Biology and Management of Root-Knot Nematodes on Potato in Washington

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Potato (*Solanum tuberosum*) is one of the most important agricultural crops grown in the Pacific Northwest. In 2001, Idaho, Oregon, and Washington produced 60.8% of the U.S. total (43). That year, 160,000 acres of potatoes were grown in Washington averaging yields of 590 cwt./a (highest in U. S.) with total value of $552 million. Approximately 90% of Washington potatoes are grown for processing and the remainder for fresh market.

The root-knot nematodes (*Meloidogyne* spp.) make up a major group of plant pathogens of economic importance (4). They are worldwide in distribution and attack almost every type of crop, causing yield losses or affecting quality. Of the more than 80 known species of *Meloidogyne* three are known to occur in the Pacific Northwest (11). The Columbia (*M. chitwoodi*) and northern (*M. hapla*) root-knot nematodes are serious pests of irrigated crops, especially potatoes. A third species, the barley root-knot nematode (*M. naasi*) has also been found in golf greens, pasture, and cereals, but is unimportant to Washington agriculture. These three species are called cool climate root-knot nematodes because unlike warm climate species they can survive freezing conditions.

M. chitwoodi and *M. hapla* blemish potato tubers and render them unmarketable (33). Root-knot nematode infection seriously affects the cooking quality of processed potato products, such as French fries and potato chips. A potato crop with 10% or less of the tubers infected with nematodes may be rejected or downgraded by the processor. Also, tubers exhibiting internal and/or external symptoms (bumps or galls) are unacceptable for fresh market. Of the potato acreage grown in Washington, 70-80% receive nematicide treatments to control these nematodes at an estimated annual cost of $20 million. Loss without chemical treatments may be as high as $40 million. Despite these costly chemical control practices, root-knot nematodes remain a serious problem, and appear to have increased over the past several years. This is probably due to inadequate fumigation practices, and the buildup of nematode population densities resulting from mild winters, unusually warm growing seasons, poor cropping sequences, and infestation of previously non-infested fields.

Geographical Distribution

Root-knot nematodes were first observed in the Columbia basin in Block 73 near Quincy, WA in 1960. Today these nematodes are widespread throughout the Columbia basin. The principal means of spread is via recycled irrigation water and infected seed potato tubers (7, 20). *M. hapla* was considered the most important to potato production in the Pacific Northwest until *M. chitwoodi* was discovered in Quincy, WA in 1978 (34). Since then *M. chitwoodi* has been reported in the U.S. from California, Colorado, Idaho, Nevada, New Mexico, Oregon, Texas, Utah, and Virginia (5, 9, 20, 22, 41, 42), and from Argentina, Mexico, and The Netherlands (6). Recently, *M. chitwoodi* has also been confirmed in Belgium, Germany, and South Africa (personal communications). Two races of *M. chitwoodi* were discovered in 1984 (36), and both races are widely distributed in the major potato growing regions of the Pacific Northwest (24). A third race was reported from California (14).

Life and Disease Cycle

Nematodes with few exceptions have six stages in their life cycle with four molts. Growth occurs after each molt, and the cuticle is shed at each molt. The young generally resemble adults, except in size and reproductive organs. However, in some like the root-knot nematodes, a condition known as sexual dimorphism occurs in which the males and females differ in gross morphological features. Root-knot nematodes have three distinct life stages in their life cycle (Fig. 1). The mature female is swollen (pear-shaped) measuring 1/64 - 1/25 in. (0.4 - 1.0 mm) in length, the male is vermiform (worm-like) and 1/32 - 1/13 in. (0.8 - 2.0 mm) long, and the second stage juvenile (J2) is also vermiform but considerably smaller than the male at 1/85 - 1/50 in. (0.3 - 0.5 mm) in length. The life and disease cycle of root-knot nematodes on potato is diagramed in Fig. 1. *M. chitwoodi* and *M. hapla* overwinter as J2 and eggs in the soil or tubers. The first stage juvenile develops within the egg, and the J2 hatches from the egg. The J2 is the only stage that can infect plant roots or tubers, and is called the infective stage. In the spring when potato roots appear, the J2 will penetrate roots just behind the root tip. After penetration, the J2 migrates to the root stele and establishes a feeding site. As feeding commences, the salivary secretions from the nematode stimulate the formation of specialized cells called giant cells. Giant cells are greatly enlarged multi nucleated cells that serve as food reservoirs for the developing nematode. These giant cells are essential for the survival of the nematode, because once a feeding site is established the nematode becomes sedentary and remains there until it dies. The nematode will then begin to enlarge and develop to the third and fourth stages. After the fourth molt the mature male or female emerges from the old cuticle. The males' role in reproduction is not clearly understood, and it is not known whether they feed after emerging. The mature female begins laying eggs about 7 days after the fourth molt. The eggs are laid in a gelatinous matrix (egg sac), which may either protrude from the root surface or remain entirely within the root. J2 hatches from the egg and may reinfect roots or tubers. The J2 infects tubers primarily through lenticels, and migrates to the vascular ring and establishes feeding sites.

Symptomology

The primary symptoms caused by *Meloidogyne* spp. are root galls or knots, therefore the name root-knot nematodes. Secondary symptoms may include stunting, chlorosis, wilting, root proliferation, and root deformity.

External symptoms produced by *M. chitwoodi* on Russet Burbank potato are quite distinct compared to *M. hapla*. *M. chitwoodi*, like other *Meloidogyne* species, produces distinct pimple-like bumps (galls) on the surface of the tuber, whereas *M. hapla* usually produces more of a general swelling (Fig. 2). It is difficult to differentiate between a tuber infected with *M. hapla* and a healthy tuber by external symptoms alone. However, internal symptoms produced by *M. chitwoodi* and *M. hapla* are similar (Fig. 3). Both species produce typical brown spots within 0.25 in. (6 mm) of the tuber surface (Fig. 4). Within each brown spot, a female nematode may be observed. She can produce 200-1,000 eggs that are deposited in a gelatinous egg sac at the posterior end of her body. Brown spots become evident only when the females begin egg production. Symptoms produced on potato roots are also distinct between the two species. *M. hapla* causes small galls and lateral root proliferation (Fig. 5), whereas *M. chitwoodi* does not (Fig. 6) (27). Root-knot nematode infection rarely causes above ground symptoms in potatoes.

However, plants with severe root-knot nematode infection may be stunted, turn yellow, wilt, or die if stressed for water.

Importance of *M. chitwoodi* and *M. hapla*

Before the discovery of *M. chitwoodi*, *M. hapla* was considered the most important nematode problem on potato. Subsequent research has shown that most of the damage of potato tubers attributed to *M. hapla* was caused by *M. chitwoodi*. *M. chitwoodi* is more important on potato than *M. hapla*, causing more severe tuber damage. Damage threshold studies show that less than one *M. chitwoodi* per half pint (250 cm^3) of soil can cause economic damage (35). The principal reason is the ability of *M. chitwoodi* to reproduce at lower soil temperatures than required by *M. hapla* (33). This is significant because potatoes in the northwestern U.S. are planted in the spring when soil temperatures range between 40 and 55 F (4.4 and 12.8 C) at 6 in. (15 cm) depth. *Meloidogyne chitwoodi* can penetrate and reproduce on potato roots earlier in the season than *M. hapla*. Consequently, *M. chitwoodi* generally has more generations during the growing season than *M. hapla*. This results in earlier tuber infection and more severe damage. The number of generations is dependent upon the number of degree days (heat units) [{(maximum - minimum daily temperature) ÷ 2} - base temperature] accumulated during the growing season. Both *M. chitwoodi* and *M. hapla* require about 1000-1100 degree days from the time of planting to complete the first generation and 500-600 for the subsequent generations (25). However, the minimum or base temperature at 8 in. (20 cm) deep for activity differs significantly between the two species; 41 F (5 C) for *M. chitwoodi* and 50 F (10 C) for *M. hapla* (10). Thus, depending on the soil temperature during the growing season and the length of the growing season *M. chitwoodi* may complete 3-5 generations and *M. hapla* 1-3. An extra generation, especially late in the season, will result in a tremendous increase in nematode populations. The first generation is completed in the roots and the subsequent generations in roots or within tubers. Second stage juveniles are unable to infect young tubers until approximately 70-75 days after planting (3). The mechanism of this resistance is not known.

Host Range

Both *M. chitwoodi* and *M. hapla* have very wide host ranges (8, 19, 21). The principal difference between these species is that many grasses are hosts for the three races of *M. chitwoodi* but are not hosts for *M. hapla*. The differences among the three races of *M. chitwoodi* lay in their differential reproduction on alfalfa (*Medicago sativa*) and the wild potato species *Solanum bulbocastanum*. Race 1 does not reproduce on alfalfa and race 2 does (19), and race 3 reproduces on *S. bulbocastanum* whereas races 1 and 2 do not (14). *S. bulbocastanum* has been a source of resistance in the USDA-ARS breeding program at Prosser, WA (1).

Nematode Migration

More than 80% of the root-knot nematode population occurs in the upper 2 ft. (60 cm) of soil where feeder roots are abundant. However, populations of *M. chitwoodi* have been observed as deep as 6 ft. (180 cm) (37). Deep nematode populations are usually associated with deep-rooted crops, such as alfalfa. Root-knot nematodes by themselves do not move downwards long distances (23). *M. chitwoodi* can migrate upwards faster and farther than *M. hapla* (23). In soil columns buried in the field, *M. chitwoodi* migrated upwards from 6 ft. (180 cm) to infect tomato roots (12). The importance of deep-placed *M. chitwoodi* populations in causing potato tuber damage was demonstrated under field conditions at Prosser, WA and Hermiston, OR (12, 29). At Prosser *M. chitwoodi* placed at 0, 1 and 2 ft. (0, 30 and 60 cm) deep could migrate upwards during the season and cause significant tuber damage. Nematodes at 3 and 4 ft. (90 and 120 cm) were not able to infect tubers. At the Hermiston site, *M. chitwoodi* from all depths were able to infect tubers. Thus, it appears that the ability of *M. chitwoodi* to migrate and cause tuber damage is influenced by soil texture. The Prosser soil contained a much higher silt content (44-55%) than the Hermiston soil (16-17%). This effect of soil type on migration was confirmed in the laboratory using soil columns (12). The sandier Hermiston soil used in these studies is more typical of soil in which potatoes are grown in Washington and Oregon. Thus, if *M. chitwoodi* is not adequately controlled to at least 3 ft. (90 cm) significant tuber damage could occur. Once the nematodes have infected roots, the degree of tuber damage will be influenced by the accumulation of degree days during the growing season and the length of the growing season. Increase in degree days and longer time periods with tubers in the ground will result in more nematode generations, and increased tuber infection.

Nematode Management Strategies

There are several strategies that may be used to manage root-knot nematode populations before planting potatoes. Management strategies may include prevention of spread, crop rotation, early harvest, use of green manure cover crops, and nematicides. The best means to suppress nematode populations would be to employ a combination of these practices.

<u>Prevention of Spread</u>

Nematodes under their own power move very short distances. Spread of nematodes from infested to non infested area is by means of soil carried on sampling tools, boots, hoofs of animals, and farm equipment, infected plant material, and in reused irrigation water. Clean boots, tools and equipment between nematode infested and non infested fields to prevent moving contaminated soil. When irrigating with reused irrigation water, the use of settling ponds will minimize the spread of nematodes. Nematodes in the settling ponds will settle to the bottom and eventually die due to lack of oxygen.

A common means of spreading root-knot nematodes is by infected seed potatoes. *M. chitwoodi* and/or *M. hapla* have been reported from most seed potato growing areas in the western U.S., and *M. hapla* from Canada. However, it is very difficult to detect root-knot nematode infection in seed potatoes. Seed potatoes are usually not as severely damaged by root-knot nematodes as are potatoes grown for processing and fresh market. The environmental conditions in seed production areas are generally not optimal for root-knot nematode development. These areas usually have cooler soil temperatures, finer textured soils, and a shorter growing season resulting in 1-2 generations compared to two or more in commercial production areas. Consequently, symptoms and damage by root-knot nematodes on seed potatoes are not evident. Although external symptoms of *M. chitwoodi* may be evident, it is often very difficult to detect any internal tuber damage because the females are immature and brown spots have not yet developed. The best means to observe these immature stages within the tuber is to make thin tissue slices and stain the nematodes red (2). Probably the best means to determine if a seed-lot is infested with root-knot nematodes is to obtain soil samples from the field in question or to sample the tare soil accumulated during the transfer of tubers from the field into storage.

Crop rotation

The crops most commonly grown in rotation with potato in the Pacific Northwest are alfalfa, corn, and wheat. Alfalfa is an excellent crop to suppress *M. chitwoodi* race 1 populations (19). Unfortunately, race 2 and *M. hapla* populations will increase to high densities on alfalfa (13). Corn (*Zea mays*) and wheat (*Triticum aestivum*) are hosts for *M. chitwoodi*, but not for *M. hapla* (8, 21). Thus, corn and wheat (and other cereals) would be excellent crops to rotate with potato to suppress *M. hapla* populations. Although both field corn and wheat are suitable hosts for *M. chitwoodi*, field corn is a longer season crop than wheat and *M. chitwoodi* can complete more generations on field corn than wheat. Thus, wheat would be a better rotational crop than field corn to minimize *M. chitwoodi* populations. Another disadvantage with field corn is that a fall harvest may interfere with proper fumigation practices. Sweet corn is preferred as a rotational crop to field corn because it is a less suitable host to *M. chitwoodi* and is a short season crop like wheat. An important factor in a crop rotation program is proper weed control in the rotational crop. Many weeds are suitable hosts for *M. chitwoodi* and *M. hapla* (8, 21). These factors are significant because the success or failure of a nematicide treatment depends on the nematode population density, and employing proper fumigation techniques.

Crops that are not suitable hosts to both *M. chitwoodi* races include asparagus (*Asparagus officinalis*), cowpea (*Vigna unguiculata*), fodder radish (*Raphanus sativus*), lima bean (*Phaseolus limensis*), Scotch spearmint (*Mentha cardiaca*), strawberry (*Fragaria chiloensis*), and several cultivars of sudangrass (*Sorghum bicolor* var. *sudanense*), popcorn and sweet corn (19, 21). Asparagus, lima bean, sudangrass and sweet corn are also unsuitable hosts for *M. hapla* (8). The use of appropriate rotational crops to reduce nematode populations will greatly aid in the performance of a nematicide or other management practices.

Early Harvest and Storage

The severity of tuber damage by *M. chitwoodi* and *M. hapla* is greatly increased the longer the tubers remain in the ground. This is because nematodes in the soil are continuously infecting tubers. Thus, by harvesting tubers as early as possible damage may be lessened (32). Early maturing potato varieties, which are harvested by early August, usually escape damage by root-knot nematodes. Early harvest is especially beneficial for fields infested with *M. hapla*, because severe tuber damage is usually not observed until late September to early October (27). On the other hand, severe tuber infection by *M. chitwoodi* may be evident by mid-August. Even if nematicide treatments were made for *M. chitwoodi*, tubers should be harvested as soon as possible. Soil samples should be taken in early August to determine if root-knot nematodes are present. If present, early harvest or an application of a post plant nematicide, such as, Vydate™ (oxamyl) may be warranted to minimize tuber infection. Tubers infected with *M. chitwoodi* should be processed immediately and not stored (32). At storage temperatures of 46-48 F (7.8-8.9 C), *M. chitwoodi* continues to develop and tuber damage becomes more pronounced. *M. hapla* is not known to increase tuber damage at these storage temperatures.

Green Manure

Control of root-knot nematodes on potatoes in the northwestern U.S. is heavily dependent on soil fumigation. The continued availability of these nematicides is of major concern to potato growers. Thus, the search for alternative measures to manage root-knot nematodes on potatoes and other vegetable crops has become increasingly important. Rapeseed (*Brassica napus* and *B. campestris*) and sudangrass *(Sorghum bicolor*) may provide an alternative method for managing nematodes. Rapeseed and sudangrass contain glucosinolate and cyanogenic glycoside compounds, respectively, which have pesticidal effects when the plants are incorporated into the soil as green manure. Following incorporation, enzymic hydrolysis produces isothiocyanate from glucosinolates and hydrogen cyanide from cyanogenic glycosides. These compounds are toxic to certain insects, fungi, nematodes, and weeds. Within the potato rotational scheme rapeseed and sudangrass may be planted in early August after harvest of short season rotation crops, such as wheat or sweet corn, and incorporated as green manure either in the fall (sudangrass) or following spring (rapeseed) 3-4 wk. before planting potato. Sudangrass requires about 2-3 mo. of growth and rapeseed 6-7 mo. (28). The cyanogenic glycoside compounds are highest in the young rapidly growing sudangrass, especially under stress conditions, such as drought or frost. However, within 12-24 hrs after a frost these compounds rapidly degrade within the plant and become less effective.

Greenhouse and field studies show that rapeseed cv. Jupiter and Humus, and sudangrass and sorghum-sudangrass hybrids cv. Trudan 8, Sordan 79 and SS-222 are toxic to *M. chitwoodi* (15, 16, 17, 28). In the field, rapeseed provides 80-90% and sudangrass and sorghum-sudangrass hybrids 50-80% control of *M. chitwoodi* on potato tubers (16, 17, 28). The effectiveness of these green manure crops, especially sudangrass, is dependant on the amount of biomass produced. Thus, low temperature conditions in the fall may limit the growth of sudangrass and the amount of green manure incorporated into the soil. When combined with the nonfumigant nematicide Mocap™ (ethoprop) these green manure crops provide control comparable to Telone II™ (1,3-dichloropropene) (17, 28). Studies with white mustard (*Brassica hirta* cv. Martigena) show that it can reduce *M. chitwoodi* tuber infection (39). Results, however, have not been as consistent as rapeseed or sudangrass. White mustard, like rapeseed, releases isothiocyanate compounds. The advantage of white mustard is that only 6-8 wk. growth is required compared to 6-7 mo. for rapeseed.

<u>Nematicides</u>

The most common method used to control root-knot nematodes on potatoes in the northwestern U.S. is by soil fumigation with 1,3-dichloropropene (Telone II™) or metham sodium (26, 30). Telone II™ is applied by soil injection with tractor-drawn chisels and metham sodium by application through sprinkler systems. Telone II™ has been more consistent in controlling *M. chitwoodi* than metham sodium. Metham sodium is an excellent nematicide; however, in certain soils metham sodium applied in 1-in. (2.5 cm) of water is unable to control nematodes below 12 in. (30 cm). This has been overcome by applying metham sodium in a broadcast spray at 14 in. (36 cm) deep with sweep shanks attached with spray nozzles followed by a broadcast surface incorporated application of metham sodium or Mocap™ (31, 39).

In fields with high and deep populations of *M. chitwoodi*, soil fumigation alone may not be adequate. Of the nonfumigant nematicides, Mocap™ has been the most effective in suppressing root-knot nematodes on potatoes. Laboratory and greenhouse studies have shown the excellent nematicidal properties of Mocap™ in controlling *M. chitwoodi* and *M. hapla* (18). However, because Mocap™ does not move readily with water its effectiveness in the field is limited to the depth of mechanical incorporation. Mocap™ is most effective when applied as a broadcast and incorporated 4-6 in. (10-15 cm) by disking or rototilling just before planting (30).

Mocap™ is registered for control of *M. hapla* on potatoes, but only for suppression of *M. chitwoodi*. The best treatments for controlling *M. chitwoodi* have been the combination of Telone II™ with Mocap™ or metham sodium. Mocap™ is applied as a broadcast-incorporated treatment just before planting (26). Excellent control of *M. chitwoodi* has been achieved with the combination of lower rates of Telone II™ and metham sodium (38, 39). Telone II™ is injected 18 in. (46 cm) deep followed by metham sodium in 0.5 in. (1.3 cm) of water instead of the normal 1 in. (2.5 cm) of water or applied as a broadcast spray and incorporated. Telone II™ provides control of the deeper placed nematodes, and metham sodium controls nematodes and certain diseases, such as early die, in the top foot. The combination of Telone II™ at 15 gal/a (140 l/ha) and Vapam HL™ at 30 gal/a (281 l/ha) is registered for use on potato.

Studies show that multiple in-season applications of Vydate™ in 0.5 (1.3) and 1.0 in. (2.5 cm) of water through a sprinkler simulator can effectively control low populations of *M. chitwoodi*. In 1998 and 1999 applications with 0.5 to 1.0 in. of water gave excellent control. However, in 2000 Vydate™ applied in 0.5 in. of water did not provide adequate control. The main difference from the previous years was the initial *M. chitwoodi* soil population density, which was higher in 2000, averaging 454 per 250 cm^3 of soil compared to 33 in 1998 and five in 1999. Research is needed to determine the effect of initial *M. chitwoodi* population levels on the efficacy of Vydate™.

In field trials at Washington State University at Prosser, WA, fosthiazate, a nonfumigant experimental nematicide similar to Mocap™, at rates of 4.5 (4.86) and 6.0 lb a.i./a (6.48 kg a.i./ha) has given excellent control of *M. chitwoodi* on Russet Burbank potato, comparable to Telone II™ at 20 gal/a (187 l/ha) (40). Currently EPA is reviewing fosthiazate for registration on potato for nematode control.

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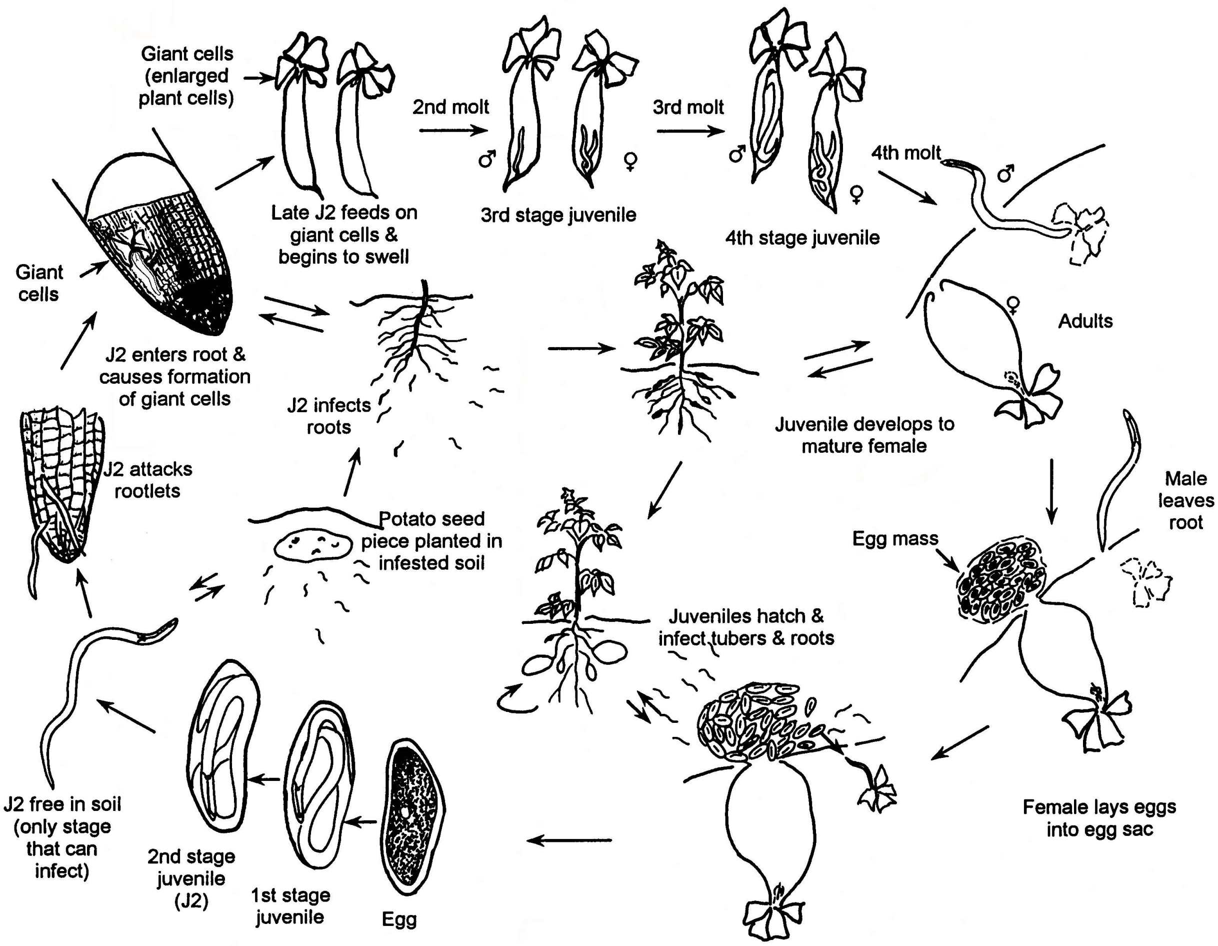

FIG. 1. Life and disease cycle of the Columbia (*Meloidogyne chitwoodi*) and northern (*M. hapla*) root-knot nematodes on potato.

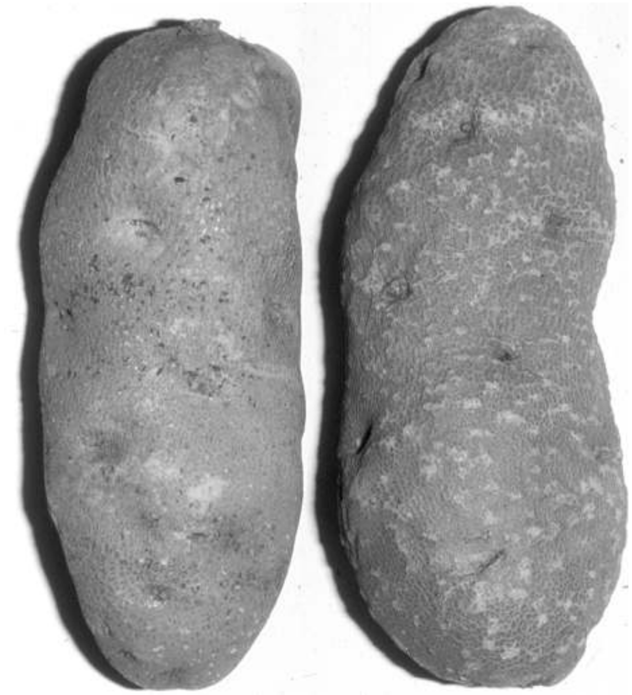

FIG. 2. Russet Burbank potato tubers infected with *Meloidogyne hapla* (left) and *M. chitwoodi* (right). Note pimple-like bumps caused by *M. chitwoodi*.

FIG. 3. Russet Burbank potato tuber infected with *Meloidogyne chitwoodi*. Each brown spot represents a nematode female and egg mass.

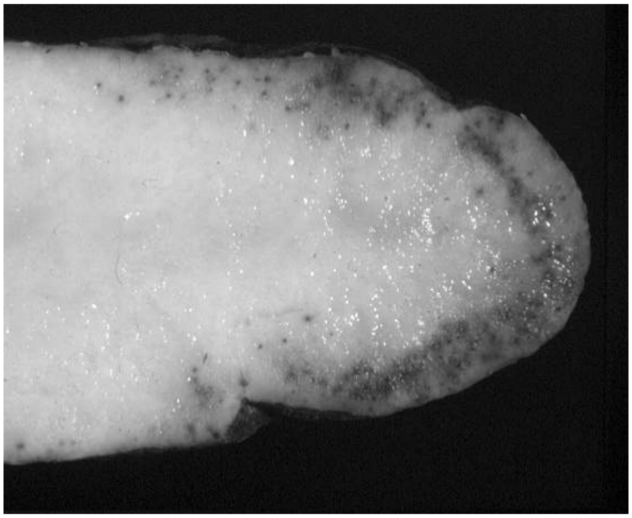

FIG. 4. Russet Burbank potato tuber infected with *Meloidogyne chitwoodi*. Infection occurs within the vascular ring about 0.25 in.(6 mm) from the surface.

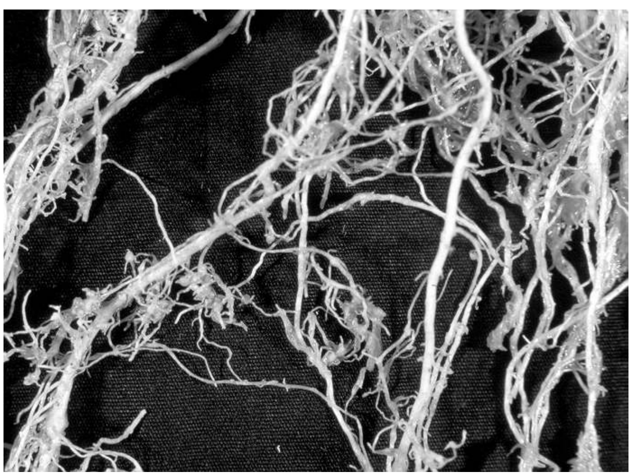

FIG. 5. Russet Burbank potato roots infected with *Meloidogyne hapla*. *M. hapla* produces small galls with lateral root proliferation.

FIG. 6. Russet Burbank potato roots infected with *Meloidogyne chitwoodi*. Note no galls and lateral root proliferation, and egg masses protruding from roots.