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Pest risk analysis of *Meloidogyne chitwoodi* for Finland

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There is a an ever-present risk of *Meloidogyne chitwoodi* extending its range to Finland because of the active import of plant material to the country. If the nematode becomes established in Finland, two factors may limit its pest potential: low temperature accumulation during the growing season and low winter temperatures. On average, the effective temperature accumulation may enable development of 1.5 generations yearly. In warm years, development of two generations is possible in the southern parts of the country. Hatching of the second generation, and infection of potato tubers, is possible in most potato-growing areas. Low soil temperatures during the winter reduce population densities but may not prevent the nematode from becoming established in Finland. If *M. chitwoodi* were to extend its range to Finland, it could become a pest of potatoes, especially seed potatoes. For other crops, such as cereals and vegetables, population densities of *M. chitwoodi* would probably remain at such low levels that yield losses would not occur under current climatic conditions. Scientific information concerning *M. chitwoodi* populations in Europe is insufficient for a fully reliable pest risk analysis. This will not be possible until the effect of abiotic and biotic factors on the nematode are well known. A data base of the distribution of the nematode, based on a geographical information system, is urgently needed for the whole of Europe. Soil temperature maps interpolated from direct measurements, or derived from air temperatures, should also be constructed because soil temperature accumulation is one of the most important factors which may limit the distribution of this polyphagous nematode.

Introduction

The Columbia root-knot nematode, *Meloidogyne chitwoodi*, is a newly discovered nematode pest in Europe (Anon., 1992). It has a wide host range and is well adapted to low temperatures (O'Bannon *et al.*, 1982; O'Bannon & Santo, 1984). In the Pacific Northwest of the USA, the nematode is a serious pest of potato (Nyczepir *et al.*, 1982; Pinkerton & McIntyre, 1987). In Europe, the nematode was found quite recently and has so far been recorded only in The Netherlands. A pest risk assessment made by Baker & Dickens (1993) confirmed that *M. chitwoodi* could reproduce in Europe. The aim of the present study was to make a pest risk analysis (PRA) of *M. chitwoodi* in Finland. The analysis follows the PRA guidelines of EPPO (OEPP/EPPO, 1993) and is based on Finnish weather data and on the use of a geographical information system (GIS).

The organism

Name and taxonomic position

Meloidogyne chitwoodi Golden *et al.* (1980) (Meloidogyninae, Meloidogynidae, Heteroidea, Tylenchina) was first recorded as a new species in 1978 attacking potatoes and many other crops (Santo *et al.*, 1980). Previously, the root-knot nematode problems on potatoes in the USA were considered to be caused by *M. hapla*. Two races of *M. chitwoodi* have so far been discovered, known as races 1 and 2 (Mojtahedi *et al.*, 1988) but a third may also exist

(Mojtahedi, pers. comm.). The breeding of new resistant cultivars may be promoting the continuous selection of new races and identification of races may become complicated in the long run. Populations with different virulence on potato have also been found (Griffin & Thomason, 1988).

Relationship with known quarantine pests

The two root-knot nematode species, *M. chitwoodi* and *M. hapla*, have often been found to occur as mixed populations, both in the USA and in The Netherlands (Nyczepir *et al.*, 1982; OEPP/EPPO, 1991). The existence of mixed populations has caused some difficulties in distinguishing the presence of *M. chitwoodi* when infected plants and tubers have been found. In a survey in the US Pacific Northwest, *M. chitwoodi* occurred alone in 83% of samples and *M. hapla* in 11%, with 6% of all samples containing both species (Nyczepir *et al.*, 1982).

The first generation of both root-knot nematodes attacks the root system of its host plant. Thereafter, *M. hapla* causes galls on roots while *M. chitwoodi* mainly infects tubers. Damage due to *M. chitwoodi* is thus more severe on potatoes and the damage threshold is lower than that for *M. hapla*. Damage caused by *M. hapla* is most severe on host plants like carrot which has the main root as its yield component (Santo *et al.*, 1988). In general, the host range of *M. chitwoodi* is wider than that of *M. hapla* (O'Bannon *et al.*, 1982).

The two closely related species, *M. chitwoodi* and *M. hapla*, also differ with respect to abiotic factors. *M. chitwoodi* is better adapted to low soil temperatures than *M. hapla* (Inserra *et al.*, 1983). *M. chitwoodi* also migrates more actively in soil, thus improving its capability to survive and to find the root system of a host plant (Pinkerton *et al.*, 1987).

In the PRA area, the climate is not warm enough for *M. hapla* to survive out of doors for a long time (Tiilikkala *et al.*, 1988). Differences in the base temperatures for development between the two species may offer more favourable opportunities for *M. chitwoodi* to reproduce, survive and cause symptoms.

Methods of identification for inspection purposes

It is important to be able to distinguish between *M. chitwoodi* and *M. hapla* because in many cases, in cool climate field conditions, these two species have been detected as mixed populations. The perennial patterns and characteristics of L2 juvenile tails are the easiest and most reliable criteria used to differentiate between *M. chitwoodi* and *M. hapla*. Other characteristics, such as the total length of L2 and position of the excretory pore in females, are essentially similar. These morphometric criteria are useful in separating the two species from many other *Meloidogyne* spp. (Nyczepir *et al.*, 1982).

The differential host test is a useful tool in determining which species is present in a sample. However, since races of *Meloidogyne* spp. are known to occur, the host test should not be the sole basis for species identification. A list of test plants has been published by Nyczepir *et al.* (1982). More recently, to separate *M. hapla* and the *M. chitwoodi* races, Mojtahedi *et al.* (1988) proposed adding carrot cv. Red-cored Chantenay and lucerne cv. Thor to the differential host list reported by Nyczepir *et al.* (1982).

The basic difference between the two races of *M. chitwoodi* is observed in their differential reproduction on lucerne cv. Thor and carrot cv. Red-cored Chantenay. *M. chitwoodi* race 2 reproduces on lucerne but not on carrot. Conversely, lucerne is a poor host and carrots are suitable for *M. chitwoodi* race 1 (Mojtahedi *et al.*, 1988).

Identification of *Meloidogyne* spp. may also be based on the use of isoelectric focussing (Lawson *et al.*, 1984) or enzyme phenotypes (Esbenshade & Triantaphyllou, 1985; Karssen, 1995). Modern molecular methods (e.g. DNA fingerprinting) which have proved successful in distinguishing other nematodes at below-species level are under development for the identification and separation of *M. chitwoodi* populations (Zijlstra *et al.*, 1995).

Methods of detection

Soil sampling and extraction of L2 juveniles is a normal procedure for detecting root-knot nematodes. General laboratory methods which have been developed for extraction of free-living nematodes can be used. In addition, inspection of plant material (roots, bulbs and tubers) is possible. A special technique for detection of females and J2 juveniles in potato-tuber tissue has been developed in Prof. Santo's laboratory at Prosser (Irrigated Agriculture Research and Extension Center, Washington State University, US). The technique is modified from a method published by Byrd *et al.* (1983). In practice, however, it is difficult to detect root-knot nematode infection of seed tubers if population densities are low. Although the external symptoms caused by *M. chitwoodi* may be evident, it is difficult to detect internal tuber damage. Just after harvesting, females of root-knot nematodes are often immature and brown spots have not yet developed. Depending on the storage temperature and status of the nematodes, symptoms on tubers may then develop during storage (Jatala *et al.*, 1982).

Biological characteristics

Life cycle

M. chitwoodi can overwinter as eggs and as juveniles. One moult occurs within the egg and the second-stage juveniles hatch out as soil temperature rises in the spring. After invasion, J2 juveniles penetrate roots of the host plant or tuber tissue, start feeding and commence development. J2 juveniles cannot penetrate potato tubers unless they are wounded or lenticels are fully developed (Pinkerton *et al.*, 1991). The larvae lose their vermiform appearance, moult three times, and eventually assume the swollen shape of the female. New eggs are produced in a gelatinous matrix by the female embedded in the host root or tuber tissue. One female is capable of producing 200–1000 eggs (Santo, 1994).

The number of generations of *M. chitwoodi* per year is dependent upon the number of degree days (soil temperature heat units) which accumulate during a growing season (the period during which air temperature exceeds a given base temperature). Both species, *M. chitwoodi* and *M. hapla,* require about 600–800 degree days from the time of planting to complete the first generation, and 500–600 for the subsequent generations. However, the minimum or base temperature for activity differs significantly between the two species; in the USA, the base temperature is 5°C for *M. chitwoodi* and 10°C for *M. hapla* (Inserra *et al.*, 1983). Second- and third-generation eggs of *M. chitwoodi* hatch after 950–1100 DD5 (accumulated degree days above 5°C) and 1500–1600 DD5, respectively. Thus, depending on soil temperature during the growing season and the length of the growing season, *M. chitwoodi* may complete 3–5 generations per year, and *M. hapla* 1–3, in the Pacific Northwest of USA (Pinkerton *et al.*, 1991). An extra generation, especially late in the season, will result in a tremendous increase in nematode population densities.

On potato, the first generation of *M. chitwoodi* is completed in the roots and the subsequent generations in roots or within tubers (Santo, 1994). On a good host like potato, eggs may be produced more rapidly than on poor hosts (Pinkerton *et al.*, 1991). *M. chitwoodi* may have parthenogenetic multiplication like many other *Meloidogyne* species.

Dissemination and dispersal

The nematode can be spread from infested to uninfested areas by means of soil carried on boots, hooves of animals and farm equipment, by infected plant material and in reused irrigation water. Natural movement of the nematode is very limited. Free-living larvae can move at most 1–2 m. The nematode does not have any specific vectors, but birds and other animals which can carry soil particles may transmit infested soil. International trade of bulbs, potato seed tubers and other kinds of seedlings may cause the highest risk of long-distance dispersal of the nematode.

Survival under adverse conditions

Mojtahedi *et al.* (1991a) have reported that *M. chitwoodi* is able to survive subfreezing temperatures like *M. hapla*. In Canada, *M. hapla* is able to tolerate freezing temperatures for 3 months (Vrain, 1978; Johnson & Potter, 1980). In the PRA area, it has been proved that *M. hapla* is able to overwinter, but the shortage of heat units during the growing season is the critical factor limiting reproduction and survival of the nematode (Tiilikkala *et al.*, 1988). Seasonal migration studies indicate that a portion of an *M. chitwoodi* population migrates downwards in the soil during the winter and summer. This behaviour may help the nematode to survive unfavourable environmental conditions (Mojtahedi *et al.*, 1991a). *M. chitwoodi* is more mobile than *M. hapla* (Pinkerton *et al.*, 1987).

Because there is very little scientific information about *M. chitwoodi* in Europe, the overwintering of European *M. chitwoodi* populations needs to be studied before the effect of winter temperatures in the PRA area can be reliably evaluated. However, because soil temperatures in the PRA area are very similar to those in parts of Canada and the northern USA, it can be surmised that overwintering of *M. chitwoodi* is likely to be possible. For example, in the potato-growing area of North Carolina (US), winter soil temperatures are too high to use freeze-kill of *M. chitwoodi* as a management tool (Viglierchio, 1987). In central Europe, the winter is similarly unlikely to be a limiting factor for population development of *M. chitwoodi.*

Adaptability

M. chitwoodi is an exceptionally polyphagous pest and is able to develop new races when kept under selection pressure from a new kind of resistance (Mojtahedi, pers. comm.). Preliminary studies in Europe have already proved that new kinds of races or populations can be found (Janssen *et al.*, 1995).

Geographical distribution of the pest

Present occurrence in Finland

M. chitwoodi has never been found in the PRA area. Neither has any other *Meloidogyne* species occurred in open fields. In glasshouses, *M. hapla* is a pest of rose production (Tiilikkala *et al.*, 1988).

World distribution

M. chitwoodi has been found widely distributed throughout the western USA (Nyczepir *et al.*, 1982; Pinkerton & McIntyre, 1987; Griffin & Thomason, 1988). It has also been reported from Virginia, US (Eisenback *et al.*, 1986), from Argentina and The Netherlands (Esbenshade & Triantaphyllou, 1985) and from Mexico and South Africa (Eisenback & Triantaphyllou, 1991). In the USA, the northernmost discoveries of *M. chitwoodi* populations are from fields which are situated a few km south of the border line between Washington State (US) and British Columbia (CA) (Nyczepir *et al.*, 1982).

Information on the distribution of the nematode in Europe is scanty. The occurrence of *M. chitwoodi* has so far been reported only in the south-east region of The Netherlands (Brinkman & Van Riel, 1990). A well organized survey is urgently needed in Europe so that realistic control strategies can be planned.

Area of origin and history of any spread from the area of origin

M. chitwoodi was first recognized as a new species in 1978 (Santo *et al.*, 1980). The real origin of the species is unknown (Santo, pers. comm.). Two races of *M. chitwoodi* were discovered in 1984 (Santo & Pinkerton, 1985) and both races are widely distributed in the major potato-growing regions of the Pacific Northwest in USA.

Overlap of world distribution of the pest with that of major hosts

The overlap in the distribution of *M. chitwoodi* and its major hosts is very limited, because the nematode is a fairly new pest with a wide host range. Only in the Pacific Northwest of the USA is the nematode widely distributed (Santo, 1994).

Host plants of the pest

Host plants reported

O'Bannon *et al.* (1982) reported that *M. chitwoodi* reproduced on 53 out of 68 plant species tested. Both monocotyledonous and dicotyledonous plant species are good hosts, indicating that the host range can be very wide. Many important crops like cereals, potato, sugarbeet, oil mustard, rape, maize, turnip, lucerne, bean, peas, clover, tomato and carrot are hosts of *M. chitwoodi.* In The Netherlands, preliminary tests have demonstated that some ornamental plants are also hosts of *M. chitwoodi* (Brinkman & Van Riel, 1990). The nematode can reproduce on many weeds, too (O'Bannon *et al.*, 1982).

Host plants grown in Finland

In the PRA area, all the above-listed host plants except maize and oil mustard are widely grown. The most susceptible host is probably potato with the production of seed potatoes especially sensitive.

Nature of the host range

M. chitwoodi is an exceptionally polyphagous pest, able to develop new races when kept under selection pressure of a new kind of resistance (Mojtahedi, pers. comm.).

Potential of the pest for establishment in the PRA area

Ecoclimatic zones of the distribution of the pest comparable with those found outdoors in the PRA area

In the PRA area, the ecoclimatic zone which is appropriate for potato production may also be suitable for development of *M. chitwoodi.* According to the literature, multiplication of the nematode is possible in areas where the temperature accumulation (soil temperature) exceeds 500–600 DD5 (Pinkerton *et al.*, 1991). In fact, *M. chitwoodi* requires the same or a slightly lower temperature accumulation for one generation than the potato cyst nematode, *Globodera* *rostochiensis* (Tiilikkala, 1987). In Finland, the northernmost discovery of *G. rostochiensis* was made near the town of Rovaniemi in Lapland, located a few km north of the Arctic Circle.

Hatching of L2 juveniles of the second generation requires about 1000 DD5. This temperature sum can be used as a minimum criterion for areas where *M. chitwoodi* can infect potato tubers and be a pest of potato production.

In areas of the USA where *M. chitwoodi* is most damaging, specifically in the Columbia river district of Washington State, the growing-season temperature sum is reported to be about 2000 DD5 and the nematode has three generations. Approximately 2800 DD5 were accumulated in eastern Washington during the 1987 growing season, which resulted in at least four generations and great nematode damage (Pinkerton *et al.*, 1991). In cooler upland regions of southern Idaho and northern Colorado (US), *M. chitwoodi* is less damaging. In areas where the northernmost *M. chitwoodi* populations have been found (in northern Washington, close to the Canadian border), the bioclimatic conditions exhibit some similarities to those experienced in southern Finland.

In order to compare these more closely, an investigation has been made of air temperatures in both regions. Time series of monthly mean air temperatures for sites in North America were obtained from the Global Historical Climatology Network (CDIAC, 1994). The analysis was confined to the period 1961/1990, although longer-term records would be available from many sites to facilitate more detailed studies of temperature variability. The initial focus was on sites lying within or close to mapped nematode regions (Nyczepir *et al.*, 1982; Fig. 1). Nine stations were selected: Clearbrook and Bellingham (Washington, US) and Abbotsford (British Columbia, CA) lie in the northernmost nematode region (referred to hereafter as Region 1) while Blaine (Washington) and Vancouver (British Columbia) represent Pacific coastal locations close to this region. Wenatchee is located on the Columbia river, just north of another major nematode region (Region 2), Kennewick is downstream at the confluence of the Columbia, Snake and Yakima rivers in the centre of the region, Sunnyside is at the southwestern fringe of the region and Yakima is further to the west and at higher elevation (Fig. 1).

Each site has at least 24 years of monthly mean temperature data, and these were used to compute growing season effective temperature sums (ETS) for each year above a base temperature of 5°C. The procedure employed is an approximation of the more conventional method which employs daily mean temperatures. A sine curve interpolation technique (Brooks, 1943) is used to obtain daily mean temperatures from the monthly means. ETS is then computed for the growing season, which is defined as that period during which air temperatures lie above 5°C. Thus, anomalously high daily winter temperatures occurring outside the main growing season are excluded from the temperature summation (although these occasional departures tend anyway to be absent from the monthly values).

The means and standard deviations for all stations are given in Table 1. The ETS values for sites in Region 2 are considerably in excess of the 2000 DD5 reported for the Columbia river district. However, this is mountainous terrain, and local temperature conditions vary widely, especially with altitude. In contrast, Region 1 exhibits little spatial variation in ETS, with mean values around 1800-1900 DD5. On the other hand, the inter-annual variability of ETS, as shown in the standard deviations, is remarkably similar at all sites (Table 1).

The same procedure has also been used to compute ETS for a site in southern Finland, Jokioinen (Table 1). There is clearly a large difference in mean ETS between the coolest areas of Region 1 (about 1800 DD5) and southern Finland (1190 DD5).

This comparison can be evaluated in terms of nematode risk. Using the observations and experiments reported above, the following set of ETS thresholds have been defined for various developmental stages of nematode populations:

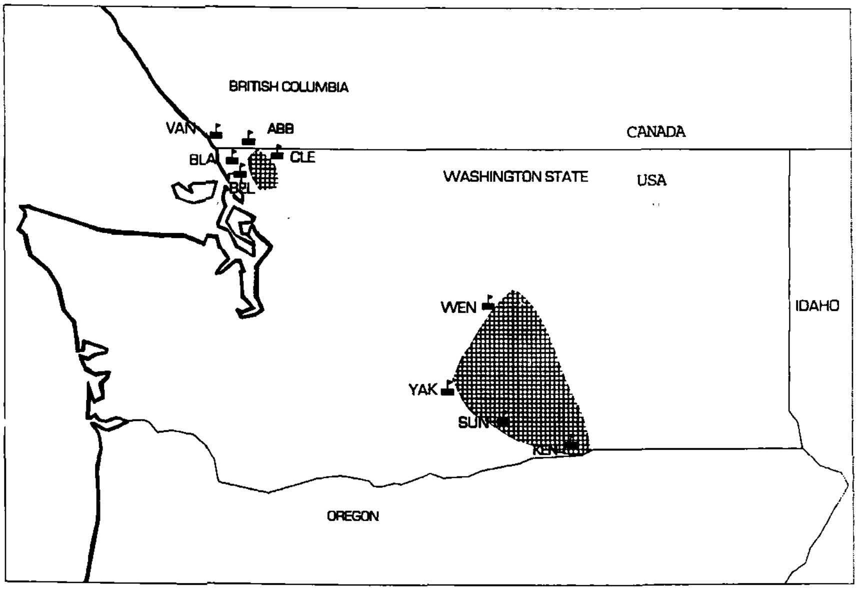

Fig. 1. Major regions where *Meloidogyne chitwoodi* is present in Washington State, US (shaded; Nyczepir *et al.*, 1982) and location of meteorological stations.
Principales régions où *M. chitwoodi* est présent dans l'Etat de Washington, Etats-Unis (foncé; Nyczepir *et al.*, 1982) et localisation des stations météorologiques.

600 DD5: 1st generation completed (G1 in Table 2)
1000 DD5: 2nd generation hatched (H2)
1350 DD5: 2nd generation completed (G2)
1500 DD5: 3rd generation hatched (H3)
2000 DD5: 3rd generation completed (G3)
2200 DD5: 4th generation hatched (H4)
2800 DD5: 4th generation completed (G4).

These values should be regarded merely as illustrative, however, as firm relationships between nematode distribution and temperature have not yet been established. Moreover, soil temperature rather than air temperature is likely to provide a more accurate measure of suitability for nematode survival (see below).

The percentage frequency with which these threshold values are exceeded has been computed for each site in Table 2 and is illustrated for selected sites in Fig. 2. The results indicate that there is potential for a third generation to hatch in all years in Region 1, with the possibility, in warm years such as 1987, for completion of the third generation. In Region 2, hatching of the fourth generation is feasible every year, with completion of the fourth generation possible at cooler sites and highly probable at the warmest locations. At Jokioinen, there is potential for a second generation to hatch in most years, and to complete in the occasional warm year (e.g. 1988).

Clearly, the conditions for *M. chitwoodi* in Finland are not as favourable as those recorded in Washington. However, in the one region of Europe where this nematode has been detected, in the south-east of The Netherlands, the mean ETS (computed from 30-year mean monthly air temperatures: 1951/1980) is about 1900 DD5, closely resembling values in Region 1.

To look further at the pest potential in Finland itself, ETS has been mapped across a regular 10 x 10 km grid for the period 1961/1990 (Fig. 3a). This was achieved using 30-year mean

Table 1. Details of meteorological stations in Canada and USA, in comparison with Finland: means and standard deviations of growing-season effective temperature sums (ETS) above 5°C (DD5)
Détails sur les stations météorologiques au Canada et aux Etats-Unis, comparés avec la Finlande: moyenne et écart-type de la somme de températures au-dessus de 5°C au cours de la période de végétation (DD5)

						ETS (DD5)	
Station	Region	Lat. (°N)	Long. (°E)	Alt. (m)	Years	Mean	S.D.
Abbotsford, B.C.	1	49.03	−122.37	58	28	1904	137
Bellingham, WA	1	48.78	−122.48	43	24	1890	154
Clearbrook, WA	1	48.97	−122.33	20	27	1862	123
Vancouver, B.C.	1 (coastal)	49.18	−123.17	3	29	1922	138
Blaine, WA	1 (coastal)	49.00	−122.75	18	26	1787	120
Wenatchee, WA	2 (north)	47.42	−120.32	195	27	2663	140
Kennewick, WA	2	46.22	−119.10	119	24	2892	159
Sunnyside, WA	2	46.32	−120.00	228	27	2630	138
Yakima, WA	2 (west)	46.57	−120.53	332	29	2327	136
Jokioinen	S. Finland	60.82	23.50	104	30	1190	123

monthly temperatures, which have been interpolated from about 150 station locations to the grid using kriging, accounting for the influence of altitude and proximity to lakes and to the Baltic Sea (Henttonen, 1991). The procedure slightly underestimates ETS (by about 20 DD5 at Jokioinen) relative to averages of annual ETS.

The ETS zones have been delimited according to the nematode thresholds defined above. Note that these zones represent mean conditions; in warmer-than-average years conditions are likely to be more favourable for nematode development. According to the analysis, in the field area used for potato production, *M. chitwoodi* can have one generation per year (ETS exceeding 600 DD5). Infection of the potato tubers associated with the hatching of eggs of the second generation is also possible over large areas of southern Finland, since values of 1000 DD5 are exceeded. In a few isolated regions the nematode could also complete the development of a

Table 2. Frequency, in %, of years achieving a given effective temperature sum threshold (for explanation, see text) at sites in Canada, USA and Finland (1961/1990)
Fréquence, en %, des années atteignant certains seuils de sommes de températures (voir texte pour explication) aux sites étudiés au Canada, aux Etats-Unis et en Finlande (1961/1990)

Station	G1	H2	G2	H3	G3	H4	G4
Abbotsford	100	100	100	100	29	4	0
Bellingham	100	100	100	100	21	4	0
Clearbrook	100	100	100	100	11	0	0
Vancouver	100	100	100	100	31	3	0
Blaine	100	100	100	100	4	0	0
Wenatchee	100	100	100	100	100	100	11
Kennewick	100	100	100	100	100	100	71
Sunnyside	100	100	100	100	100	100	11
Yakima	100	100	100	100	97	86	0
Jokioinen	100	93	10	0	0	0	0

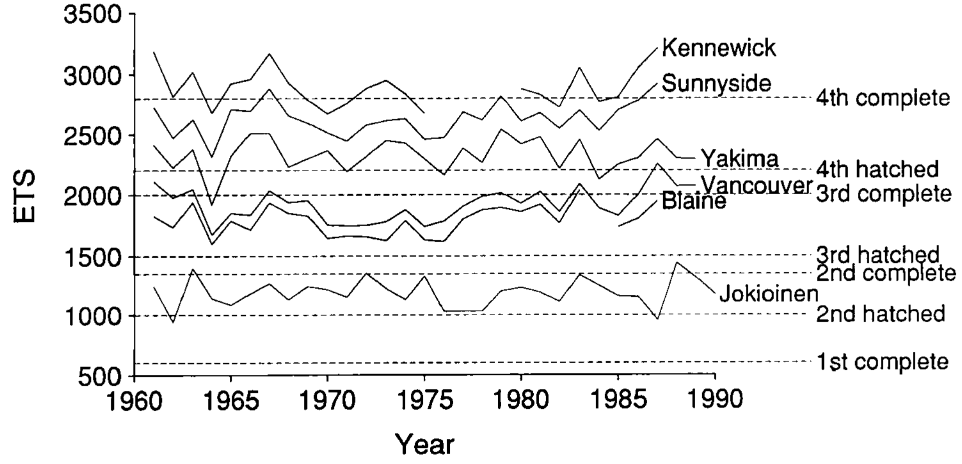

Fig. 2. Effective temperature sums above 5°C (degree days) for the growing season at selected sites (1961/1990) (see Table 1).
Sommes de températures au-dessus de 5°C (degrés j) pendant la période de végétation aux sites d'études de 1961 à 1990 (voir tableau 1).

second generation under average conditions (Fig. 3a), while in very warm years this could be achieved over a larger area (Fig. 2). The hatching and development of a third generation is not possible under the present climatic conditions.

Over future decades, it is possible that this situation could change, however, due to warming of the climate associated with the enhanced glasshouse effect (Houghton *et al.*, 1990). Warming

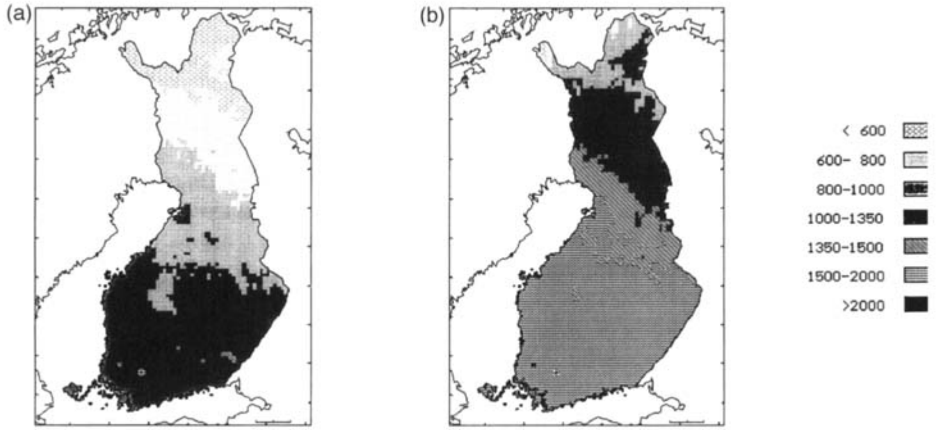

Fig. 3. Mean effective temperature sums for growing season in Finland, according to requirements for development of *Meloidogyne chitwoodi*: (a) present climate (1961/1990); (b) scenario of 3.3°C mean annual temperature warming by 2100.
Sommes moyennes de températures durant la période de végétation en Finlande, par rapport aux besoins thermiques du développement de *M. chitwoodi*: (a) climat actuel (1961/1990); (b) scénario de réchauffement de la températue annuelle moyenne de 3,3°C en 2100.

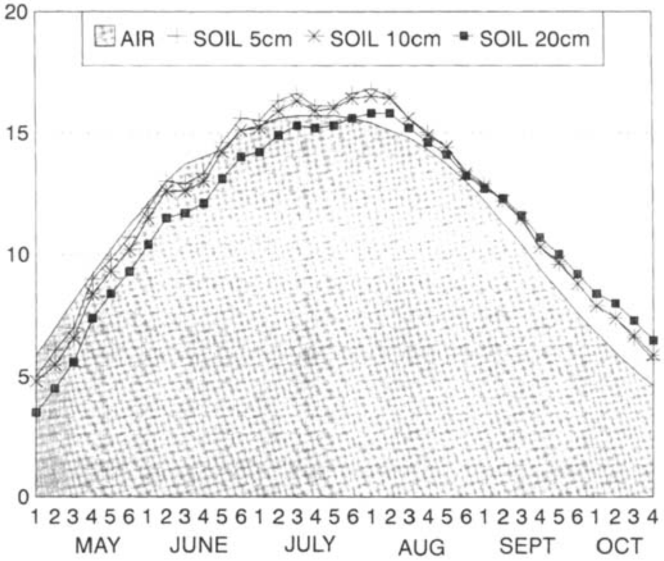

Fig. 4. Relationship between air and soil temperature at 10 cm at Jokioinen (FI). Mean values for 1961/1990; soil temperature observations made every 5th day.
Relation entre la température de l'air et la température du sol à 10 cm de profondeur, à Jokioinan (FI). Valeurs moyennes pour 1961/1990; température du sol mesurée tous les 5 j.

would allow the northward extension of *M. chitwoodi* as well as a range of other nematodes in Europe (MacKerron *et al.*, 1993). Recent climate model estimates for the Finnish region indicate that mean annual air temperature could increase by some 0.3°C per decade, producing a warming of about 3.3°C by 2100 (Carter *et al.*, 1993). Using this as a simple scenario of future climate in Finland, ETS has been recalculated and mapped (Fig. 3b). Under this scenario, the potential for tuber infection extends well into Lapland, a second generation could be completed and a third generation hatched over much of southern and central Finland, and in a few regions, especially in warm years, there would be potential for a third generation to be completed (Fig. 3b).

Soil temperature measurements

Threshold temperatures for the development of *M. chitwoodi* and the temperature requirements of different generations are determined experimentally using soil temperature measurements. Unfortunately, soil temperature data is not as complete as data from air temperature measurements. An initial attempt to construct an interpolated soil temperature map for Finland, using a combination of direct measurements and a soil temperature model based on air temperatures, was unsuccessful. This was primarily due to the sparse coverage of direct measurements, a lack of information on soil types across Finland, and the poor ability of the model to simulate soil temperatures at sites for which data was available.

However, comparison of soil temperature measurements and air temperature measurements (Fig. 4) indicated that temperature sums based on air temperature measurements are a satisfactory substitute for this kind of risk analysis. At the beginning of the season, the accumulation of temperatures is overestimated when using air temperatures, while in the second half of the season, the accumulation is underestimated. The total sum is almost the same whether based on air or soil temperatures (Heikinheimo & Fougstedt, 1992).

Records of the pest in protected cultivation

No published information about records in protected cultivation was found.

Agroclimatic suitability for outdoor host plants in Finland

The main host plant of *M. chitwoodi* is potato. It is grown over the whole country from the southern coastline up to Lapland. Potato and barley fields can be found north of the Arctic Circle in areas where the effective temperature sum exceeds 700 DD5 (Fig. 3a). Oats are grown up to the Arctic Circle in areas where ETS is about 850 DD5. The northern limit of spring wheat cultivation is further south at approximately 62°N (Kettunen *et al.*, 1988). Across the whole country, long day lengths during the growing season promote the maturing of cultivated plants, but do not stimulate directly the development of nematodes. Cultivated plants thus have good possibilities to escape injury caused by nematodes like *M. chitwoodi.*

Control of the pest

Control measures in regular use

Management strategies in the USA have included prevention of spread, crop rotation, early harvest, nematicides and green-manure cover crops. The most common method used to control root-knot nematodes on potatoes in the northwestern USA is by soil fumigation with 1,3-dichloropropane or metham sodium. Of the non-fumigant nematicides, ethoprophos has been widely used. In the northernmost areas, *M. chitwoodi* has been controlled by prevention of spread, crop rotation, early harvesting and using green manure (Santo, 1994).

Despite costly chemical control practices, *M. chitwoodi* has remained a serious problem for potato production and appears to have increased over the past few years (Santo *et al.*, 1992). However, there is no evidence to suggest resistance to plant protection products. The main reasons for increased nematode problems in the USA are inadequate fumigation practices, the build-up of nematode population densities resulting from mild winters, unusually warm growing seasons, and poor cropping sequences (Santo *et al.*, 1992). The wide host range of *M. chitwoodi* decreases the usefulness of crop rotation as a control practice against the nematode.

In the USA, because of health and environmental concerns, the continued availability of soil fumigants and nematicides is uncertain. Alternative methods to control *M. chitwoodi* include the cropping of selected rape cultivars and *Sorghum sudanense* as green manure. Nematode densities can be reduced by incorporating the plant material into the soil (Mojtahedi *et al.*, 1991b, 1993).

In areas where *M. chitwoodi* does not exist (like Canada), the most important practice to control it is to use nematode-free seed material by enforcing tight plant quarantine regulations (Kirkham, pers. comm.). In Finland, cultural practices which are effective in controlling potato cyst nematodes (Tiilikkala, 1991) may not be sufficient to control a polyphagous species like *M. chitwoodi.*

Records of eradication

There are no records of eradication of *M. chitwoodi* from any country, but in Canada, for example, the spread of *M. chitwoodi* from the USA has so far been successfully prevented by using special plant quarantine regulations (Vrain, pers. comm. 1993).

Transport of the pest

Method of natural spread elsewhere in the world

See 'Dissemination and dispersal' under the heading 'Biological characteristics'.

Pattern of international trade in the major host plants

International trade of potato (Santo, 1994) (especially seed potato) and bulbs of ornamental plants (Santo, pers. comm. 1993) may constitute the highest risk to the spread of *M. chitwoodi.* In Europe the main exporting country of this material is The Netherlands. Almost all European countries import host plants of *M. chitwoodi.* The material is transported mainly by shipping as dormant plants.

Records of interceptions of the pest on host plants in international trade

No records are available.

Records of movement other than on host plants

No records are available. However, transport of nematodes in infested soil attached to non-host plants or other articles moving in trade is a well-known pathway for movement of other *Meloidogyne* spp. (Kurppa, 1985) and could also be a pathway for *M. chitwoodi.*

Specific pathways for the pest from infested host plants in its country of origin to susceptible host plants in the PRA area

The most probable pathway for the pest is the trade in seed potatoes. Introduction of root-knot nematodes to the PRA area has occurred regularly (Kurppa, 1985). In 1992, infection with *Meloidogyne* spp. was the reason for rejecting six imported potato shipments. One of the lots was to be imported as seed potato. The origin of the rejected potato lots was the USA in one of the cases; in all other cases, the origin was The Netherlands (National Board of Agriculture, Plant Quarantine Service of Finland, pers. comm. 1993). In addition, in 1992 altogether 36 000 ornamental plants were rejected because of infection with *Meloidogyne* spp. (Anon., 1992). So far none of the populations of *Meloidogyne* spp. found by the Plant Quarantine Service of Finland has been identified as *M. chitwoodi.*

Plant propagation material is imported to the PRA area mainly from central Europe and occasionally from non-European countries (Anon., 1976/1980). For example, in 1992, altogether 156 million ornamental plants and 15 million kg of potato were imported (Anon., 1992).

Economic impact of the pest

Type of damage

M. chitwoodi is the predominant pest of potato in the Pacific Northwest of the USA. Economic losses result from the reduction in tuber quality caused by internal spots and galled tubers (Pinkerton *et al.*, 1986). The nematode infection seriously affects the cooking quality of processed potato products. Santo *et al.* (1981) determined the economic threshold of *M. chitwoodi* on potato to be less than one juvenile per 250 cm^3 soil at planting. Most of the potato cultivars which are grown in Europe are susceptible to external symptoms caused by *M. chitwoodi*, and significant differences between some cultivars have been found (Van Riel, 1993.)

M. chitwoodi reduces the root weight of carrots but is not regarded as a serious threat to the carrot industry in the Columbia Basin area of Washington (Santo *et al.*, 1988). *M. chitwoodi* may also reduce the productivity of wheat, maize, barley and oat (Santo & O'Bannon, 1981). A tolerance limit of wheat to *M. chitwoodi* is between 0.03 and 0.18 eggs per cm^3 of soil (Nyczepir *et al.*, 1984). Cereals are especially prone to productivity losses when these crops are grown in rotation with susceptible crops such as potatoes.

Recorded economic impact on each major host plant

In the USA, of the potato acreage grown in the State of Washington, 70-80% receives nematicide treatment to control root nematodes at an estimated annual cost of 20 million USD. The loss of potato without chemical treatments has been estimated to be 40 million USD (Santo, 1994). The loss of other crops is not well documented but is much less than that of potatoes. In areas where *M. chitwoodi* had one generation per year, only slight tuber symptoms were observed and the impact of the nematode on fresh market potato was negligible (Pinkerton & McIntyre, 1987).

In Europe, no information about the economic impact of *M. chitwoodi* is available. However, preliminary reports indicate that yield losses are possible and may be connected with exceptionally warm growing seasons (Brinkman & Van Riel, 1990). More scientific information is needed before the pest potential and economic impact of *M. chitwoodi* can be reliably estimated. Analysis of climatological data indicates that *M. chitwoodi* could become a major pest in many parts of Europe.

Estimated effect of the presence of the pest on exported commodities

If *M. chitwoodi*-infested plant material cannot be exported, the presence of *M. chitwoodi* may restrict the number of ornamental plants that are available in Finland. For exporting countries like The Netherlands, the presence of *M. chitwoodi* may also be economically harmful if it restricts this trade.

The export of infested plant material to Finland would pose a threat to potato production. In particular, production of high-quality seed potatoes may suffer from the risks caused by nematode infestations and costs of tighter plant quarantine activities. The utility value of the high-graded area of seed potato production in Finland could easily be destroyed. In the long run, it would be a serious loss, both nationally as well as at the European scale.

The market value of infested material is likely to be low in most cases, but especially so for seed potatoes, table potatoes and plant propagation material.

Effect of control measures used against the pest on the control of other pests

In the USA, chemical control of *M. chitwoodi* has employed the same kind of plant protection products as those which are used in Europe for control of many plant-parasitic nematodes. Nematicides and soil fumigants affect many kind of pests and can be integrated into numerous control strategies. On the other hand, the general use of chemicals in Europe to keep potato cyst nematodes under control may have affected *M. chitwoodi* populations, too. The newer control strategy for *M. chitwoodi*, based on the use of crop rotation and green manure, fits well with integrated pest management strategies in Europe. Improved crop rotation and use of organic amendments may decrease yield losses which are caused by soil-borne pests in general.

Undesirable side-effects

The side-effects of soil fumigants and nematicides which have been used for the control of *M. chitwoodi* are the same as the negative environmental effects of these compounds used for other purposes. Environmental risks caused by chemical control of nematodes are numerous and already well known (Leistra & Boesten, 1989).

Costs of exlusion compared with costs of control

Finland

If *M. chitwoodi* becomes established in Finland, it may cause difficulties to potato production and especially to the production of seed potatoes. Population densities of *M. chitwoodi* would probably stay at such low levels, however, that yield losses in other crops would be low under the current climatic conditions.

No nematicide is registered in Finland to be used on open fields. Control of *M. chitwoodi* should be based on phytosanitary regulations and cultural practices. Complete control, which is needed in seed potato production, would be difficult.

The costs of exclusion of the nematode would depend on the size of the infested area and number of infestations. Estimation of all possible costs is impossible because of inadequate information concerning *M. chitwoodi.* However, the national resources needed for soil inspection and other plant quarantine activities would be much more expensive if the nematode were present than if, as now, it is not. The occurrence of *M. chitwoodi* in Finland would also increase the costs of maintaining the high-graded area of seed-potato production free from quarantine pests.

Europe

In central Europe, the climate is much more suitable for *M. chitwoodi* than in Finland. The pest potential of the nematode in The Netherlands has been found to be comparable with the situation in the cooler regions of the US Pacific Northwest. This being so, the value of control costs should be calculated as millions of ECU per year depending on the size of infested area. Costs of exclusion might be much higher.

Analyse du risque phytosanitaire présenté par *Meloidogyne chitwoodi* pour la Finlande

Il existe un risque constant de la dissémination de *Meloidogyne chitwoodi* en Finlande, compte tenu du volume important de végétaux importés par ce pays. Si le nématode s'établit en Finlande, deux facteurs sont susceptibles de limiter son potentiel nuisible: la faible somme de températures pendant la période de végétation et les conditions très froides de l'hiver. En moyenne, la somme de températures permettrait le développement de 1,5 générations par an. Deux générations seraient possibles dans le sud du pays, pendant un été chaud. L'éclosion de la deuxième génération et l'infection des tubercules de pomme de terre sont possibles dans la majorité des zones de culture. Les températures hivernales devraient réduire la densité des populations, mais sans pour autant empêcher le nématode de s'établir en Finlande. Une fois introduit dans le pays, *M. chitwoodi* serait nuisible à la pomme de terre, et notamment aux cultures de semence. En ce qui concerne les autres cultures comme les céréales et les légumes, les densités de population de *M. chitwoodi* seraient trop faibles pour que les dégâts soient évidents dans les conditions climatiques actuelles. Les informations sur le comportement des populations de *M. chitwoodi* en Europe sont encore insuffisantes pour utilisation en PRA. Il faudrait mieux connaître les effets de l'ensemble des facteurs abiotiques et biotiques sur le nématode. A cette fin, il serait utile de disposer d'une base de données sur la distribution géographique du nématode, sous la forme d'un système d'information géographique, pour l'Europe entière. La cartographie devrait aussi porter sur la température du sol, interpolée à partir de mesures directes ou estimée à partir de la température de l'air, car la somme des températures du sol est l'un des meilleurs indices de la distribution potentielle de ce nématode polyphage.

Анализ фитосанитарного риска заражения *Meloidogyne chitwoodi* в Финляндии

Постоянный риск заселения *Meloidogyne chitwoodi* в Финляндии присутствует из-за интенсивного импорта растительного материала в страну. Если нематодам удасться распространиться, два фактора могут отрицательно повлиять на их губительное воздействие: низкая сумма температур во время вегетативного периода и условия низких температур зимой. В среднем при эффективной сумме температур возможно развитие 1,5 поколения ежегодно. В теплые годы в южных частях страны возможно развитие двух поколений. Развитие второго поколения и инфицирование клубней картофеля может происходить в большинстве районов выращивания картофеля. Низкие температуры почвы в зимний период сокращают плотность популяций, но не могут предотвратить заселение нематодами Финляндии. При занесении в страну *M. chitwoodi* может стать паразитом картофеля, в особенности, семенного. Что касается других культур, таких, например, как зерновые и овощные, плотность популяций нематод может остаться на таком низком уровне, что потери урожая при существующих климатических условиях будут незначительными. Для проведения действительно надежного анализа риска научная информация в отношении популяций *Meloidogyne chitwoodi* в Европе еще не достаточна. Такой анализ возможен только при наличии знаний действия на нематоды биотических и абиотических факторов. В масштабах Европы необходимо срочное создание основанной на системе географической информации базы данных по распространению нематод. Должны быть составлены также карты почвенных температур, интерполированные по прямым измерениям или построенные по температурам воздуха. Такие карты необходимы потому, что сумма почвенных температур является одним из важнейших факторов, которые могут ограничить распространение полифаговых нематод.

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