Potato cyst nematodes - a technical overview for England and Wales

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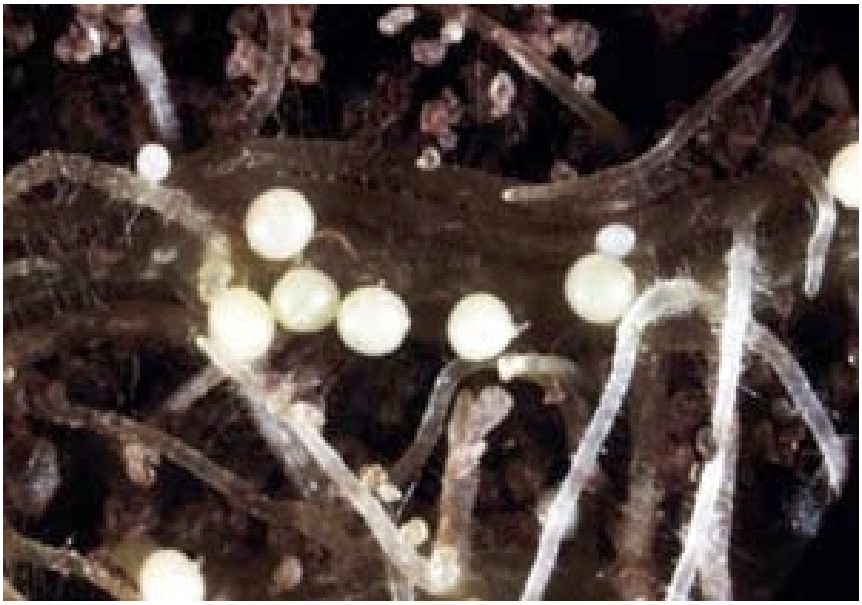

(Maturing females and cysts of *Globodera pallida*)

(Maturing females and cysts of *Globodera rostochiensis*)

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Executive Summary

The pests

Potato cyst nematode (PCN) is the name commonly given to two species of cyst nematode that attack potato, namely *Globodera pallida* (Stone) Behrens and *G. rostochiensis* (Wollenweber) Behrens. They are two of the most important pests of potato in England and Wales, feeding on potato roots, causing losses of yield and costs that vary and are difficult to estimate. Published papers usually quote losses of about 9% of annual yield, estimated at about £43 million for the UK, based on the mean value of the crop from 1990-1995.

Adaptations to a plant-parasitic life

In both species the female forms a hard covering around her eggs when she dies, creating a 'cyst' which protects the eggs and developing juveniles from desiccation, predation and chemical control. Only a proportion of the eggs hatch from the cyst each year, and in *G. pallida* this occurs at a slower rate and with a later annual peak of hatching than *G. rostochiensis*. Most eggs have usually hatched after 7-10 years, but hatching can continue for 25-30 years.

Spread and Distribution of PCN in England and Wales

PCN cysts are usually spread by contaminated soil, attached to tubers, plants for transplanting or to farm machinery. The introduction of a few PCN cysts will usually go unnoticed for several years until the infestation reaches a level at which it is detected either by pre-cropping sampling and testing, or, more significantly, the appearance of symptoms such as stunted plants. Thus infested soil can be spread unwittingly within and between farms by normal agricultural practices before the pest is detected. Surveys have shown PCN to be distributed wherever potatoes are grown, though it is rare in areas used for seed potato production. There has been a change in the proportion of each species present, with *G. pallida* now the most common species, followed by mixtures of the two species.

Current statutory measures

As trade in potatoes developed, legislative measures were introduced to reduce the risk of spread of PCN. These have concentrated on the production of certified seed on land tested and found free of PCN before planting, but have also involved reducing the amount of contaminated soil to minimal levels, rotations of at least four years (to allow viable egg numbers to fall), the use of resistant cultivars, testing of soil where tubers and other plants are for export, and prohibiting the growing of plants for transplanting (i.e. nursery stock and bulbs) on scheduled fields.

Pathotypes and resistant cultivars of potato

Many pathotypes (or races) of each species of PCN are known to exist, with the origin of development in South America. In England and Wales relatively few pathotypes exist. All resistant cultivars currently used here incorporate the H_1 (ex *andigena*) gene for resistance. Such cultivars work well against PCN populations lacking the gene that confers virulence against this gene, i.e. *G. rostochiensis* Ro1, but have no effect on other pathotype populations of this species, or on *G. pallida*. This explains why the latter has become predominant when such resistant plants have been grown continuously.

Control methods

Preventing the introduction of PCN to a clean field requires adherence to a strict management programme and, in the case of land used for seed potato or transplant production, depends on statutory measures. Preventing the build-up of PCN on ware land also requires careful management, involving the use of pre-cropping sampling to determine species, viability and level of infestation, the use of resistant varieties if possible, combined with chemical treatment and between cropping intervals of at least six years. Hygiene measures to prevent spread between fields and premises are also important. Failure to follow such guidelines is the main reason why PCN is such an important pest of potatoes in England and Wales.

Introduction

The PCN species are two of the most important pests of potato in England and Wales, feeding on potato roots, causing losses of yield and costs that vary and are difficult to estimate. Published papers usually quote losses of about 9% of annual yield, estimated at about £43 million for the UK, based on the mean value of the crop from 1990-1995. Several agricultural sectors are affected by PCN either because of the damage it causes (to potatoes), or because of costs attributed to contamination by this pest (transplanted crops such as bulbs, nursery stock and fruit plants).

Average yield losses of about 9% in total ware potato production have been estimated previously, but a recent published assessment has not been done. This and other cost estimates will vary from season to season and farm to farm, but they clearly need to be updated, especially as there is only limited information about other associated costs such as the cost and effectiveness of nematicides, programmes for breeding resistance, research and development and the cost of lengthening crop rotations. Recent efforts to develop mathematical models to estimate the impact of PCN on yield have highlighted these shortcomings. The impact of legislation may also add to costs, if, for example, a seed potato or ware export crop has to be marketed at a lower grade or sold on the domestic market.

PCN: species and diagnosis

The present EC Control Directive 69/465 refers to PCN as *Heterodera rostochiensis*. However, in 1973 it was concluded that observed differences in morphology and biology between populations of this species were sufficient to create two new species. In 1975 these were named *G. pallida* (Stone) Behrens and *G. rostochiensis* (Wollenweber) Behrens. As both of the pests in question are still 'PCN', this fundamental change did not result in any change in policy. However, subsequent research with each species has resulted in a greater understanding of differences in their biology and hence appropriate methods for control.

The first stage in the diagnosis of PCN is to distinguish it from other cyst nematode species which might be found in soil. *Globodera* species have round cysts, whilst all other groups (Heterodera/Punctodera) have lemon-shaped cysts. The *Globodera* group also includes other species which are not PCN; *G. achilleae* (Golden & Klindic, 1973) Behrens is occasionally found in England and Wales and feeds on Yarrow (*Achillea millefolium*). This needs to be distinguished from the PCN species in tests of soil samples to avoid unnecessary scheduling of land or chemical treatments. Such diagnosis still relies on the expertise of nematologists using traditional microscopy techniques, which involve measuring characters found in both juveniles and females.

Over the last 10-20 years there have been great advances in techniques to diagnose species. The use of iso-electric focussing in the 1980s proved to be of great assistance to diagnostic laboratories, but was not appropriate for statutory samples as about 25 cysts need to be collected to provide sufficient material to confirm species. In addition, *G. achilleae* cannot be distinguished from *G. rostochiensis* by this technique, with obvious implications for both advisory and statutory samples. Recent advances in DNA-based diagnostic techniques have provided some additional help, but here again caution has to be exercised as positive results can be obtained with empty or non-viable cysts. In addition, neither method is presently able to

distinguish between all native species of *Globodera*, which includes *G. achilleae*. These limitations could lead to an unnecessary scheduling of land.

Biology of PCN species

Plant-parasitic nematodes are slender, eel-shaped, unsegmented worms. They are a large and diverse group that are parasitic on or within plant tissues. Cyst nematodes are highly specialised plant-parasites. The free-living, eel-like juveniles migrate to enter plant roots, where young females develop round bodies as eggs develop inside them, and as they die their translucent body becomes a hard, brown protective covering (the 'cyst') to protect the eggs (Fig. 1).

The cyst protects up to 400 eggs, each of which contains a fully-formed juvenile, from extremes of environmental conditions. Most juveniles go into a form of dormancy known as diapause. In this state, most will remain viable for many years, with hatching continuing for 25-30 years and exceptionally instances of infestations over 40 years old being reported. The juveniles are generally stimulated to hatch by exudates produced by actively-growing potato root tips. Under favourable conditions this may stimulate over 80% of the juveniles to hatch. In the absence of a host crop a variable spontaneous hatch occurs, averaging about 30% annually for *G. rostochiensis*, but less (about 20%) for *G. pallida*, depending on soil type and temperature.

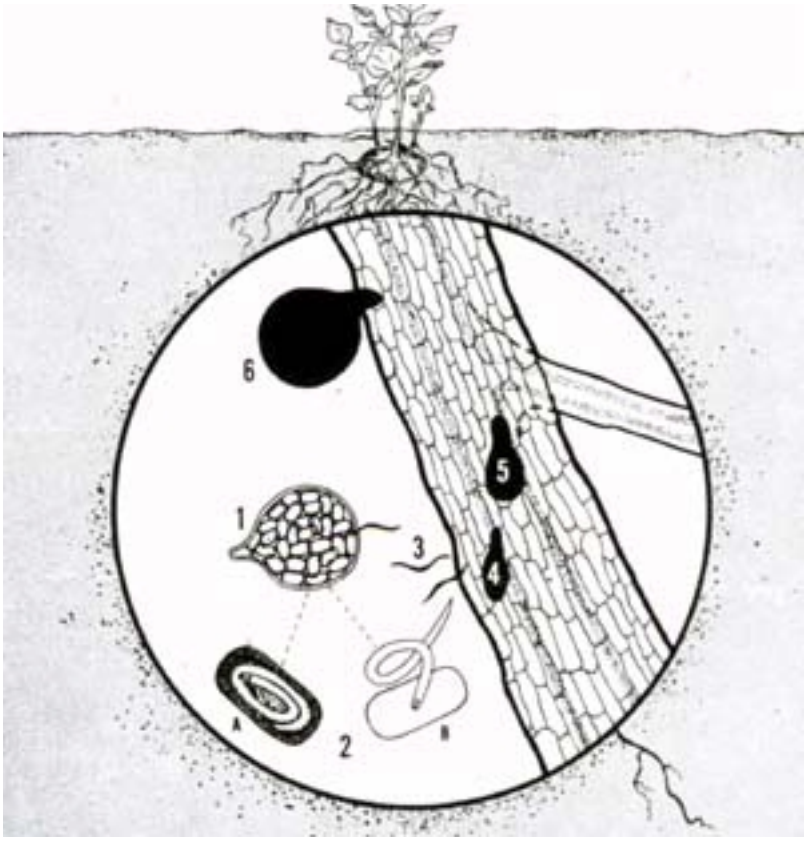

Fig.1. Life cycle of PCN. 1. Juvenile nematode leaving cyst. 2A. Appearance of juvenile in egg. 2B. Juvenile nematode hatching from egg. 3. Juveniles entering potato root. 4 and 5. Immature females inside root. 6. Mature female.

The identification of the two species of PCN in 1973 prompted research which shows that their respective life histories demand different approaches to control, mainly due to differences in hatching periods and longevity. *G. pallida* has been shown to have a prolonged hatch with a later annual peak of activity than *G. rostochiensis* during the growing season (which may therefore extend beyond the effectiveness of any chemical treatment), and this, combined with a slower rate of decline than *G. rostochiensis* in all soil types, helps to explain why this species is more difficult to control. Perhaps more importantly, DNA studies have shown that races or pathotypes of *G. pallida* are much more heterogeneous and variable than *G. rostochiensis*. Thus although the detection of PCN per se might not require detailed diagnosis, laboratory identification to species is necessary to support the most appropriate control methods.

Detection

Soil sampling is necessary to determine the presence or absence of PCN and thus determine which fields can be used for seed potato production. The sampling and extraction systems used by the Plant Health Service in England and Wales (based on the European and Mediterranean Plant Protection Organisation (EPPO) Quarantine Procedure for *G. pallida* and *G. rostochiensis*) provide a practical and reliable indicator of the presence of PCN. Soil samples are taken from an area up to 4 hectares, usually by following a 'w'- shaped path and taking regular samples en route with a corer. About 55-60 cores are required to collect a 500g sample for testing. The combination of producing seed potatoes only on land that has been officially tested and found 'free' from PCN, together with a tight tolerance for the quantity of 'soil permitted with seed tubers, has greatly reduced the risk of spread through seed potatoes. Soil sampling methods promoted in The Netherlands use larger quantities of soil (6-11 kg of soil), and are often advocated in order to achieve higher levels of statistical confidence, but they are more costly. The EPPO sampling method is currently under review.

For ware growers, soil sampling can provide further information on the number, species and viability of cysts as indicators of likely damage, and is thus an essential part of an integrated control programme management plan. If the grower intends to retain part of a ware crop for planting (i.e. as home-saved seed), it is advisable to plant only from a crop which has been grown on land which has been tested and found free from PCN. Otherwise PCN may be spread when the harvested tubers are replanted.

The use of global positioning systems has been investigated as a means of reducing costs by locating foci of PCN infestation for nematicide application. However, the sampling grid needed to establish sufficient detail of an infestation has to include many sampling points if an accurate distribution of this usually randomly-distributed pest is to be obtained. In practice most 'grids' are probably too coarse to allow efficient detection of all pockets of the field infestation and hence control may be inadequate.

Host plants of PCN

There is potential for PCN to develop on a range of crop and weed hosts in the Solanaceae family (which includes potato, tomato and aubergine), but in practice, potato ground keepers, rather than other hosts, are the main cause for concern between crops. Their elimination is therefore an important part of PCN management. There are very few imports of solanaceous plants, and these are carefully monitored to reduce the risk of importing new strains of PCN. The Plant Health Service also monitors the trade in transplanted material, which does not usually act as a host of PCN but may serve to spread the pest if contained in soil moving with the plants.

Symptoms

Typically, PCN damage may appear as signs of mineral deficiency (as roots are unable to absorb sufficient nutrients) or as patches of stunted yellowing plants, or as wilting due to an inefficient root system, but such symptoms usually only appear when infestation levels are already high. From July onwards cysts may be seen on the roots, but PCN may not be the only problem: the fungal diseases *Rhizoctonia* and *Verticillium* wilt are often at least contributory causes of poor growth.

Damage

PCN reduces potato yield and this loss may or may not be accompanied by other obvious symptoms in the haulm as described above. Several factors almost certainly interact either to increase or decrease nematode damage: for example, differences in yield potential between sites, differences between cultivars in their tolerance of damage, differences in husbandry, weather, etc.

Pathotypes and Host Plant Resistance

Many pathotypes (or races) of each species of PCN are known to exist, but there is no universally agreed means of describing them. For the sake of consistency, this review will use the terminology of one of the international systems developed to differentiate between pathotypes on the basis of their multiplication rates on a series of differential potato clones, namely the Kort system, but its shortcomings are acknowledged.

In England and Wales, according to results of the last survey published in 1986 and ad-hoc samples taken since, there are relatively few pathotypes, namely Ro1 (*Globodera rostochiensis*), Pa1, Pa2 and Pa3 (*Globodera pallida*). However, problems in distinguishing Pa2 and Pa3 led to the adoption of the term Pa2/Pa3 to describe the wide spectrum of virulence exhibited by European non-Pa1 *G. pallida*.

Recent research in Scotland has revealed the presence of both Pa1 and Pa3 pathotypes, whilst in Northern Ireland, populations showing a mixture of Pa1, Pa3, and a mixture of Pa2/Pa3 pathotypes have been recorded. In Europe, a slightly wider range of pathotypes exists, but it is still small in comparison with the range found in South America. These differences are assumed to be a direct result of the few introductions that have been made into Europe, but they may also have been determined by the use of different cultivars and environments which would all contribute to the eventual expression of virulence. In Western Europe, all countries have reported Ro1, as in England and Wales, but pathotypes from Ro2 to Ro5 have also been reported in Germany, The Netherlands, Norway and Sweden. By contrast, the range of pathotypes of *G. pallida* in Europe is thought to be similar to that in the UK. In Central and Eastern Europe, where the potato crop is also of major significance, less data is available, but the intensive use of cultivars resistant only to Ro1 is likely to lead to the preponderance of *G. pallida* pathotypes, as has happened in England and Wales.

Undoubtedly the greatest range of pathotypes is to be found in South America, where potatoes originated and where PCN evolved in conjunction with many other solanaceous plants. DNA-based diagnostic tests on populations from the UK, Europe and South America have shown that the latter can be clearly separated from European populations, but in addition a build up of different virulent types (reflecting the genetic variability and potential of different populations to adapt to different environments and overcome resistance) has also led to regional characteristics in populations.

Recent advances with DNA techniques have not clarified the situation; in some cases, pathotypes are being amalgamated and in others divided. More importantly, in practical terms, different populations of apparently the same pathotypes may not always show the same virulence (ability to multiply) on a particular cultivar. Such events serve to illustrate the complexity of this subject.

Knowing the characteristics of pathotypes is important to plant breeders trying to develop cultivars resistant to PCN (defined simply as those that prevent the development of juveniles to adults). The use of resistant cultivars has been permitted under Article 10 of the present PCN Directive. However, the existence of a range of pathotypes, and the ability of different populations of the same pathotype to show a range of virulence on the same cultivar, can make advice on the use of resistant cultivars difficult.

All resistant cultivars currently used in England and Wales incorporate the H_1 (ex *andigena*) gene for resistance. Such cultivars work well against PCN populations lacking the gene that confers virulence against this gene, i.e. *G. rostochiensis* Ro1, but have no effect on other pathotype populations of this species, or *G. pallida*. Sustained use of such cultivars has selected for the latter species. Unfortunately, because of the inherent genetic variability of *G. pallida*, it is proving very difficult to develop a cultivar that is resistant to all populations. In the UK and Europe, some cultivars claiming partial resistance exist (e.g. cvs. Nadine, Valor, Rocket). These allow a proportion of juveniles to reach maturity, but significantly less than would be the case if a susceptible cultivar was grown. However, there is little information on their long-term effect in the field – prolonged use may result in virulent pathotypes becoming more common, as has happened at species level in England and Wales.

A major issue is that pathotypes not yet established in England and Wales could become established here because they (i) might overcome the resistance currently bred into our most commonly used cultivars, and (ii) might be more virulent than any of the populations currently found here. The range of pathotypes in prospective members of the EU must be assessed, but the evidence so far suggests that it does not differ significantly from that currently found within the EU. A far wider range of pathotypes is to be found in South America where some of the most virulent strains are found, hence imports from this part of the world are subject to close scrutiny (including a prohibition on imports of potatoes), not only for PCN, but for a wide range of pests and diseases not found in England and Wales.

Further research into pathotypes is needed to enhance the characterisation and monitoring of PCN field populations and their interaction with resistant cultivars, so as to improve the overall understanding and control of this pest.

Distribution and spread in England and Wales

It is most likely that PCN was introduced during the mid-1880s, when there was an intensive search for, and introduction of, blight-resistant varieties. However, recent evidence using DNA-based technology suggests that there were few such occasions of import, because the range of pathotypes recorded in England and Wales is less than that recorded in South America.

PCN can be introduced to clean fields by seed tubers, either with the tiny cysts (about 0.5mm) which can easily escape unnoticed in the tuber eyes, or with soil containing cysts which may adhere to tubers at harvest. However, this means of spread is most likely to occur with farm-saved seed produced on land that may be contaminated, as the controls in place to prevent infestation of certified seed potatoes will minimise the risk of spread by this means. With the

increase in levels of PCN throughout England and Wales (between 60% - 70% of ware potato land is now infested), a more likely route of spread is through soil residues spread on machinery from infested fields, by wind-blown contaminated soil, or by transplanting plants from PCN-infested land.

Surveys have shown PCN to be distributed throughout England and Wales, wherever potatoes are grown (Figs. 2 and 3), though it is rare in areas used for seed potato production.

Fig. 2. Areas of England and Wales with more than 1% of land used for potato production (Agricultural Census Statistics for the United Kingdom, 1998).

Fig. 3. Sites where PCN cysts were found in a recent survey (Minnis et al.)

There has been a change in the proportion of each species present, with *G. pallida* now the most common species (Fig. 4), followed by mixtures of the two species, with fields containing mostly or only *G. rostochiensis* in the minority (Fig. 5).

Fig. 4. Sites which contained *G. pallida* cysts in a recent survey (Minnis et al.)

Fig. 5. Sites which contained G. rostochiensis cysts in a recent survey (Minnis et al.)

The low incidence of PCN in land tested prior to seed production in England and Wales confirms the effectiveness of the various seed potato regulations in controlling PCN in seed potato land i.e. pre-planting sampling, specified intervals between cropping, and minimal soil tolerances.

Distribution in Europe and elsewhere

In 1913, PCN was found causing damage to potatoes in Germany, and it has subsequently been found all over Europe. Table 1 presents a selection of first records. The rate of spread, however, cannot be truly measured because such data is usually only indicative of when surveys were done, or when damage was first noticed.

Table 1. First recordings of PCN in west European countries

Year of first recording	**Country**	**Year of first recording**	**Country**
1913	Germany	1952	Spain
1913 (probably)	Scotland	1953	Iceland
1917	England	1954	Greece
1922	Sweden	1954	Czech Republic
1922	Ireland	1955	Luxembourg
1928	Denmark	1955	Norway
1940	Austria	1956	Portugal
1941	The Netherlands	1958	Switzerland
1946	Finland	1961	Canary Islands
1948	France	1961	Italy
1949	Belgium	1996	Hungary

1951	Faroe Islands	2002	Yugoslavia

The PCN species have been recorded in most European countries (Table 2). Some countries, such as the Azores, Denmark, Greece and Madeira have only reported interceptions, not field infestations of *G. pallida*.

Table 2. The distribution of *G. pallida* and *G. rostochiensis* in Europe, according to published records

Country	***G. pallida***	***G. rostochiensis***
Albania	-	+
Austria	+	+
Belgium	+	+
Belorussia	-	+
Croatia	-	-
Cyprus	+	+
Czech Republic	+	+
Denmark	-	+
Estonia	-	+
Faroe Islands	+	+
Finland	+	+
France	+	+
Germany	+	+
Greece	-	+
Crete	+	+
Hungary	-	+
Iceland	+	+
Ireland	+	+
Italy	+	+
Latvia	-	+
Lithuania	-	+
Luxemburg	+	+
Malta	+	+
The Netherlands	+	+
Norway	+	+
Poland	-	+
Portugal	+	+
Azores	-	-
Madeira	-	+
Romania	+	+
Russia	-	+
Slovak Republic	-	+
Spain	+	+
Canary Islands	+	+
Sweden	+	+
Switzerland	+	+
UK	+	+
Ukraine	-	+
Yugoslavia	-	+

PCN has been recorded in every continent except Antarctica. In many countries, given the pathotypes recorded, it is likely that PCN has spread from Europe. However some spread of PCN from South America direct to other countries (for example to Japan in sacks of guano used as a fertiliser) has probably also occurred. The range of virulence present in the Andean region (Peru, Bolivia and Argentina) is wider than that known to be present elsewhere and new Andean pathotypes (and even species) are still being discovered in this area. This is one of the reasons why potatoes originating in South America may not be imported.

Statutory management of PCN

Implementation

Measures to address the control of PCN, particularly for seed potatoes, were incorporated into Council Directive 69/465/EEC issued on 8 December 1969. The aim was to protect potato cultivation from the spread of PCN, then known only as *Heterodera rostochiensis*. At that stage, PCN was already known in a few Member States, but it was realised that, without effective international control measures, PCN would pose a permanent risk to potato production. Further controls are included in the Directives 66/403/EEC (the 'Seed Potatoes Directive') and 2000/29/EC (the 'Plant Health Directive'). Requirements are also imposed by some importing countries.

Regulations stipulate that seed potatoes must be grown on land that has been tested and found free of PCN, that seed potatoes must be free of PCN, and that plants for transplanting must not be grown on PCN-infested land. There must also be a minimum allowable period between seed potato crops (to allow any non-detectable infestation to decline naturally and remain non-detectable).

Apart from export testing, restrictions are implemented only when fields have been officially tested and scheduled, and hygiene measures, such as the cleaning of machinery, whilst preferable, are infrequently implemented.

The main statutory requirements are summarised in the Table 3, with details of implementation in England and Wales.

Table 3. Requirements and Implementation of EC Council Directive 69/465/EEC

Directive requirement	**Implementation**
69/465	
Art.2 - seed potatoes for marketing to be grown only on plots recognised as uncontaminated by PCN	• PHSI take soil samples for stocks entered for certification under SPCS; non-chargeable and valid for up to 4 years or 1 potato crop • Other seed (e.*g.* farm saved seed) is not covered by this testing requirement
Art.3 - plots to be demarcated ('scheduled') if PCN is recorded	• The only plots where PCN is likely to be detected are those where official testing is carried out, i.e. seed potatoes and plants/bulbs/potatoes for export • There is no requirement for notification when an unofficial sample or field symptoms indicate the presence of PCN

Directive requirement	Implementation
Art.8 - on demarcated plots potatoes may only be grown if: - they are being used for scientific purposes, tests or selection; or - (ware only) they are a variety resistant to PCN;or - (ware only) they will be harvested before PCN cysts mature or the land has been disinfested	• Surveys indicate that a substantial area of potato growing land is infested by PCN, but the area scheduled is very limited (see above), which limits the number of growers who are affected by these restrictions
Art.4 - plants for planting may not be grown or stored on contaminated plots	• Only scheduled land must be avoided
Art.5 - PCN contaminated seed potatoes must be decontaminated before being distributed as seed	• Washing to remove all traces of soil and cysts; dry brushing is not acceptable. This practice is not widely used, and indeed has not been used at all in recent years because the efficacy of this method is difficult to achieve (as small cysts are difficult to remove from 'eyes'),
Art.6 – member states to revoke measures against PCN only when it is no longer present	• Seed potatoes: (CC class) – retesting 4 years after the last potato crop or finding of PCN • Seed potatoes: (higher grades) – retesting 12 years after the last potato crop; 6 years if that crop was a resistant variety or grown on disinfested land • Ware potatoes: retesting 6 months after PCN finding if the land has been disinfested; otherwise 12 months • Nursery stock (inc. bulbs): retesting 6 months after PCN finding if the land has been disinfested; otherwise 12 months • Descheduling soil tests, including soil sampling, are arranged by the PHSI and are non-chargeable
66/403	
Annex I - production ground for seed potatoes must not be infested by PCN	• Covered by the soil test described above
Annex II - lots of seed potatoes must be free from PCN	• Achieved mainly by soil tests, but PHSI visual inspections provide an additional check (although of limited value unless infestation is severe)
2000/29	
Annex IAII – further spread of PCN within the Community is banned	• This is a general requirement (including ware production). But PCN is only likely to be detected if official testing is carried out, which only applies in limited cases as described above. • This provision also allows interceptions of consignments being traded when PCN is detected
Annex IVAI – potatoes for planting from outside the Community must be accompanied by an official statement that they originate from a field known to be free of PCN; an official statement is also needed for plants for planting that they originate from a place of production known to be free of PCN	• Required as part of phytosanitary certification for imports

Directive requirement	Implementation
Annex IVAII - potatoes for planting from within the Community must be accompanied by an official statement that they originate from a field known to be free of PCN; evidence is required that plants for planting must originate from a place of production known to be free of PCN	• SPCS soil test provides evidence for seed potatoes. But testing is not carried out on farm saved seed • For plants for planting, evidence is generally based on the fact that no potatoes have been grown on the land for 10 years
Annex IVB – seed potatoes being moved within a Protected Zone must be accompanied by an official statement that 69/465 has been complied with	• Not applicable in UK for PCN
Export requirements	
Some countries require PCN freedom in export consignments of seed potatoes; nursery stock (including bulbs); and ware potatoes	• In such cases a chargeable soil test is carried out to determine the absence of PCN cysts. If non-viable cysts only are detected, the land is not scheduled, but the consignment may not be exported

In both England and Wales, the successful continuation of freedom from PCN for the seed trade can be attributed to the principles used in regulatory controls on seed-growing areas through seed potato classification schemes and, for exports, to the ability to meet the phytosanitary requirements of importing countries. Many growers have become increasingly aware of the latter, as better markets are found outside the EU. The need to control the increasing incidence of *G. pallida* has highlighted the importance of PCN control throughout all stages of potato production. It is in all farmers' interests to consider a long-term strategy for potato cropping, and to exercise prompt management of the first signs of a PCN infestation. The increase in PCN in ware land does give cause for concern, because it must increase the likelihood of spread to seed-growing areas (and uninfested land) unless the fundamental principles are strictly adhered to.

In light of an increasing awareness of the distribution of PCN across Europe, an EC Review of legislative controls is being carried out. Further information is provided in a consultation paper published on 19 July 2002 and available at http://defra/corporate/consult/default.asp

Scheduling

Approximately 20,000 hectares of land are currently scheduled. Land is scheduled if official sampling finds one viable cyst of PCN. Thereafter, descheduling is determined by subsequent sampling and tests done between 4 and 12 years later, depending on the grade of seed potato being grown and the use of the land since scheduling. These intervals are based on the average life-cycle of PCN; most juveniles hatch during the first seven years or so, with any infestation either decreasing between cropping, or becoming non-viable.

Ware potato production on scheduled land has been permitted only if resistant cultivars are grown and/or nematicides are used. In addition, the production of early varieties has been acceptable if lifting occurs before 1 July, before adult PCN mature.

Management of PCN in ware potatoes

Preventing the build-up of PCN on ware land requires careful management, but has been exposed to short-term strategies and commercial pressures. It is important that sampling is done pre-cropping to determine the proportion and numbers of each PCN species present, as well as the viability of eggs in the cysts, to enable control measures, including chemical treatment, to be

refined. PCN infestation levels should be kept low, because chemical treatments are more likely to be effective in such situations. Numbers of PCN can be reduced by leaving intervals between potato crops of at least six years, using only certified seed, alternating resistant or partially resistant cultivars with susceptible ones, cleaning footwear and machinery between fields and returning tailings to the field from whence they came. However, in practice, it is likely that only some of these measures will be taken, either for economic or practical reasons, thus allowing PCN infestation levels to build up. For example, if the PCN species is identified as *G. pallida*, there are no fully resistant cultivars available. It is also doubtful whether adequate cleaning of footwear or machinery often takes place.

Chemical methods

According to unpublished data from the Pesticide Usage Survey of Arable Crops in 2000, approximately 21,395 hectares were treated with nematicides, an area comprising about 16% of the total potato cropping area in Great Britain that year. Chemical control methods can be divided into two types, namely pre-planting fumigation methods, and granular nematicides.

The liquid fumigant Telone II (1,3-dichloropropene) comprises the greatest proportion, by weight, of nematicides applied. Whilst methyl bromide was the most effective fumigant available, the alternatives are not thought to be so effective. This is mainly due to the protection afforded the juveniles by the cyst. Good soil conditions at the time of fumigation treatment, including the appropriate temperature and moisture content, are critical to the success, so timing may mean an application in the rotation a year or two ahead of the prospective potato crop. In addition, there is no point in applying the treatment if a good surface seal cannot be produced.

Both the granular carbamate and organophosphate types are more correctly referred to as nematistats, because their mode of action is to disrupt the metabolism, feeding and movement of the juveniles which does not necessarily result in death. Their effectiveness also depends upon several factors, including the method of application and soil conditions. The problem with such treatments is that the apparently prolonged hatch of *G. pallida* in comparison with *G. rostochiensis* means that the pesticide may have decomposed by the time most of the juveniles become active, and so be ineffective.

Neither method offers complete control of PCN in soil or on potatoes, thus they should be used in conjunction with other methods to improve protection. This includes derogations for potato cultivation on scheduled land.

Non-chemical methods

Resistant and tolerant cultivars

The current legislation allows for the use of resistant cultivars in any control programme, and cultivars with different resistant ratings are available in the UK and in Europe. The UK National List produced for the EC, however, lists only cultivars resistant to *G. rostochiensis* (Ro1 type) (Table 4).

Table 4. PCN-RESISTANT POTATO CULTIVARS ON THE UNITED KINGDOM NATIONAL LIST FOR 2002.

Accent	Navan
Admiral	Pentland Javelin
Amour	Pomeroy
Argos	Rathlin
Bimonda	Red Cara
Buchan	Revelino
Cabaret	Riviera
Cara	Rocket
Celine	Roscor
Dundrod	Saxon
Harborough Harvest	Sebastian
Horizon	Spey
Jamila (Atlas)	Stemster
Kingston	Sunbeam
Kirrie	Tay
Maxine	Valor
Maris Piper	White Lady
Midas	Winston
Nadine	

As has been illustrated, repeated use of these cultivars in England and Wales has allowed the build up of *G. pallida*.

The term 'tolerance' is often used, and should not be confused with 'resistance' or 'partial resistance'. It is expressed in some cultivars by a vigorous top growth, which helps them to yield well despite any effect of PCN damage, and in others by an extensive root system that can rapidly compensate for damage caused by PCN invasion. Problems arise when partially-resistant cultivars are extremely intolerant, thus limiting the beneficial effects of the resistance in some PCN-infested soils, unless a chemical treatment is also applied.

Breeding has produced potato varieties with resistance to the European pathotypes of PCN. This has been most effective against *G. rostochiensis*, pathotypes Ro1 and Ro4. However, in a recent survey, 25% of fields in England and Wales contained a mixture of *G. pallida* and *G. rostochiensis*. This means that if a cultivar resistant to *G. rostochiensis* is grown repeatedly, *G. pallida* will still be able to reproduce and hence will become the dominant species. Repeated use of resistant cultivars has been the main reason for the increased proportion of *G. pallida* in many parts of England and Wales - farmers cannot now assume that they are dealing with one species only, even if only one species is detected during soil testing.

Properly managed programmes, which alternate resistant varieties with susceptible ones and manipulate the known biology of the species, and use chemical treatments when necessary, are vital. The ability of PCN to overcome host plant resistance serves to show the complexity of PCN control, and thus the importance of statutory measures designed to limit the spread of PCN. It also illustrates the limited life of most resistant cultivars, and the need to manage their use very carefully.

Trap cropping

The present Control Directive includes a derogation to allow trap cropping as a method of controlling PCN on infested land. It has long been known that early lifting can limit nematode reproduction by destroying plants before females mature, but the idea of deliberate planting of a trap crop to control *G. pallida* was recently revived. A recent test of the technique in England has revealed the need for very careful timing: the crop must grow long enough for the plants to establish root systems of reasonable size, but not so long that any of the female nematodes mature. Current research work in Northern Ireland is investigating the use of wild, highly resistant but tolerant potato cultivars in trap cropping schemes. It is hoped that their ability to stimulate high levels of juvenile hatch and tolerance of high levels of PCN invasion could be utilised in organic potato production.

Biological control

Biological control of PCN has been investigated at IACR-Rothamsted, primarily using the parasitic fungi *Paecilomyces lilacinus* and *Verticillium chlamydosporium*. It may be an appropriate control measure for ware production, where large numbers of PCN would support reproduction of the parasites, but it is currently not acceptable for seed crops, which require total freedom from PCN.

Rotation

The length of rotation has been a consideration in statutory control programmes since legislation was introduced, and should be regarded as a key element in the management of PCN. In the absence of a host crop, the prolonged period of hatching causes PCN populations to decline slowly. Prescribed intervals between cropping have relied on estimates of a theoretical population decline of 30% per year but recent research has shown that the situation is much more complicated, with populations of the two species declining at different rates. The rate of decline is affected by the susceptibility/tolerance of the variety and by environmental factors, such as the soil type. The barely detectable levels found on scheduled land should therefore decrease to undetectable levels within a few years of the last sampling if no host crops are grown. Applications for retesting of land for the lowest grade of seed are accepted after a minimum of four years in England, but this grade is not normally used for further seed production. For the higher grades of seed a minimal interval of 12 years is required.

Integrated Management Systems

A comprehensive guide to the management of PCN was provided by 'Potato Cyst Nematode: A management guide', produced by MAFF in October 1999. Whilst some details have changed, it remains a useful reference for control strategies, and can be obtained from DEFRA Publications via their web-site http://www.defra.gov.uk/corporate/publications/default.htm

Conclusion

Both species of PCN are damaging pests to the potato industry and are difficult to control. This paper provides a technical overview of their biology, distribution and control. It is intended that this information should assist in the review of EC statutory controls against PCN which is taking place from September 2002. For those using it for that purpose, reference should also be made to the consultation paper published on 19 July 2002.

Some preliminary thoughts on the economic consequences of the various options being considered are included in the consultation paper. These will be developed further. If those within industries affected by PCN controls, or others who have an interest in this area can provide further details which will help to refine this document; their contributions will be very much appreciated.

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Fig. 2: Agricultural Census Statistics for the United Kingdom, 1998 (MAFF) (HMSO).
Fig. 3, 4, and 5: S.T.Minnis, P.P.J Haydock, S.K. Ibrahim, I.G. Grove (Harper Adams University College), K. Evans, M.D.Russell (Nematode Interactions Unit, IACR Rothamsted)