The Plant Parasitic Nematodes Important in Japan and the Related Researches*

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The land of Japan extends in a long range from 45°N to 24°N which includes the sub-frigid zone, the temperate zone, and the subtropical zone together. The land itself consists of 4 main islands and hundreds of small islands, all of which are surrounded by oceans. These islands are mostly mountaneous (arable land: 15%, woody land: 67%) and have a plenty of annual rainfall (800–3,000 mm, average: 1,700–1,800 mm).

These diversities in climatic and topographic conditions of Japan give the land an abundant vegetation which is rich in volume as well as in variety. We grow sugar-beets in Hokkaido, the northernmost island, and sugarcane in Okinawa, the southernmost island, in the same summer season. These diverse conditions and intensive cropping allow the distribution and prevalence of various kinds of soil-inhabiting nematodes throughout the country. Some of them are harmful to the crop plants and some others are rather beneficial to the soil.

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Important groups of the plant parasitic nematodes in Japan

More than a hundred of species of plant parasitic nematodes have been found and identified so far in Japan mostly on the crop plants. A part of them which are thought to be important in agriculture are listed in Table 1.

The Japanese administration of agriculture started a campaign in around 1955 to raise up the productivity of upland crops in addition to the paddy rice. In connection to this campaign, the government initiated a program so-called "The Pilot Control of Nematodes" in 1959 with a term of 5 years and it was extended for a few more years. This program involved a nation-wide survey of soil-inhabiting nematodes in nurseries, fields, orchards, and paddies. The survey work was conducted mostly by the prefectural agencies who employed and trained specialists for the program. These specialists were able to continue and expand further work on nematode control in each prefecture after the program was terminated.

The nematode survey revealed the real condition of nematode distribution and its density all through the country. Soil treatment with D-D, EDB, or DBCP partly subsidized by the government further showed the damage caused by the nematodes and the economic importance of the nematodes in the crop production in Japan.

1) *The root-knot nematodes, Meloidogyne spp.*

Six to seven species have been recognized

Table 1. Nematodes selected for their importance in Japan

No.	Nematode species	Crops being infected or damaged
1.	*Ditylenchus destructor*	Iris
2.	*Ditylenchus dipsaci*	Narcissus, Lily, Tulip, Hyacinth
3.	*Paratrophurus* sp.	Sugarcane
4.	*Tylenchorhynchus claytoni*	Rhododendron, Cryptomeria, Pine, Japanese cypress
5.	*Globodera rostochiensis**	Irish potato
6.	*Heterodera avenae*	Wheat, Barley
7.	*Heterodera elachista*	Rice (upland)
8.	*Heterodera glycines***	Soybean, Azuki-bean, Kidney-bean
9.	*Heterodera humuli*	Hop
10.	*Heterodera trifolii*	White clover
11.	*Meloidodera* sp.	Vine
12.	*Meloidogyne arenaria*	Peanut, Eggplant, Tomato, Gladiolus, Konjak
13.	*Meloidogyne camelliae*	Camellia, Sasanqua
14.	*Meloidogyne hapla***	Sugar-beet, Peanut, Azuki-bean, Irish potato, Pea, Tomato, Eggplant, Green pepper, Tobacco, Carrot, Lettuce, Red clover, Alfalfa
15.	*Meloidogyne incognita***	Sweet-potato, Carrot, Great burdock, Cucumber, Japanese radish, Tomato, Eggplant, Green pepper, Tobacco, Irish potato, Okra, Lettuce, Pea, Chinese cabbage, Sugarcane, Corn, Konjak, Clovers, Peach, Mulberry
16.	*Meloidogyne javanica**	Tobacco, Tomato, Eggplant, Soybean, Konjak
17.	*Meloidogyne mali*	Apple, Mulberry
18.	*Helicotylenchus dihystera*	Sugarcane
19.	*Helicotylenchus erythrinae*	Tea
20.	*Hirschmanniella imamuri*	Rice(paddy), Rush
21.	*Hirschmanniella oryzae*	Rice(paddy), Rush
22.	*Pratylenchus coffeae***	Taro, Sweet-potato, Irish potato, Tobacco, Soybean, Konjak
23.	*Pratylenchus convallariae*	Lily of the valley
24.	*Pratylenchus crenatus*	Great burdock
25.	*Pratylenchus fallax*	Chrysanthemum, Carrot, Great burdock
26.	*Pratylenchus loosi*	Tea, Citrus, Pear
27.	*Pratylenchus neglectus*	Eggplant, Soybean, Azuki-bean
28.	*Pratylenchus penetrans***	Strawberry, Japanese radish, Carrot, Great burdock, Soybean, Rape, Lettuce, Ginseng, Lily, Mint, Apple, Gentian, Butterbur, Italian ryegrass, Tree seedling
29.	*Pratylenchus vulnus**	Strawberry, Lily, Japanese radish, Peach
30.	*Pratylenchus zeae*	Corn, Grasses
31.	*Rotylenchulus reniformis*	Sweet-potato, Great burdock
32.	*Tylenchulus semipenetrans*	Citrus, Persimmon
33.	*Criconemoides* spp.	Peach
34.	*Crossonema civelle*	Citrus
35.	*Hemicriconemoides kanayaensis*	Tea
36.	*Paratylenchus curvitatus*	Mint, Tea, Radino clover
37.	*Nothotylenchus acris*	Strawberry
38.	*Aphelenchus avenae*	Sweet-potato
39.	*Aphelenchoides besseyi**	Rice, Strawberry
40.	*Aphelenchoides fragariae**	Strawberry, Lily, Begonia
41.	*Aphelenchoides ritzemabosi*	Chrysanthemum, Strawberry
42.	*Bursaphelenchus xylophilus***	Pine
43.	*Longidorus martini*	Mulberry
44.	*Xiphinema americanum*	Narcissus, Citrus, Vine
45.	*Xiphinema bakeri*	Mulberry
46.	*Xiphinema insigne*	Lily, Mulberry
47.	*Paratrichodorus minor*	Aster, Tobacco
48.	*Paratrichodorus porosus*	Chinese yam

* more important, ** most important

in *Meloidogyne*. Among them, the southern root-knot nematode, *M. incognita*, and the northern root-knot nematode, *M. hapla*, are the most important and wide-spread ones followed by the Javanese root-knot nematode, *M. javanica*.

M. incognita is distributed widely in the central, western, and southern parts of Japan. It attacks quite a large number of crop plants because of its wide host range. Of them sweet-potato, carrot, cucumber, and tomato are typically suffering severe injury by the nematode. Black cracks having a lozenge shape are induced on the surface of the tuberous roots of sweet-potato by the infection of this nematode. Since many of these vegetable crops are grown repeatedly in a given field or in the vinyl- or glass-houses, the nematode density increases readily. Although the racial status of *M. incognita* occurring in Japan is not clear enough, it is likely that the race 2 is predominant so far as the data indicate.

M. hapla is distributed in the northern part of the country and in the high land of mountainous areas even in the southern part. This species has a wide range of host plants too, but it does not go to graminaceous crops such as wheat, barley, corn, and rice. The damage is often seen in carrot, sugar-beets, tomato, lettuce, peanut, and others.

M. javanica causes damage to tobacco, tomato, and others in warmer areas of the country and in the vinyl- and glass-houses. *M. arenaria* is found only in a limited area and the damage has not been investigated in detail yet. *M. mali* was described in Japan by Itoh, Ohshima, and Ichinohe in 1969. This nematode primarily parasitizes on the apple roots in Hokkaido and Nagano Prefecture. It causes gall formation of the roots and growth retardation of the shoots, eventually yield reduction. This nematode also attacks mulberry trees. The ecological as well as morphological studies have been in progress.

2) *The cyst nematodes, Heterodera spp. and Globodera sp.*

The cyst nematodes have rather specific importance in general, primarily because of their narrow host ranges. Since they form the egg-containing cysts which protect the eggs for a long while under unfavorable conditions without the host plants, the control of them by either crop rotation or soil fumigation is rather difficult.

The soybean cyst nematode, *Heterodera glycines*, was described by Ichinohe in 1952 and is the most important species of the group in Japan. Although it attacks soybean, azuki-bean, and kidney-bean, the damage is extreme in the former two. This nematode has long been recognized as one of the limiting factors for the soybean production particularly in Hokkaido. The growers often encounter severe damage when they grow those varieties which are susceptible to the nematode especially in the case of frequent cropping for soybeans. The soybean cyst nematode is known to have several races. Four races were designated first in USA in 1970 and the 5th race was reported by Inagaki in Japan in 1979. At present, race 1, 3, and 5 have been found in Japan with race 3 as dominant one and it is reported that USA has all of these 5 races. Breeding of resistant varieties has been in progress and has already released some successful ones. The hatching factors of the nematode are still being investigated.

The potato cyst nematode, *Globodera rostochiensis*, was found in Hokkaido in 1972 for the first time in Japan. There is a report which indicates the possible introduction of the nematode into Japan from Peru by means of Peruvian guano. More than 2,800 ha of the field has been found to be infested with this nematode in 1981 and it is said that the infested area has still been increasing. To our fortune, however, the infested area is limited to only two locations of Hokkaido at present and no other place has been reported as being infested in Japan.

This nematode attacks Irish potato, tomato, and eggplant. The latter two are negligible in terms of the damage. Irish potato is one of the most important crops especially for Hokkaido agriculture. They used to plant more than 60% of their fields to potato every year for a long while. This intensive cropping with potato interfered with the normal system of crop rotation and eventually increased the nematode population in the soil. Then, the acreage of potato was reduced to lower than 40% in those particular areas to allow the introduction of another kinds of crops such as corn, beans, and asparagus in addition to sugar-beets and wheat, all of which are non-host for this nematode.

It has been considered that the pathotype of the nematode occurring in Hokkaido is Ro1 of *G. rostochiensis* according to the information available at present. Appearance of the other pathotypes due to wide use of resistant varieties must be investigated very carefully.

3) *The root-lesion nematodes, Pratylenchus spp.*

Twelve species have been identified and 4 unidentified species are reported in this group of nematode in Japan. The host range is generally wide for these root-lesion nematodes and they remain in the soil mostly together with the infected or decaying root tissues. Therefore arrangement of crop rotation to control them is not easy and no resistant variety is available except a few cases.

P. coffeae, the southern root-lesion nematode (Japanese common name), is one of the two most important species of the root-lesion nematodes and is predominant in the central, western, and southern parts of Japan which have warmer climate. This nematode is particularly pathogenic to taro in case of repeated cropping in a given field (Table 2).

P. coffeae also attacks sweet-potato and causes damage in the southern part of Kyūshū. The skin of the tuberous roots becomes coarse and scabs are formed, so that the marketability is badly reduced.

The second most important species of this nematode group is *P. penetrans*, the northern root-lesion nematode (Japanese common name). This nematode is distributed generally in the central and northern parts of the country, while it is found very often in the high elevation areas of the western and southern parts. *P. penetrans* is said to be parasitic on more than 350 species of plants.

Table 2. Yield reduction in taro due to *P. coffeae* (Miyaji & Shirasawa, 1979)

Cropping conditions	*P. coffeae* (50 g of soil, Aug.)	Taro yield (ratio)
First cropping (control)	7	100
After 2-year continuous cropping	64	65
After 3-year continuous cropping	236	33
After 4-year continuous cropping	292	23
After 2-year crop rotation	0	—
After 3-year crop rotation	4	102

Various and wide range of crop plants are reported as being attacked by this nematode. The nematode causes root decay of strawberry. The strawberry plants are dead before fruiting when the nematode population is very high in the soil of the vinyl-houses as well as of the ordinary upland fields. In case of Japanese radish the nematode induces the water-blister-like symptom on the skin of the roots. This symptom is produced even by a small number of the nematode. Although the symptom itself is rather faint, the products lose the marketability. The nematode also attacks another root crops such as great burdock and ginseng in addition to leaf vegetables like lettuce and flower plants like lily and gentian.

4) *The foliar and stem nematodes, Aphelenchoides spp. and Ditylenchus spp.*

The white-tip nematode, *Aphelenchoides besseyi*, once disappeared from the growers' fields, but the disease has come again to be found often in the paddy rice in these years. The rice plants infected with this nematodes show the white-tip symptom on the tip end of the flag leaves typically. This disease is called in Japan as "Hotaru Imochi" ("Hotaru" is firefly and "Imochi" is rice blast) because the white to yellow leaf tips are just like fireflies or lighting bugs when the leaves are trembling in the twilight. When the panicles are parasitized by the nematodes, the kernels are injured. Many of the infected kernels show the wedge-shaped dark spots. These kernels are called "Kokuten-mai", which literally means "Black-spotted rice". In Japan, if the rice contains these blackened grains at a level higher than 0.7%, the grade of the rice is reduced so much that the value in price is correspondingly reduced very much (0.0–0.1%: top grade, 0.1–0.3%: second grade, 0.3–0.7%: third grade, 0.7%–: the grade below). These infected hulls become inoculum for the next year if sown. The reason for the current increase of this nematode is not clear yet, but it is considered that the use of shallow seedling cases for growing rice seedlings for machinery transplanting may furnish favorable conditions to the nematode infection. Negligence of the seed treatment might be another reason.

A. fragariae is often found in the strawberry plants. It causes poor growth and shrinking of the plants by parasitizing on the bud tissues ectoparasitically. The plants are dead in severe cases in hot summer or under dry condition. *Nothotylenchus acris* also induces similar disease in strawberry plants. These nematodes are transmitted through seedlings in many cases.

A. ritzemabosi mostly attacks the leaves of chrysanthemum. The nematodes overwinter in the tiny plants surviving on the surface soil or in the infected and fallen old leaves. The nematodes move to new young plants in spring and as the plants grow they migrate upward when the stems are wet with dew or rain. The infected leaves show brown necrosis enclosed by the veins. Severely parasitized leaves are dead and fallen down.

Injury by *Ditylenchus dipsaci* is found only sporadically in narcisus. No noticeable damage is reported so far in alfalfa and onion in Japan.

5) The other kinds of important nematodes

Bursaphelenchus xylophilus, the pine wood nematode, is known to be the pathogen of die-back disease of Japanese pine trees which is serious problem in the temperate zone of Japan. A symbiotic relation was discovered between the nematode and a kind of insects, Japanese pine sawyer, *Monochamus alternatus*. The nematodes are transmitted by this insect.

Two species of rice nematodes, *Hirschmanniella imamuri* and *H. oryzae*, are both parasitic on rice plants. A large number of them are often found in the roots of rice plants grown in paddy, but the actual damage in plant growth and yield has not been well demonstrated yet. The nematodes also attack rush plants in paddy fields and some growth reduction has been reported under a high nematode density.

Paratrichodorus porosus has been reported as the causal agent of root decay of Chinese yam. Infected plants show malformation and browning of the tuberous roots, which in turn cause reduction of the yield and marketability.

6) The nematodes undiscovered in Japan

Some of the world-important species of nematodes which have not been found in Japan at present are listed in Table 3.

Table 3. World-important nematodes of which the distribution has not been recognized yet so far in Japan in 1983

Ditylenchus angustus	Rice stem nematode
Globodera pallida	Potato pale cyst nematode
Heterodera schachtii	Sugar-beet cyst nematode
Radopholus similis	Burrowing nematode (citrus)
Xiphinema index	Dagger nematode (grapevine)

Although Japan has a strict system of plant quarantine, invasion of these nematodes must be prevented through the routine carefulness too. At the same time, a systematic and long-run survey program is needed to check the appearance of new pathotypes or races in the commercial fields.

Nematode-induced complex diseases in Japan

It has been generally considered that, in the case of crop diseases of which the host-

Table 4. Plant viruses transmitted by nematodes in Japan

Viruses	Nematode species	Crop plants
Tobaco rattle v.	*Paratrichodorus minor*	Aster
Tobacco ringspot v.	*Xiphinema americanum*	Narcissus
Arabis mosaic v.	*Xiphinema bakeri*	Narcissus
Mulberry ringspot v.	*Longidorus martini*	Mulberry

Table 5. Examples of disease complexes involving nematodes, fungi, and bacteria which have been found or studied in Japan

Nematodes	Fungi or Bacteria	Crops	Diseases
Meloidogyne incognita	*Fusarium oxysporum* f. *cucumerinum*	Cucumber	Fusarium wilt
Meloidogyne incognita	*Pythium aphanidermatum*, etc.	Cucumber	Damping-off
Meloidogyne incognita	*Fusarium oxysporum* f. sp. *lycopersici*, etc.	Tomato	Fusarium wilt
Meloidogyne incognita	*Fusarium* sp.	Tobacco	Fusarium wilt
Meloidogyne incognita	*Pellicularia filamentosa*	Tobacco	Damping-off
Meloidogyne incognita	*Phytophthora parasitica* var. *nicotianae*	Tobacco	Black shank
Meloidogyne incognita, etc.	*Fusarium solani* f. sp. *radicicola*	Irish potato	Storage tuber rot*
Meloidogyne incognita	*Pseudomonas solanacearum*	Tomato	Bacterial wilt
Meloidogyne incognita	*Xanthomonas campestris*	Japanese radish	Black rot
Meloidogyne spp.	*Erwinia carotovora*	Konjak	Soft rot*
Meloidogyne hapla	*Pellicularia filamentosa*	Sugar-beet	Damping-off
Pratylenchus penetrans	*Fusarium oxysporum* f. sp. *lycopersici*	Tomato	Fusarium wilt
Pratylenchus penetrans	*Fusarium* sp., etc.	Great burdock	Black rot*
Pratylenchus penetrans	*Pythium* sp.	Strawberry	Root-rot*
Pratylenchus penetrans	*Corynespora cassiicola*	Soybean	Root-rot*
Pratylenchus penetrans	*Rhizoctonia solani*	Flax	Damping-off*
Pratylenchus penetrans & *Paratylenchus curvitatus*	*Phoma strasseri*	Mint	Black rot*

* name after the symptom.

parasite interaction involving infection takes place within the soil, more diseases are caused by a group of pathogens or by one main pathogen and one or more pathogens or undifferentiated pathogens living together than those which are caused only by a single pathogenic agent. The plant parasitic nematodes inhabiting widely in the soil play important roles in the disease complexes.

Although the research and experimental work relating to this aspect are comparatively behind in Japan, some of the instances reported and investigated so far are as follows.

1) Virus transmission

Some Dorylaimoid nematodes are able to transmit plant viruses. About 33 species of 5 genera of nematodes are currently known as the vectors of plant viruses in the world. Only 4 examples have been reported up to date in Japan (Table 4).

Since those nematodes which may concern with the virus diseases of crop plants are often found in various places of the country, further investigation is needed.

2) Interaction with fungal and bacterial pathogens

Many cases in which nematodes and fungi or bacteria are involved together in the occurrence and development of crop diseases have already been reported in the world. A little more than 20 examples have been reported in Japan and some of them are listed in Table 5.

These nematode-induced complex diseases

are often noticed firstly by finding frequent association of particular species of nematodes and diseases and secondly by treating the soil with nematicides. While many other cases were first demonstrated by laboratory experiments. Therefore, it is necessary to pay more attention to the indication or occurrence of nematode association in crop diseases in the fields. The investigation and research works on the complex diseases have mostly been spent for searching instances and only a few of the works dealt with the mechanism of the complexes. Physiological approach is needed in addition to histo-pathological studies. In some cases, root-knot-Fusarium complex in tomato for example, the nematode infection breaks or weakens the host resistance to fungal or bacterial pathogens. So, to introduce resistance against nematodes into the crop varieties together with that against fungal or bacterial pathogens is basically preferable.

Control of nematodes

1) Crop rotation and chemicals

Crop rotation is basically important to suppress the nematode population in the soil and is effective in many cases. But many species of nematodes cannot be controlled by the crop rotation alone because of their wide host ranges. So, many vegetable growers treat the soil with nematicidal fumigants such as D-D, EDB, and chloropicrin. They, at the same time, aim to control soil-borne fungal or bacterial diseases together. However, the prices of these soil fumigants are rather high, so the use of these chemicals is limited to only those farms where they can grow high value crops. For example, 30 *l* of D-D, an average level to treat 10 a of field, cost them about $25 in Japan.

2) Soil solarization

In some parts of Japan where enough solar radiation intensity is available, they seal the soil surface with vinyl sheet for 1–2 months during summer season in the closed vinyl- or glass-houses, so that they can get good control of the nematodes and the soil-borne dis-

control in profitable conditions.

3) Resistant varieties

Resistant varieties are available for several kinds of crops against some nematodes in Japan (Table 6).

Table 6. Examples of Japanese crop varieties resistant to some important nematodes

Tomato—*M. incognita*:
Kyōryoku gokō, Kyōryoku tōkō, Kyōryoku nikkō 1, Kyōryoku nikkō 2, Shin fukuju 2, Aoiwase, etc.
Sweet-potato—*M. incognita*:
Taihaku, Nōrin 2, Nōrin 3, Nōrin 9, Hayato-imo, Benisengan, Beniwase, Kantō 84, etc.
Sweet-potato—*P. coffeae*:
Gifu 1, Koganesengan, Satsuma-aka, Tamayutaka, Nōrin 1, Nōrin 9, Minamiyutaka, etc.
Soybean—*H. glycines*:
Suzuhime, Tōzan 93

eases. The principle of this method is to raise the soil temperature up to 50°C or higher by the solar heating. Shallow flooding and organic amendment have additive effect to the

Development of resistant varieties has long been conducted in Japan at either governmental stations or private companies especially for sweet-potato and tomato against *M. incognita*, soybean against *H. glycines*, and Irish potato against *G. rostochiensis*. Since the growing places are distributed in the long range from the north to the south, various types of varieties are necessary for each crop to suit various climatic as well as day-length conditions. So that the breeding programs have ever been carried out at different places throughout the country.

Advantages of breeding resistant varieties are (i) scientifically approachable, (ii) pollutionless, and (iii) relatively less expensive for the farmers. While the weak points are (i) it takes time, (ii) combination of the resistance with high yield and high quality is rather difficult, and (iii) appearance of resistance-breaking races of the pathogens.

If the nematode population level is not so high, the tolerance would be enough to keep an average yield. But, especially in the case of the cyst nematodes, the nematodes increase in number on the tolerant roots and remain in the soil, so that the nematode population is raised up to cause damage to the succeeding crops. Therefore, it is preferable to develop those varieties which at least do not increase the nematode population in the soil or preferably which decrease it due to the trapping reaction.

4) Trap plants

There are some plants which are called "trap plants". Some of maligold (*Tagetes* spp.) are practically used to control nematodes. Three-month cultivation of French maligold in summer is effective to control *Pratylenchus penetrans* of autumnal Japanese radish. Peanut plants may be considered as a trap plant of *Meloidogyne incognita.* Highly resistant crop varieties can also be used as trap plants since the nematodes penetrate into the roots of even resistant varieties as same as susceptible ones but they die there without reproduction. Eventually the nematode population is remarkably decreased after these plants. Advantage of the trap plant principle is not to destroy the natural fauna and flora of soil-inhabiting micro- or minute-organisms if compared with chemical treatment.

5) Natural enemy

Practical use of natural enemy is scarce, though it must be certainly working in the natural soils. Researches on the nematode-attacking fungi and bacteria have been done, but no practical application method has been arranged yet. Information from these researches, however, is available as the knowledge to maintain the soils in good condition.

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