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Site-Specific Management of Nematodes—Pitfalls and Practicalities[1]

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Abstract: The greatest constraint to potato production in the United Kingdom (UK) is damage by the potato cyst nematodes (PCN) *Globodera pallida* and *G. rostochiensis*. Management of PCN depends heavily on nematicides, which are costly. Of all the inputs in UK agriculture, nematicides offer the largest potential cost savings from spatially variable application, and these savings would be accompanied by environmental benefits. We mapped PCN infestations in potato fields and monitored the changes in population density and distribution that occurred when susceptible potato crops were grown. The inverse relationship between population density before planting and multiplication rate of PCN makes it difficult to devise reliable spatial nematicide application procedures, especially when the pre-planting population density is just less than the detection threshold. Also, the spatial dependence found suggests that the coarse sampling grids used commercially are likely to produce misleading distribution maps.

Key words: GPS, IPM, potato cyst nematode

There have been many estimates of world population trends since the first attempts and warnings by Malthus at the end of the 18th century. However, the direst warnings of the 1960s appear not to have come true and, at the turn of the century, world population is, if anything, slightly less than the most carefully researched predictions of the 1970s. As falling birth rates interact with longer life expectancies, world population is likely to stabilize between 2030 and 2050 at 8 to 10 billion (Avery, 1995).

To feed its population, the world is currently cropping about 15 million km^2 of land, almost exactly equivalent to the area of South America. Without the benefit of farm chemicals (including pesticides), the land-area equivalent of North and South America combined, some 40 million km^2, would be needed to produce the same outputs. It has been calculated that substituting synthetic pesticides by organic pest control would reduce yields of soybean by 37%, wheat by 38%, corn by 53%, cotton by 62%, rice by 63%, and peanuts by 78% (Avery, 1995). Thus, it can be argued that high-yield farming is saving about 25 million km^2 from cultivation.

Another point to realize is that when marginal land is taken into cultivation, each new hectare is less suited for agriculture than the previous and therefore has a smaller yield potential. Thus, for each hectare of productive land unused for food production, or used below its potential, more land of lower quality has to be taken into agriculture elsewhere. The accumulation of food stocks that are not subsequently re-distributed has a similar implication. With an enlightened approach to food production, however, it should be possible to feed the predicted peak world population.

Since the 1960s, it has been fashionable to complain about the dangers posed by pesticides and those complaints have almost certainly helped provide us with safer pesticides and safer guidelines for their use. In turn, this has helped their integration into agricultural systems that have allowed food production more or less to keep pace with population. Although a proportion of the world's population can afford the luxury of insisting on production methods that do not rely on synthetic pesticides or other farm chemicals, this is not true for most of the world's population. Low-yield farming systems have been around for thousands of years, and their re-discovery in recent years would have us producing less rather than more food. The soundest way of producing the necessary extra food is in high-yield systems that embrace Integrated Pest Management (IPM). This therefore means embracing the use of pesticides while recognizing their enormous benefits as well as their dangers and public dislike of their use. This public concern is best satisfied by a responsible attitude to pesticides in a policy of good stewardship, with integrated systems to minimize their use and the risks of environmental pollution.

This concern to protect the environment, coupled with the recent narrow gross margins in potato production in the UK, have stimulated the investigation of site-specific application of nematicides for controlling potato cyst nematodes (PCN). Global Positioning System (GPS) technologies have made it possible for modulated treatment with nematicide to be accurately targeted (Haydock and Evans, 1995), and commercial packages have followed (Anonymous, 1997). We have considered the potential that such systems offer and some of the pitfalls that can occur. This paper reports the findings from some of our work.

PCN in the UK

The potato cyst nematodes *Globodera pallida* and *G. rostochiensis* are the most problematic pests faced by po-

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tato growers in Britain because they are both persistent and capable of causing substantial loss of yield (Trudgill, 1986). A recent survey of 484 potato fields in England and Wales showed that 64% of them were infested with PCN and that, of the infested fields, 67% contained only *G. pallida* (Minnis et al., 2000). This is a marked change from the situation in the 1960s, when 50% of infestations were essentially pure *G. rostochiensis* (Brown, 1970). The recent survey showed only 8% of the populations as pure *G. rostochiensis,* with 25% containing mixtures of the two species. This switch of species is a result of *G. pallida* being less easy to control using crop rotation, resistant cultivars, or nematicides than *G. rostochiensis* (Evans, 1993). Yield is lost at population densities as small as 5 eggs g^{-1} soil (Trudgill, 1986), which means that nematicides are essential to control PCN if profitable yields are to be maintained. Barker et al. (1998) have shown how nematicides influence the yields and gross margins of potato crops grown on *G. pallida*-infested land, and that it is common for potato production in such circumstances to be more profitable if two different types of nematicide—a fumigant and a granular nematicide—are used in combination. Thus, the difficulty of controlling *G. pallida* has led to increased use of nematicides.

Against this background, the possibility of site-specific application of nematicides and thereby site-specific nematode management offers the possibility of either using less pesticide overall or treating nematode-infested areas of more fields without using more nematicide. The environmental argument for this approach is supported by a powerful economic argument, as nematicides are by far the most expensive input that has the potential to be applied variably in potato production in the UK (Table 1).

MAPPING PCN POPULATIONS

The more data that are available, the more accurate distribution maps will be. But extra data cost more, and there is a limit to the frequency at which fields can be sampled. We have sampled several fields at sample spacings of 20 m, and geostatistical analysis has shown that nematode density is usually correlated over a range of 40 to 60 m. Figure 1 is a variogram of PCN distribution in a typical ware potato production field and shows how the variance between estimates of PCN density is correlated with sample separation. There is a positive intercept on the γ-axis, known as the 'nugget' variance. Variance eventually reaches a constant value (the "sill") at a separation determined by the "range," the finite limit of spatial correlation. Thus, it seems reasonable to generate maps from counts made on samples spaced at 20 m. This is borne out when subsets of data are used to generate maps from counts made on more widely spaced samples, illustrated by taking subsets of PCN densities after cropping in the field referred to in Figure 1 to generate the distribution maps in Figure 2. The general pattern seen from the 20-m-spaced sampling is still visible at 40 m, but the patterns are increasingly different as the distance between samples increases. The pattern generated from 100-m-spaced samples would be a poor reflection of the true distribution of PCN in this field.

An analysis of the potential benefit to cost ratios shows that sampling costs would be recovered even for a sample spacing as close as 20 m, provided that the resulting map permitted the decision not to treat 42% of the field with a granular nematicide, 27% with a fumigant, or 16% if the grower were considering joint applications of granular and fumigant nematicides (Table 2). These proportions would, of course, be greater if the cost of processing samples were greater.

Spatial applications are most easily made if decisions over whether to apply nematicide are made for 1-ha blocks, but the sophisticated positioning equipment

TABLE 1. Inputs for potato production in the United Kingdom and their potential for spatial application.

Input	Potentially variable?	Cost[a] (£ ha^{-1})	Potential saving (£ ha^{-1})
N, P, K fertilizer	Yes	220	33 (15%)
Lime	Yes	30	6 (20%)
Herbicides (i) pre-emergence	No	60	–
(ii) post-emergence	Yes	60	60 (100%)
Fungicides	No	144	–
Insecticides	Yes	26	26 (100%)
Nematicides (i) granular	Yes	360	360 (100%)
(ii) fumigant	Yes	550	550 (100%)

[a] Costs are taken from Anonymous (1999), and figures in parentheses in the final column represent the maximum amount by which each input might be varied.

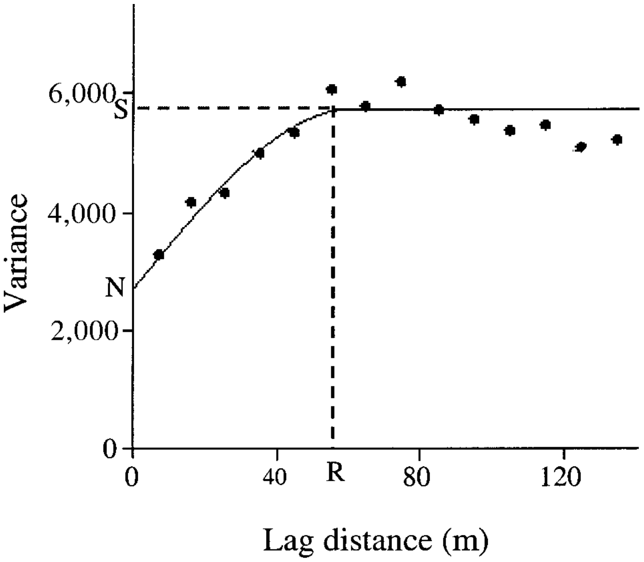

FIG. 1. Variogram of PCN density after cropping an 8-ha field at Ram Farm, Nocton, Lincolnshire, England, with a susceptible potato cultivar (Estima), and with a spherical model $\gamma(h)$ = 2753 + 2658 sph(53.5) fitted to the data. (S = Sill, N = Nugget, R = Range; see text for explanation of these terms).

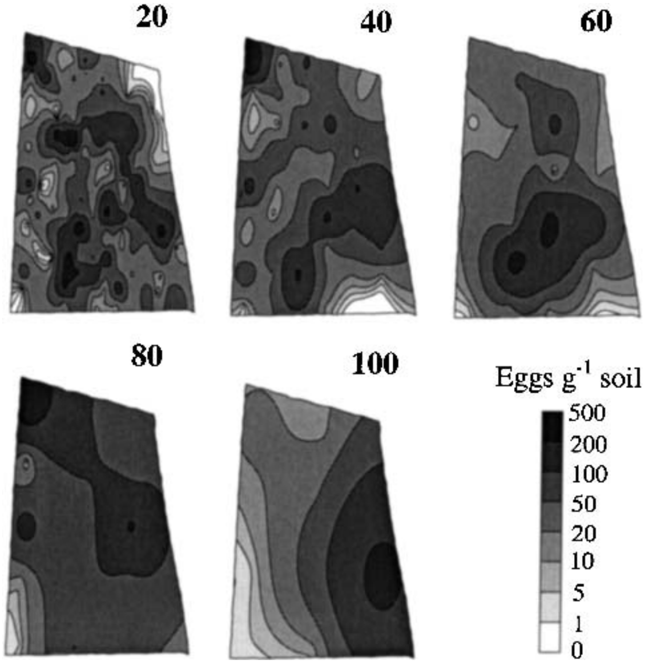

FIG. 2. Interpolated maps of the PCN density in the 8-ha field at Ram Farm produced from 20, 40, 60, 80, and 100-m spaced samples.

now available makes it possible to apply nematicide to very specific positions within a field. Taking the field referred to in Figure 1 again as an example, but this time using the PCN distribution before planting, we can draw maps of areas in the field where the PCN density exceeds various thresholds. In Figure 3, the patches where PCN density exceeded 5, 10, or 20 eggs g^{-1} soil are shown, and these correspond to 34%, 14%, and 8% of the field, respectively. Much greater economy of nematicide is possible in this way than if treatment decisions are made for square blocks of the field.

POTENTIAL PITFALLS

The problems associated with sampling for PCN have been reviewed several times (Haydock and Perry, 1998), but never for the purpose of generating within-field distribution maps. Our pre-planting maps have been generated from single point samples taken with a trowel. This is on the understanding that, over a five-course rotation of potatoes followed by four non-host crops for PCN, the soil would be thoroughly mixed by cultivation and little would be gained by taking a series of individual cores from around the sampling station and bulking them. Post-harvest maps have been generated in the same way, but we have also taken series of cores to make up bulk samples because root density is uneven both within and across the rows of the crop. The variation in root density produces post-harvest PCN populations that vary in a similar manner, and the multi-core samples are required to give a reasonable estimate of the average PCN density around sampling stations.

Failure to detect patches (1): Whatever strategy is adopted for taking individual samples, the natural patchiness of PCN means that it is possible for any sampling to miss patches. The largest single patch that can be missed is one that fits neatly between sampling stations. Thus, sample stations spaced 20 m apart on a square grid could miss a patch of up to $\sqrt{2} \times 20 \approx 28$-m diam. (Fig. 4). While this may seem unlikely, precisely this seems to have happened in one field that we sampled. The pre-cropping and post-harvest maps from this field are shown in Figure 5, and points A and B are where severe crop damage was noted when the growing crop was inspected. Although the PCN density before planting was enough to cause crop damage at point A and was very much larger after harvest, the density at point B, even on the post-harvest map, was less than 1 egg g^{-1} soil. This anomaly was shown to be due to a patch of PCN of 15-m diam. that fell between sample stations and had a post-harvest PCN density at its center of 423 eggs g^{-1} soil.

Failure to detect patches (2): Detection of patches may also fail for an entirely different reason—that of the PCN density simply being less than the detection threshold of the sampling and processing system. Densities may be small either because a patch is still developing and the density has yet to exceed the detection threshold or because a previously detectable density has declined to one that is no longer detectable during a period without host crops. Whatever the reason for the small pre-cropping density, a patch of this type is also visible (at point C) in the maps for the field in Figure 5.

Of the two different reasons for failing to detect patches given above, the first carries a yield penalty, whereas the second carries no yield penalty but brings with it a long-term problem in managing the nematode.

PRACTICAL EXAMPLES

As noted above, the most practical approach to site-specific application of nematicide is to apply the mate-

TABLE 2. Proportions of a 10-ha field that a grower would need to leave untreated with nematicide (£360 ha^{-1} for a granular, G; £560 ha^{-1} for a fumigant, F) to recover the costs of processing samples at a unit cost of £6.

Sample spacing (m)	No samples	Cost (£)	Proportions that need to be left untreated with – G at £360	F at £560	G + F at £920
20	250	1,500	0.42	0.27	0.16
40	63	380	0.11	0.068	0.041
60	28	170	0.047	0.03	0.018
80	15	90	0.025	0.016	0.01
100	10	60	0.017	0.011	0.007

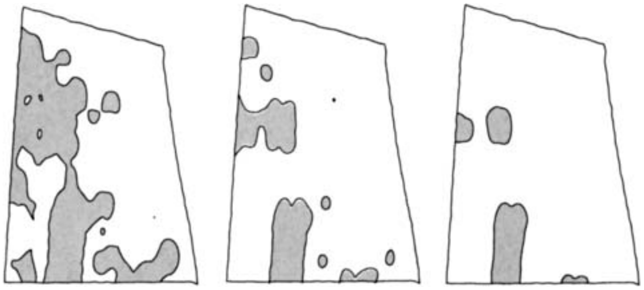

FIG. 3. Areas of the 8-ha field at Ram Farm where the pre-cropping density of PCN exceeded 5 (left), 10 (center), or 20 (right) eggs g^{-1} soil.

rial to discrete patches; the more squared-off these are, the more manageable the application. This was the approach we adopted in the field shown in Figure 6, where the pre-planting population at densities likely to cause any effect on the crop was largely confined to the northeast quarter of the field. This area (delineated in Fig. 6) was treated with 1,3-dichloropropene in the autumn before planting, and the whole field was treated with oxamyl immediately before planting. The post-harvest map shows that the population density reached in the more heavily infested but fumigated area was no greater than in the rest of the field, and that spatial application of the fumigant was successful in minimizing long-term problems. However, there was an area of large density after harvest that was not indicated in the pre-planting map, providing another example of a patch missed even at a 20-m sampling interval.

There is no correlation between the PCN density before planting and yield in a field treated with nematicide, but a field that we sampled and that was not treated with nematicide provided an opportunity to map yield and pre-planting density (Fig. 7). Immediately, a visual inverse correlation between the two is obvious. However, the Pearson correlation coefficient, *r*, was only 0.336, with a regression coefficient of yield on density of -0.09 kg of tubers per plant for every increase in PCN density of 20 eggs g^{-1} soil. The weak correlation is almost certainly due to inaccurate relocation of the sampling stations using backpack GPS apparatus. Although a differential signal receiver was used for the pre-planting sample positions, and the deliberate down-grading of the GPS signal known as Selective Availability was switched off before harvest, the positions could not be re-located with an accuracy of closer than 1 to 2 m.

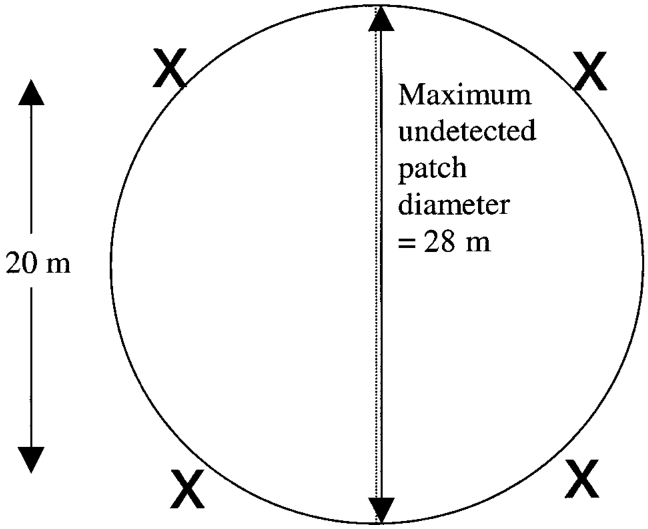

FIG. 4. Illustration of the maximum diameter of a patch that might be missed by sampling on a regular, square grid with 20 m between sample stations.

An unexpected relationship between PCN populations before planting and after harvest was found in a field we sampled on black organic soil (Fig. 8). From

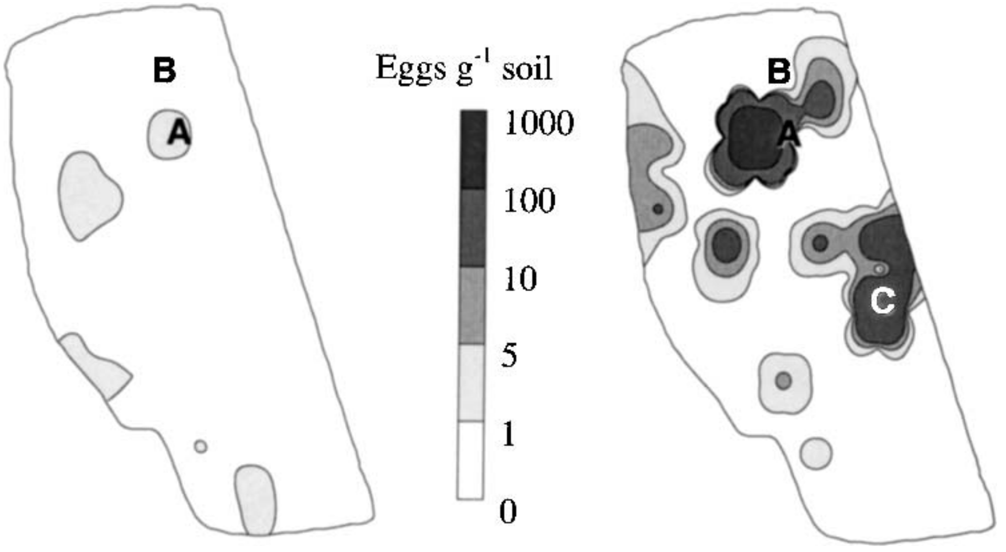

FIG. 5. Interpolated maps of the pre-cropping (left) and post-harvest (right) PCN density in a 6-ha field at the Scott Abbott Arable Crops Station, Sacrewell, Cambridgeshire, England. Points A, B, and C are referred to in the text.

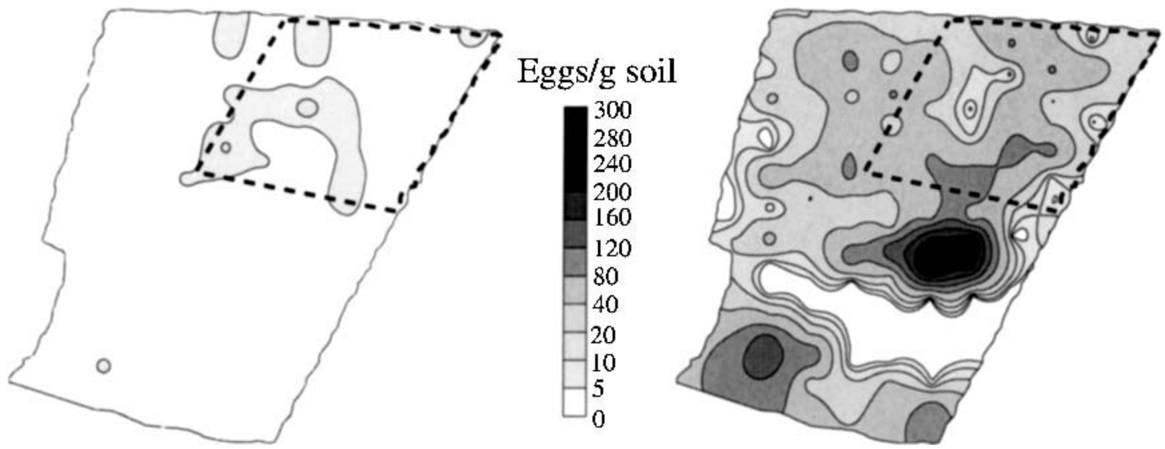

FIG. 6. Interpolated maps of the pre-cropping (left) and post-harvest (right) PCN density in a 10.5-ha field at Loveden Estates, Dawsmere, Lincolnshire, England. The fumigated area is marked by the dotted line.

the average PCN density before cropping of 29 eggs g^{-1} soil, we expected a very large increase. However, the average post-harvest density was unchanged at 29 eggs g^{-1} soil. Soil samples taken from areas where the population density seemed actually to have declined were assayed for the presence of natural control organisms for PCN, and the nematophagous fungus *Verticillium chlamydosporium* was detected. Thus, the serendipitous finding of this isolate (due to the spatial information on PCN distribution that our mapping generated) has provided a potentially useful agent for PCN control.

CONCLUSIONS

The high cost of nematicides relative to other potentially variable inputs for potato production, and the fact that some growers use two types of nematicide on a single crop, combine to make powerful economic and environmental arguments for a proper assessment of site-specific application of nematicides to be made. The high costs involved mean that the potential savings are large. This, in turn, means that sufficiently intense sampling to make reliable maps is economically viable.

Geostatistical analysis and visual appraisal of maps generated at a variety of sampling scales indicate that sampling at spacing of no more than 40 m is essential, and at 20 m is desirable. Even with 20-m spacing, however, one might fail to detect PCN patches, and we have examples of this. In the worst-case scenario, the whole infestation in a field would consist of patches that were all discrete and all lay between sample positions. However, cyst nematode infestations do not build up in this way. They begin with a primary focus, which spreads into smaller, secondary foci. At the same time, the primary focus becomes larger and elongated in the direction of cultivation (Jones, 1980). Thus, it would be unusual to miss many foci with 20-m sampling, and, even if a missed focus were of a heavy infestation, the overall yield penalty for the field would be small.

Greater positional accuracy from GPS, now that Selective Availability is switched off, makes small spot applications rather than large block applications of nematicides a possibility. Economic and environmental benefits would be greater with spot than with block applications because less nematicide would be used. The full potential of GPS-controlled nematicide appli-

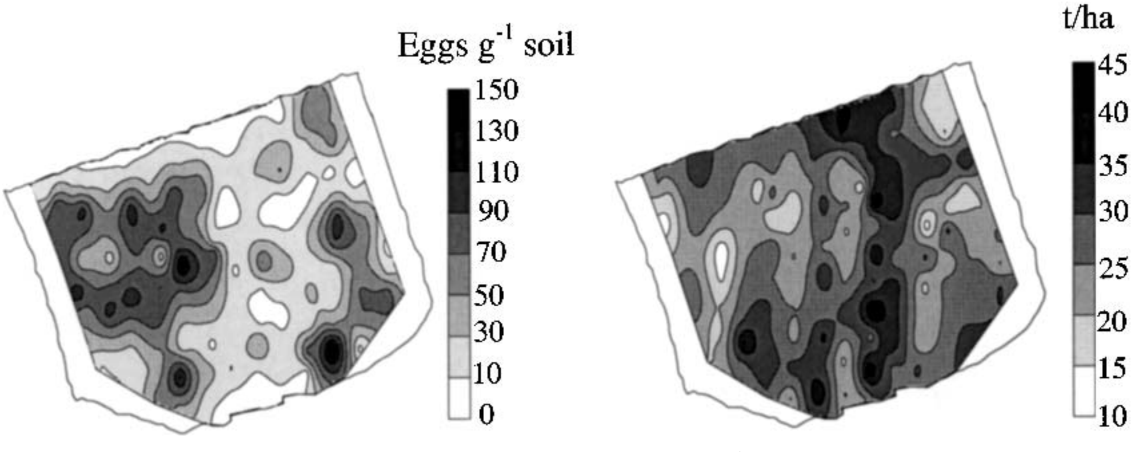

FIG. 7. Interpolated maps of pre-cropping PCN density (left) and yield (right) in a 7-ha field at the Scott Abbott Arable Crops Station, Sacrewell, Cambridgeshire, England.

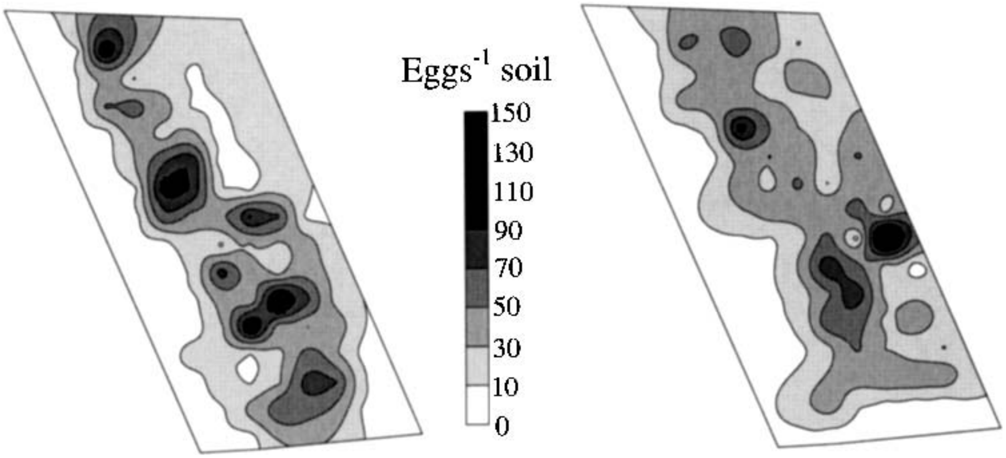

FIG. 8. Interpolated maps of the pre-cropping (left) and post-harvest (right) PCN density in a 7.5-ha field at Lane Farm, Ely, Cambridgeshire, England.

cation has yet to be explored as we have not yet had a full season in the absence of Selective Availability.

Failure to detect latent PCN infestations that are less than the detection threshold at the time of sampling is inevitable. Such infestations would cause no yield loss but, with potential multiplication rates in excess of 100-fold, could cause future management problems. The best current advice in terms of site-specific application of nematicides is to treat ''hot spots'' of infestation with the more expensive fumigants and treat the whole field with a granular nematicide to prevent excessive multiplication of the nematode.

As growers accumulate information on the dynamics of populations within individual fields, they will almost certainly come to realize that individual populations behave very differently from one another. Eventually, they will be able to fit field-specific parameters to models of PCN population dynamics that are under development (Elliott et al., 2000). With such information, it may be possible to generate a within-field distribution map at the end of a cropping cycle from that at the beginning of the cycle in the manner suggested by Yang et al. (2000). This would immediately halve the cost of map production and increase the economic viability of site-specific application of nematicide.

Whatever tactics are used, the overall strategy must be planned to fit one of two possible objectives: (i) to employ short-term tactical management simply to prevent yield loss in the current crop, or (ii) to aim for longer-term strategic management that will ensure that PCN populations remain static or even decline over the rotation (Parker, 1998). In making these decisions, it must be recognized that every field will have a unique pattern of PCN distribution, and that that population will behave in a unique manner when potatoes are grown. If site-specific treatments are to be employed, then information on PCN distribution and density must be collected at a scale appropriate to the decisions that might be made.

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