6). The terminal branches of these roots are fine lateral or feeder roots. The feeder roots do not develop secondary

tissues, have a limited life span, and are replaced several times each season. The structural roots develop secondary tissues and eventually become dark or black woody perennial roots (Figure 7). Perennial roots result from the development of secondary growth and thick-walled suberized tissues. Perennial roots act as storage organs and conduct water with minimal mineral uptake. The corky secondary growth starts just outside the vascular tissue (Figure 8) and cuts off the cortex and epidermis, which die and become the black surface of perennial roots (Figure 9). Lesion nematode symptoms are commonly seen on young structural roots, but the relation between *P. penetrans* and root anatomy had not previously been determined. Damage from nematode infection ranges from the death of individual cells (Figure 10) to the development of elliptical lesions resulting from multiple cell death and necrosis (Figure 11). Lesion nematode damage may reduce overall root growth, result in early discoloration of the endodermis (Figure 12), and stimulate suberized root production, shifting the balance between root types toward perennial roots, thereby negatively influencing strawberry growth and vigor.



Figure 5. Strawberry structural roots and associated feeder roots.

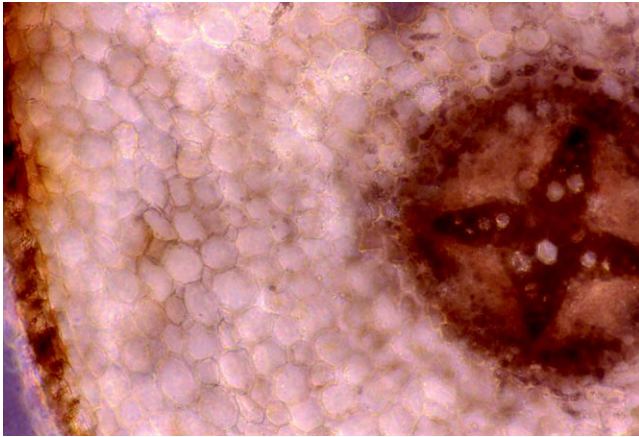


Figure 6. Cross section of a structural root. Note the well-defined root cortex surrounding a central vascular ring.

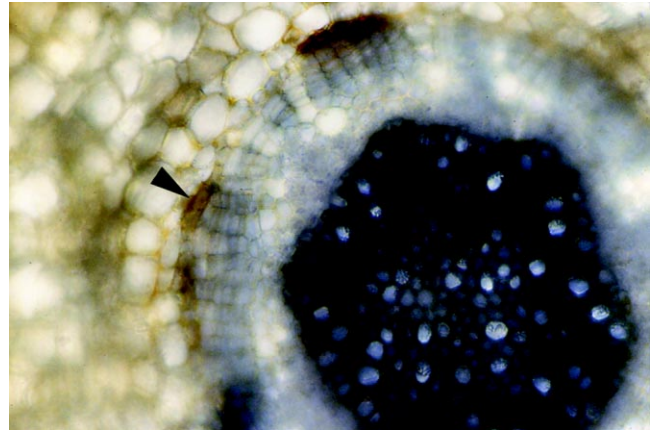


Figure 8. Cross section of a structural root showing the initiation of secondary growth just outside the vascular tissue.



Figure 7. Strawberry perennial roots and associated feeder roots.

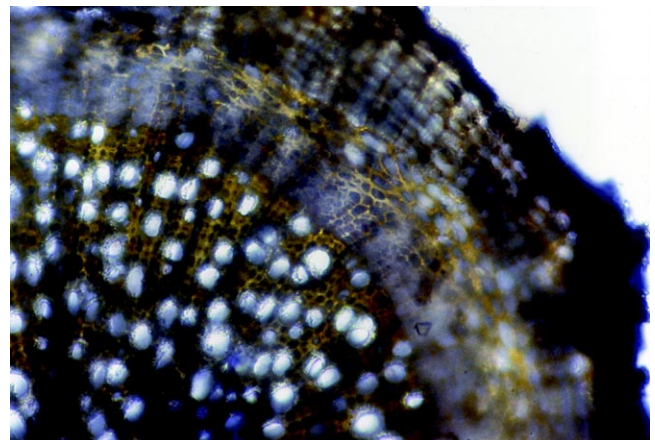


Figure 9. Cross section of a perennial root. Note that the cut off cortex and epidermis has died and become the black surface of perennial roots.

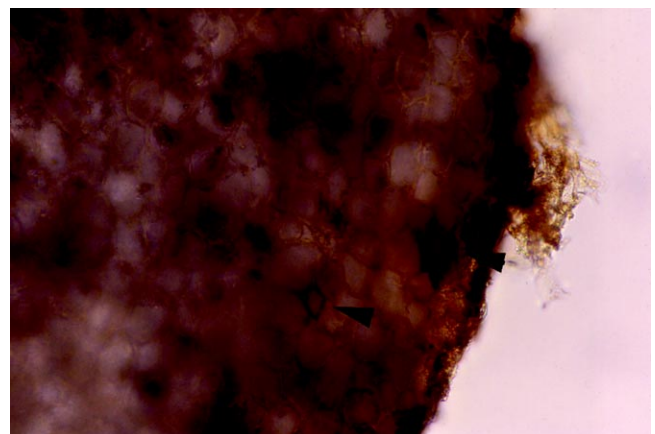


Figure 10. Damage from lesion nematode infection to an individual cortical cell.

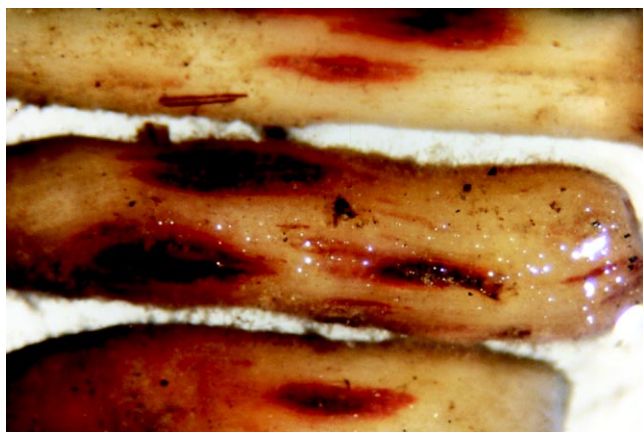


Figure 11. Elliptical cortical lesions resulting from *Pratylenchus penetrans* infection.

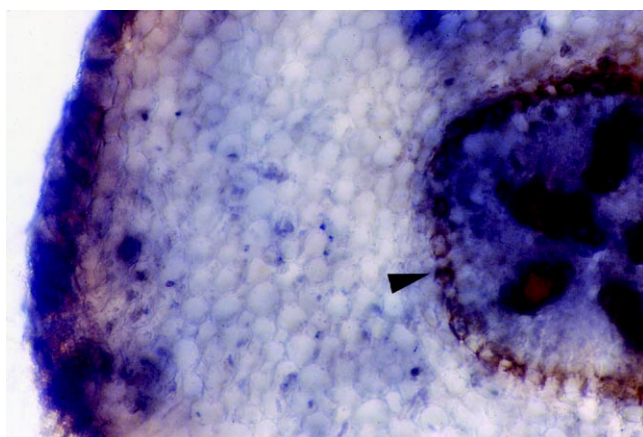


Figure 12. Cross section of a structural root with early discoloration of endodermis tissues resulting from *Pratylenchus penetrans* infection.

Pratylenchus penetrans occupy niches both in soil and in morphologically distinct strawberry roots at different times of the year. The variation in nematode numbers over time reflects changes in the distribution of morphological types of strawberry roots that occur over the season. In experiments over two years, we found that *P. penetrans* population densities peaked at about the end of May (LaMondia, 2002). The subsequent decline in numbers corresponds to changes in total strawberry root weight and root type distribution. The loss of nematode habitat results both from loss of roots of all types due to disease and also from a natural change in root type from structural root to suberized perennial root unsuitable for nematode infection.

In our studies, relatively few nematodes were extracted from soil, diseased roots, or suberized roots without associated feeder roots. Previous research in New Jersey (DiEdwardo, 1961) and in Poland (Szczygiel and Hasiior, 1972) reported that *Pratylenchus* densities in soil were low and did not exhibit seasonal variation. They reported that numbers extracted from strawberry roots were higher in young roots than in older, black root rot

symptomatic roots. Lesion nematode numbers peaked in June and precipitous declines were associated with aging roots (the development of perennial roots) (DiEdwardo, 1961) or a drop in the percentage of young white roots (Szczygiel and Hasiior, 1972). There were no effects of root age on the proportion of female, male, or juvenile nematodes (DiEdwardo, 1961). The high correlation between percent healthy white roots and lesion nematode numbers in all of these studies heavily underscores the fact that the recovery of these obligate parasites from severely diseased crowns is unlikely, regardless of whether nematodes were initially involved in the disease complex.

Structural strawberry roots and healthy suberized perennial roots normally produce successive crops of soft absorptive feeder roots (Wilhelm and Nelson, 1970). During the period of spring fruit production, extensive loss of all root types may occur. Strawberry roots were also reported to decline during fruiting. Lesion nematode populations mirrored the decline of root growth (DiEdwardo, 1961; Szczygiel and Hasiior, 1972). Root growth recovered by fall, but nematode population density recovered more slowly than roots, probably resulting from the dilution effect of slowly increasing nematode numbers in more quickly increasing root biomass.

The health, vigor, and productivity of the crown are determined by the extent to which structural roots are produced, converted to perennial roots, and produce successive flushes of feeder roots unimpeded by root pathogens (Wilhelm and Nelson, 1970). Infection of strawberry roots by both *P. penetrans* and *R. fragariae* results in significant and severe root rot (LaMondia and Martin, 1989). Black root rot caused by *R. fragariae* reduced healthy structural root length by the development of cortical rot and also reduced feeder root length (LaMondia and Martin, 1989). Strawberry black root rot-affected plants exhibit areas of cortical necrosis, a rattail symptom on structural roots resulting from the death of extensive areas of the root cortex, and the collapse of perennial roots. The cortical root rot symptoms are transient, as rotted roots disappear over a short time, and the loss of root biomass, especially feeder roots, is of primary importance in the decline of the strawberry crown (LaMondia and Martin, 1989). While this disease may increase the inoculum potential of *R. fragariae* over time, populations of *P. penetrans* are already fluctuating with the cycle of root growth and are further reduced by the destruction of remaining healthy roots and the loss of feeder root production. As a consequence, these nematodes must migrate to adjacent healthy roots to survive. These nearby roots may be strawberry or weed host roots. Our results suggest that in order to optimize diagnostic sampling to best determine lesion nematode density and their involvement in black root rot disease, samples should be taken in late May or early June (prior to fruiting) or later in the year after mid-August. Additionally, crowns exhibiting symptoms of severe black root rot with poor or a lack

of healthy roots should not be sampled. Rather, nematodes should be recovered from plants adjacent to diseased areas that still have significant amounts of healthy structural and feeder root tissue.

Interaction of Lesion Nematodes and *R. fragariae*

The demonstration that *P. penetrans* increased the severity of black root rot was an important step in understanding the disease complex, but many additional questions remained. We next conducted a series of experiments to determine whether *P. penetrans* had a local or systemic influence on *R. fragariae* infection and strawberry root rot and to examine the extent of *R. fragariae* infection of morphologically different strawberry root types alone and in relation to lesion nematode infection (LaMondia, 2003). The extent of *R. fragariae* infection of morphologically different strawberry roots was determined from an established planting of 3-year-old Honeoye strawberry crowns in field plots infested with lesion nematodes and the black root rot pathogen, *R. fragariae*. Plants were sampled from March to June over two years. Root systems were washed free of soil and separated into four classes: black suberized perennial roots, new healthy (no root-rot) structural roots, fine lateral (feeder) roots from perennial roots and fine lateral roots from structural roots. Structural roots were further subdivided into roots with or without typical lesions caused by *P. penetrans*. *Rhizoctonia fragariae* was isolated on acidified water agar from 10 0.5-cm sections of surface-sterilized roots in each class. Cross sections of morphologically different strawberry roots also were examined microscopically.

First-year strawberry structural roots have a well-defined cortex that becomes disrupted and detached as a result of secondary growth. Polyderm and phellogen (alternating layers of suberized and unsuberized cells) formation isolates and ruptures the cortex, which is sloughed off with the endodermis and epidermis as secondary growth occurs. The resulting perennial roots consist in large measure of woody xylem, polyderm, and phellogen (Esau, 1977). The remains of the cortical and epidermal cells are retained on the exterior of the perennial roots as an amorphous black layer (Figure 9).

Rhizoctonia fragariae infection, as indicated by isolation of the fungus from structural roots, was increased in root segments with typical *P. penetrans* cortical lesions compared to similar roots without nematode-induced lesions. The isolation of *R. fragariae* from structural roots increased over time during strawberry fruit production and the initiation of secondary growth associated with the transition from structural to perennial roots. This result is consistent with our previous observation that strawberry root mass declined in field soils at fruiting due to fungal infection and root rot (LaMondia, 2002). May and Pritts

(1994) also noted that the strawberry root system was the only plant part that declined in biomass during fruiting. Townshend (1963) and Wilhelm and Vertrees (1964) observed that the development of polyderm due to *P. penetrans* infection was associated with the presence of fungal hyphae visible in the cortex of strawberry roots.

Pratylenchus penetrans primarily infect feeder and structural roots rather than perennial roots (LaMondia, 2002) and tend to be aggregated in the root cortex. Zunke (1990) described two types of lesion nematode feeding: brief feeding episodes that weaken cells without cell death and extended feeding resulting in cell collapse and death. We observed the death of individual cells through which lesion nematodes had moved, along with lighter discoloration of cells adjacent to these dead cells (Figure 10), perhaps as a result of feeding or diffusion of substances. Discoloration of the endodermis was observed in proximity to nematode infection without adjacent cell damage (LaMondia, 2003). Townshend (1963) and Zunke (1990) also reported that the presence of lesion nematodes was associated with discoloration of the endodermis despite the observation that lesion nematodes did not feed on the endodermis cells. Areas of *P. penetrans* aggregation in the cortex were distinguished by a reddish brown discoloration and eventually by a distinct, usually elliptical, sunken lesion resulting from cell necrosis. Fungal hyphae that appeared to be *R. fragariae* were observed in typical *P. penetrans* lesions. Chen and Rich (1962) observed that fungi infected roots more readily at necrotic areas caused by *P. penetrans* than at healthy areas of the root.

We demonstrated that *R. fragariae* was consistently isolated from both healthy and diseased perennial roots, which is consistent with previous observations that *R. fragariae* infects the sloughed cortex (Wilhelm and Nelson, 1970; Wilhelm *et al.*, 1972). This colonized tissue on the exterior of woody perennial roots may act as a source of infection for adjacent feeder and structural roots. In fact, we determined that feeder roots attached to perennial roots were significantly more likely to be infected with *R. fragariae* than feeder roots attached to structural roots (LaMondia, 2003).

The role of *P. penetrans* in disease complexes may differ with the interacting root pathogen, with the crop plant, or with environmental conditions. The lesion nematode systemically increased Verticillium wilt in mint, caused by the vascular wilt pathogen *Verticillium dahliae*, in a split-root system (Faulkner *et al.*, 1970). *Pratylenchus penetrans*, but not *P. crenatus*, interacted with *V. dahliae* to increase the severity of Verticillium wilt in potato, suggesting that the mechanism of interaction with the vascular-infecting fungus may be due to more than simply root wounding due to infection and feeding. *Pratylenchus scribneri* increased wilt under high temperature stress, but not in a cool year (Riedel *et al.*, 1985). However, lesion nematodes had no systemic effect on Verticillium wilt in

tomato in a split-root system, and a disease increase was instead attributed to an increase in local infection courts (Conroy *et al.*, 1972).

Our experiments using individual plants with split-root systems allowed the investigation of local versus systemic pathogen interactions. *Pratylenchus penetrans* increased the severity of strawberry black root rot caused by *R. fragariae* in a local, rather than systemic, manner in these experiments (LaMondia, 2003). Infection of one half of a split-root system with both pathogens exhibited greater levels of black root rot than when similar numbers of the same pathogens were infecting different halves of the same root system. As cortical root rot pathogens, *Rhizoctonia* species have not been associated with systemic disease. The northern root-knot nematode, *Meloidogyne hapla*, has been shown to increase root rot by *R. solani* by increasing the number of infection courts, presumably due to wounding and increased nutrition available to the fungal pathogen (Khan and Muller, 1982). Similarly, the local influence of *P. penetrans* on black root rot suggests that increased numbers of infection sites due to wounding or the predisposition of limited areas of the cortex to infection may be responsible for the increased disease in strawberry roots seen in these experiments.

It appears that *R. fragariae* commonly resides on the sloughed cortex of healthy perennial roots. In fact, our isolation of the pathogen from noninoculated crowns in split-root experiments has demonstrated that *R. fragariae* was present at low levels on commercially produced healthy strawberry crowns. From this source, the fungus may then infect structural or feeder roots, especially when the plant is under stress or roots are damaged. Lesion nematodes aggregate in the root cortex. Nematode feeding and movement directly result in cell damage and death. The indirect effects of lesion nematode infection are discoloration of the endodermis and early polyderm formation, followed by localized areas of secondary growth and cortical cell senescence or death. Weakened or dying cells resulting from the direct or indirect effects of *P. penetrans* are more susceptible to *R. fragariae*, thereby increasing the extent of infection and cortical root rot.

Facultative pathogens, such as *Rhizoctonia solani* and certain *Fusarium* spp., may infect root cortical tissues without causing damage until the plant host is placed under stress (Leach, 1947). *R. solani* is a common mycorrhizal fungus in orchid roots, assisting the plant with nutrient extraction from soil. However, when environmental conditions are unfavorable for the orchid host, the fungus may become an aggressive pathogen of the very same roots (Harley, 1969). In fact, previous research has reported an apparent pathogenic and mycorrhizal relationship between *R. fragariae* and strawberry roots similar to the orchid and *R. solani* relationship (Molot *et al.*, 1986; Ribeiro and Black, 1971) and consistent with our results.

Disease Management

Management of strawberry black root rot is difficult but very important. The *R. fragariae* and *P. penetrans* pathogens are widespread and common in strawberry plantings. Martin (1988) was able to isolate *R. fragariae* from more than 70% of plants from commercial strawberry fields in cultivation for more than one year. A survey of 41 commercial strawberry fields in Connecticut (paired for healthy versus stunted in each field) demonstrated that lesion nematodes occurred in greater than 75% of sampled plants. Stunted plants had nearly twice the *Pratylenchus* populations of adjacent healthier plants and populations ranged from undetectable to 2,350 per g root (LaMondia, unpublished).

Black root rot caused by *R. fragariae* and *P. penetrans* can have severe economic consequences. An economic analysis of lesion nematode populations in *R. fragariae*-infested field soils was conducted based on the regression of yield data with *P. penetrans* populations in small plots at the Connecticut Agricultural Experiment Station Valley Laboratory in Windsor, Connecticut. A "Strawberry Profit Spreadsheet Template" model developed by DeMarree and Riekenberg (1998) was used to analyze the effects of nematodes on profitability. Based on four years of projected fruiting from a planting, strawberry profit expressed as a percentage of gross sales was predicted to be 33%, 30%, 18%, or 0% (operation at a cumulative loss) over four harvest years at initial densities of 0, 12, 50, or 125 *P. penetrans* per g root, respectively. Half of the samples from surveyed growers' fields in Connecticut had populations in excess of 125 nematodes per g root.

Disease Management: Chemical

Management of a disease complex caused by soil-borne fungal and nematode pathogens may be achieved by fumigation with a broad-spectrum biocide such as methyl bromide or chloropicrin (Wolfe *et al.*, 1990; Yuen *et al.*, 1991). In fact, virtually all of the strawberry acreage in California is produced on soil fumigated with one of these two compounds (Martin and Bull, 2002). But fumigation is not always successful for a variety of physical and biological reasons, and the application of metham-sodium did not increase root growth, health, or fruit yield (Yuen *et al.*, 1991). The only management tactic associated with nearly complete control of lesion nematodes in Connecticut was fumigation with methyl bromide (LaMondia, unpublished).

The overall result of soil fumigation may be greatly reduced if the black root rot pathogens are reintroduced on the crowns transplanted into the field. *Rhizoctonia fragariae* consistently has been isolated from healthy nursery-produced planting stock (Ribeiro and Black, 1971;

LaMondia, unpublished) and lesion nematodes also may be extracted at low frequencies (LaMondia, unpublished). Therefore, the use of healthy planting stock is of particular importance after fumigation or rotation, and the use of fumigation and other control tactics is especially important in nursery production.

In the absence of soil fumigation, alternative control tactics may be targeted at each of the pathogens in the complex. Application of nonfumigant nematicide, such as fenamiphos (Nemacur), may result in temporary nematode control and can increase strawberry vigor and yield. However, nematode population densities still may increase later in the season and may eventually be higher in nematicide-treated plants than in severely diseased plants, which lack sufficient roots to support nematode populations (LaMondia, 1999a). Repeated applications of nematicides or alternate methods for suppressing nematode populations may be required to maintain plant health and productivity over time.

The use of fungicides to suppress *R. fragariae* has been attempted and is currently under investigation, but no success has yet been reported. Fungicidal control of *R. fragariae* may best be targeted at eliminating nonsymptomatic infections from planting stock.

Terbacil (Sinbar) herbicide application has been associated with increased levels of strawberry root disease based on correlation analyses of grower survey responses (Wing *et al.*, 1995). Our research in small plots at two locations over four years at up to four times label rates indicated that terbacil did not affect the development of black root rot in perennial, structural, or feeder roots (Mervosh and LaMondia, 2004). Correlation analyses should not be used to imply causality and the correlation between terbacil use and root disease may rather be the result of increased weed pressure in declining strawberry fields.

Disease Management: Cultural and Biological

A number of nonchemical means of control also have been investigated. Rotation was one of the first management tactics suggested for black root rot (Zeller, 1932), and current recommendations continue to suggest rotation into small grains for two years (Pritts and Wilcox, 1990; Schroeder, 1988). Small grains have been suggested to suppress *Rhizoctonia solani* (Zeller, 1932), but some *R. solani* AG are pathogenic to small grains (Weller *et al.*, 1986) and the effects on *R. fragariae* are unknown. Rotation away from strawberry to unspecified crops reduced *R. fragariae* isolation from plants to about one third of that seen from continuous strawberry production (Martin, 1988). A dense planting of small grains may reduce broadleaf weeds, but the lesion nematode has a wide host range, including most small grains (Mai *et al.*,

1977), and rotation with grains has been associated with increased lesion nematode damage to potato (Florini and Loria, 1990). Growers in Connecticut have rotated to small grains and still observed poor strawberry growth and black root rot symptoms in replanted fields.

Nematode antagonistic rotation or cover crops, such as 'Saia' oat, sorgho-sudangrass, *Rudbeckia hirta*, pearl millet '101' and 'Polynema' marigold, have been reported to suppress lesion nematode populations (LaMondia, 1999b; LaMondia and Halbrendt, 2003), but many of these crops have serious drawbacks that limit their utilization, such as seed availability, difficulty in establishment, or cost. Additional plant species need to be evaluated for efficacy against *P. penetrans* and the black root rot complex, seed availability, low cost, and ease of establishment.

Black root rot also may be reduced through the management of mineral nutrition. Ammonium forms of nitrogen nutrition resulted in less black root rot than when plants were fertilized with nitrate nitrogen. The application of ammonium rather than nitrate nitrogen forms to field plots (Elmer and LaMondia, 1995) and microplots (Elmer and LaMondia, 1999) reduced the severity of root disease by 10% to 20% and yields were increased by about 15%. Nitrogen form may influence plant mineral composition, the pH of the rhizosphere and the microbial ecology of the rhizosphere (Elmer and LaMondia, 1999), any of which may affect the development of disease.

Biological and physical approaches to disease management also have been attempted. Entomopathogenic nematodes have been implicated in the reduction of root-knot nematode diseases (Bird and Bird, 1986), and *Trichoderma harzianum* (RootShield) has been an effective biological control of a number of fungi, including *Rhizoctonia* spp. (Yuen *et al.*, 1994). In small plots and field microplots, inundative application of entomopathogenic *Steinernema carpocapsae* or *S. feltiae* did not impact *P. penetrans* populations and *T. harzianum* did not affect the development of strawberry black root rot by *R. fragariae*. In the Pacific Northwest, soil solarization for two months significantly reduced strawberry root necrosis and root infection by a number of fungi, including *R. fragariae* (Pinkerton *et al.*, 2002). However, solarization did not eliminate the pathogens from the soil.

Disease Management: Summary

Black root rot management, in the absence of fumigation, may need to rely on the combination of several factors, some still under development, to be effective. These management tactics may include rotation into new fields with low or undetectable lesion nematode populations; rotation to fields not previously planted to strawberry or rotated away from strawberry for 1 or 2 years; planting of effective and practical nematode and *R. fragariae*-antagonistic rotation or cover crops; the possible future use of fungicides effective against

R. fragariae, the use of pathogen-free crowns as planting stock; control of lesion nematodes with nonfumigant nematicides such as Nematicur; fertilization with ammonium forms of nitrogen rather than nitrate forms; the use of raised beds with irrigation to avoid soil compaction and excess water or drought; mulching to avoid winter injury; and weed control to reduce plant stress as well as plants that are often hosts of lesion nematodes.

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