Field evaluation of the nematicide fluensulfone for control of the potato cyst nematode *Globodera pallida*

Patrick M Norshie, a* Ivan G Grove b and Matthew A Back b

Abstract

**BACKGROUND:** Three field experiments evaluated the performance of the nematicide fluensulfone against the potato cyst nematode *Globodera pallida* in Shropshire, England.

**RESULTS:** Experiments 1 and 2 showed reduced root infection and lowered multiplication of *G. pallida* following fluensulfone (Nimitz 15G®) soil treatments at five rates (1.95, 3.00, 4.05 (full rate), 5.05 and 6.00 kg AI ha⁻¹) and Nimitz 480EC® at the full rate. Experiment 3 demonstrated a positive interaction between the full rate of Nimitz 15G and the potato variety Santé in the reduction of *G. pallida*. The fluensulfone treatments at the full rate had more consistent effects than the lower rates, and there were no greater effects for the treatments higher than this full rate. Generally, fluensulfone was less efficacious than oxamyl or fosthiazate, which suggests that the treatment may not be reliably integrated within shorter potato rotations.

**CONCLUSION:** The data suggest that fluensulfone soil application could make a useful addition to the few available nematicide treatments for the control of *G. pallida* rather than be a substitute for these treatments.

© 2016 The Authors. *Pest Management Science* published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.

**Keywords:** fluensulfone; fosthiazate, nematicide; *Globodera pallida*; oxamyl

1 INTRODUCTION

The potato cyst nematodes (PCNs) *Globodera rostochiensis* (Wollenweber) Skarbilovich and *G. pallida* (Stone) Behrens are the most economically important and well-studied species within the genus *Globodera*. They are primarily root parasites, the activities of which cause reductions in both the yield and quality of the potato crop (*Solanum tuberosum* L.). The PCNs are reported to cause yield losses ranging from 10 to 12% worldwide,1,2 and 9% in Europe.3 Annual losses in the UK production system are estimated at £26 million.4 Both PCN species are well established within the main potato-growing areas of the United Kingdom,5 but *G. pallida* incidence has increased in England and Wales, where 67% of infestations were purely of this species.5

Control of PCNs in the United Kingdom is traditionally done following an integrated pest management strategy comprising crop rotation, the growing of resistant varieties and the application of nematicides. Nonetheless, the lack of cultivars with satisfactory resistance to *G. pallida* and the economic limitations associated with long rotations required for effective control of PCNs7 underpin the reliance on chemical control strategies for managing PCNs in the United Kingdom. Soil treatment with granular nematicides in the form of the organophosphate fosthiazate (as Nemathorin 10G; Syngenta Crop Protection Ltd, Cambridge, UK) and the carbamate oxamyl (as Vydate 10G; DuPont Crop Protection Ltd, Stevenage, UK) are widely practised for control of PCNs in the United Kingdom.8 However, human health issues, environmental concerns and changing EU legislation9 may restrict the future availability of these nematicides. Under such circumstances, the Agriculture and Horticulture Development Board Potatoes Division estimated a twofold increase in the cost of PCN management.10 In addition to the drawback of being inherently toxic, the increasing incidence of *G. pallida* in land receiving treatment of these nematicides suggests that they provide inadequate control of this species.11–13 Moreover, accelerated degradation has been suggested as a further reason for lack of nematicide efficacy.14,15 Rotational use of the different active ingredients within the nematicides has been proposed as a means of managing degradation and efficacy in the control of PCNs.16 Consequently, a greater number of active ingredients would be beneficial, and so the testing of new products as they become available is justifiable to improve PCN management.17
Fluensulfone [5-chloro-2-(3,4,4-trifluorobut-3-ene-1-sulfonyl)-1,3-thiazole], from ADAMA Agricultural Solutions Ltd (Airport City, Golan Street, Israel), is a molecule belonging to the fluoroalkenyl chemical group. Early studies have demonstrated the nematocidal activities of fluensulfone against the root-knot nematode (Meloidogyne species) on tomato (Solanum lycopersicum L.), on peppers (Capsicum annuum cv. Hazera 1195) and on Caenorhabditis elegans in vitro.

The experiments reported here were used to evaluate fluensulfone for efficacy in the control of G. pallida in UK potato production. The objectives were (i) to determine the effects of fluensulfone soil treatments on the infection of potato roots by G. pallida and the subsequent population development and (ii) to determine the control of G. pallida by integration of fluensulfone treatment with partially resistant potatoes. The central hypothesis tested was that fluensulfone possesses nematocidal activity to provide control of G. pallida, thus reducing population development and improving the growth and tuber yield of the potato crop.

2 MATERIALS AND METHODS

2.1 General methodology

2.1.1 Selection of experimental sites and general agronomy

The selection of sites for the experiments was based on the history of PCN infestations and the suitability of the sites as determined by PCN species composition and population density. Each site was sampled preliminarily following a 10 m² grid. Soil cores were extracted using a 2.5 by 30 cm 'cheesecorer'-style auger, following a W-shaped sampling pattern. Soil cultivations included subsoiling, ploughing to a depth of 30 cm, bed forming and destoning. The experimental plots measured 3.6 m wide and 6.0 m long in experiments 1 (2010) and 2 (2011), and 3.6 m wide and 9.0 m long in experiment 3 (2011). Each plot comprised four ridges (potato drills), the outer two of which were served as guards. The experiments utilised certified potato (Solanum tuberosum ssp. tuberosum) seed (Super Elite grade II graded to 35–45 mm) of cultivars Estima (susceptible) and Santé and Vales Everest (partially resistant) from Hazera (Sussex) Ltd (Doncaster, UK). The EC fluensulfone was surface applied using a 2 m Oxford Precision Sprayer and incorporated similarly to the granules. Percentage ground cover was determined by visual grid method.20 Plant biomass (fresh root and shoot weights) was determined at ca 4 and 6 weeks after planting by removing a pair of plants from the harvest rows at each assessment. A 2 g subsample of the entire root system was examined for G. pallida root infection following an acid fuchsin staining procedure.21 The root infection was expressed as number of G. pallida g⁻¹ root.

2.2 Experiment 1 (Woodcote, 2010)

Experiment 1 was conducted at Woodcote, ca 4 km south of Newport (UK Ordnance Survey Grid Reference: SJ 76901 15708). The soil was a sandy clay loam (1.8% organic matter, pH 6.6, 14.8% moisture content at 5 kPa). The P₁ ranged from 2.0 to 34.3 eggs g⁻¹ soil. The experiment studied fluensulfone treatments as Nimitz 15G at five rates (1.95, 3.00, 4.05, 5.05 and 6.00 kg AI ha⁻¹) and as Nimitz 480EC at a single rate of 4.05 kg Al ha⁻¹, in comparison with fosfathizate (as Nemathomirin 10G; Syngenta Crop Protection Ltd., Cambridge, UK) and oxamyl (as Vydate 10G; Du Pont Protection Ltd. Stevage, UK) treatments at 3.00 and 5.50 kg Al ha⁻¹ respectively, and a plot was left untreated. The treatments were applied on 19 May 2010, and were followed by tuber planting on 20 and 21 May 2010. Ground cover was measured starting at 25 days after planting (DAP), then at 7 day intervals until 53 DAP, by which time there was...
Control of potato cyst nematodes with the nematicide fluensulfone www.soci.org

### Table 1. Plant biomass (g) and number of *Globodera pallida* (g⁻¹ root) at 29 and 44 days after planting (DAP) and tuber yield (t ha⁻¹) of potato variety Estima at 149 DAP in soil treated with fluensulfone (as Nimitz 15G or Nimitz 480EC) in comparison with fosthiazate (as Nemathorin 10G), oxamyl (as Vydamec G) or soils left untreated at Woodcote in Shropshire, England, 2010

| Nematicide          | Rate (kg Al ha⁻¹) | 29 DAP | 44 DAP | 29 DAP | 44 DAP | 29 DAP | 44 DAP | Ware | Total |
|--------------------|-------------------|--------|--------|--------|--------|--------|--------|------|-------|
| Untreated          | –                 | 5.6 (258.5)a | 6.2 (602.8)a | 6.3a | 5.5a | 109.5a | 374.5a | 46.7a | 50.2a |
| Fluensulfone G     | 1.95              | 4.3 (688.8)b | 5.3 (277.5)ab | 6.3a | 5.5a | 110.2a | 368.8a | 49.1a | 52.7a |
| Fluensulfone G     | 3.00              | 4.4 (816.1)b | 4.3 (104.2)b | 9.1a | 5.5a | 94.0a | 438.0a | 41.0a | 44.3a |
| Fluensulfone G     | 4.05              | 4.1 (616.1)b | 4.1 (95.6)b | 6.7a | 4.9a | 97.4a | 446.3a | 51.2a | 54.5a |
| Fluensulfone G     | 5.05              | 4.6 (914.1)b | 4.2 (72.2)b | 8.3a | 4.4a | 91.0a | 422.5a | 50.9a | 54.6a |
| Fluensulfone G     | 6.00              | 4.6 (974.1)b | 4.2 (89.2)b | 6.4a | 4.4a | 94.1a | 379.1a | 36.3a | 39.3a |
| Fluensulfone EC    | 4.05              | 4.5 (797.5)b | 4.5 (157.5)b | 5.0a | 5.1a | 92.7a | 380.3a | 40.5a | 43.7a |
| Fosthiazate        | 3.00              | 4.5 (95.6)c | 4.3 (135.8)b | 6.5a | 6.3a | 93.1a | 430.8a | 45.4a | 48.9a |
| Oxamyl             | 5.50              | 4.1 (50.4)c | 3.8 (37.3)c | 4.4a | 4.7a | 81.1a | 375.9a | 52.2a | 57.2a |

*Experiment 1 at Woodcote in 2010. Back-transformed means are shown in parentheses. Means followed by the same letter (within individual columns) are not different according to Tukey’s post hoc test at *P* > 0.05.

### Table 2. Plant biomass (g) and number of *Globodera pallida* (g⁻¹ root) at 28 and 42 days after planting (DAP) and tuber yield of Estima potato (t ha⁻¹) at 138 DAP in soil treated with fluensulfone as Nimitz 15G or Nimitz 480EC in comparison with fosthiazate (as Nemathorin G), oxamyl (as Vydamec G) or soils left untreated at Howle in Shropshire, England, 2011

| Nematicide          | Rate (kg Al ha⁻¹) | 28 DAP | 42 DAP | 28 DAP | 42 DAP | 28 DAP | 42 DAP | Ware | Total |
|--------------------|-------------------|--------|--------|--------|--------|--------|--------|------|-------|
| Untreated          | –                 | 5.8 (358.3)a | 7.6 (1893.3)ab | 3.1a | 7.4a | 27.0a | 128.9a | 15.6a | 18.8a |
| Fluensulfone G     | 1.95              | 5.6 (283.3)a | 6.9 (1200.0)ab | 2.1a | 5.8a | 26.2a | 88.1a | 23.7a | 27.1a |
| Fluensulfone G     | 3.00              | 5.1 (116.7)abc | 6.9 (1106.7)ab | 2.1a | 8.7a | 21.1a | 105.6a | 27.2a | 30.7a |
| Fluensulfone G     | 4.05              | 5.0 (140.0)abc | 6.9 (1120.0)ab | 2.8a | 7.5a | 34.8a | 103.6a | 20.7a | 24.4a |
| Fluensulfone G     | 5.05              | 5.3 (183.3)abc | 6.7 (826.7)abc | 3.5a | 9.7a | 32.8a | 98.0a | 26.3a | 29.7a |
| Fluensulfone G     | 6.00              | 5.3 (206.7)abc | 6.0 (600.0)abc | 2.5a | 8.6a | 26.7a | 115.9a | 24.8a | 28.5a |
| Fluensulfone EC    | 4.05              | 4.1 (86.7)c | 5.9 (453.3)abc | 3.4a | 7.7a | 31.2a | 165.7a | 26.9a | 24.0a |
| Fosthiazate        | 3.00              | 4.3 (45.0)c | 5.6 (336.7)c | 3.7a | 7.4a | 35.6a | 91.1a | 32.1a | 35.2a |
| Oxamyl             | 5.50              | 4.0 (83.3)c | 5.6 (352)c | 4.3a | 6.7a | 27.9a | 137.3a | 30.6a | 33.4a |

*Experiment 1 at Woodcote in 2010. Back-transformed means are shown in parentheses. Means followed by the same letter within a column as per variety, nematicide and variety × nematicide interaction are not different according to Tukey’s post hoc test at *P* > 0.05.

100% ground cover. Plant biomass and PCN root infection were determined at 29 and 44 DAP. Tubers were harvested on 17 October 2010 (149 DAP). The soil temperature during the experiment averaged 16.6 °C (range 9.6–23.3 °C). Total precipitation received (rainfall + irrigation) amounted to 379mm, 29.8% of which was irrigated during May (8 mm), June (60 mm) and July (45 mm).

#### 3.2 Experiment 2 (Howle, 2011)

Experiment 2 was located at Howle ca 5.1 km north of Newport (UK Ordnance Survey Grid Reference: SJ 69485 23830). The soil was a sandy clay loam (2.2% organic matter, pH 5.6, 13.9% moisture content at 5 KPa). It was infested with *G. pallida* at 2.1–27.7 eggs g⁻¹ soil. The experiment studied the same treatments as detailed for experiment 1. The treatments were applied on 20 April 2011. Tubers were planted on 21 and 22 April 2011, and harvested on 7 September 2011 (138 DAP). Ground cover was measured at 21, 33, 40 and 56 DAP. Plant biomass and PCN root infection were determined at 28 and 42 DAP. Soil temperature ranged from 11.5 to 21.0 °C, with a mean at 15.3 °C. Total precipitation was 370.1 mm, 46.0% of which was irrigated during April (25 mm), May (80 mm), June (40 mm) and July (25 mm).

#### 3.4 Experiment 3 (Howle, 2011)

Experiment 3 was located in the same field as experiment 2 and therefore experienced similar soil and environmental conditions. The *P* range was from 6.2 to 14.6 eggs g⁻¹ soil. The treatments were applied on the same day as experiment 2. Each potato variety was planted on a third of the plot length (four rows each of 12 potatoes) on 22 April 2011. The nematicides and variety were allocated to the plots using separate randomisations. On 7 September 2011, 2 m of the harvest rows were lifted (138 DAP) and assessed for tuber yield.

### 3 RESULTS

#### 3.1 Experiments 1 (Woodcote, 2010) and 2 (Howle, 2011)

#### 3.1.1 Plant biomass and tuber yields

Ground cover (data not shown), plant biomass and tuber yield did not differ among the treatments (Tables 1 and 2).

#### 3.1.2 Root infection

The root infection in experiment 1 (Table 1) differed among the treatments at 29 DAP (*P* < 0.001) and at 44 DAP (*P* = 0.025). All fluensulfone treatments, except fluensulfone at 1.95 kg Al ha⁻¹,
had reduced infection at both sampling times when compared with the plot left untreated at 44 DAP. The oxamyl treatment had the greatest effect, and differed from fluensulfone at 5.05 and 6.00 kg Al ha\(^{-1}\) at 28 DAP, and 1.95 kg Al ha\(^{-1}\) at 44 DAP (\(P < 0.05\)). No differences were found between the fluensulfone and fosthiazate treatments. In experiment 2, reduced infection was given by fluensulfone at 6.00 kg Al ha\(^{-1}\) at 42 DAP, and by the EC fluensulfone treatment at both sampling times (\(P = 0.029\)), when compared with the plot left untreated (Table 2). The oxamyl treatment had greater effects than fluensulfone at 1.95, 5.05 and 6.00 kg Al ha\(^{-1}\) at 28 DAP and then at 1.95, 3.00 and 4.05 kg Al ha\(^{-1}\) at 42 DAP (\(P < 0.05\)). The fosthiazate treatment had greater effects than fluensulfone at 1.95 kg Al ha\(^{-1}\) at 28 DAP (\(P = 0.038\)), and at 1.95, 3.00 and 4.05 kg Al ha\(^{-1}\) at 42 DAP (\(P < 0.05\)).

### 3.1.3 Multiplication rate and final population density

Experiment 1 at Woodcote showed a lower \(P_i/P_r\) ratio (\(P < 0.001\)) and \(P_i/P_r\) (\(P = 0.006\)) only after the fluensulfone treatment at 5.05 kg Al ha\(^{-1}\) when compared with the plot left untreated (Table 3). Fluensulfone at 1.95 and 3.00 kg Al ha\(^{-1}\) gave a higher \(P_i/P_r\) ratio than either of the standard nematicide treatments (\(P < 0.05\)). The \(P_i/P_r\) ratio after the granular fluensulfone treatments was dosage dependent (\(r^2 = -0.761; P < 0.001\)). Except for the 5.05 kg Al ha\(^{-1}\) application, the fluensulfone treatments had lesser effects on the \(P_f\) than the oxamyl treatment (\(P < 0.05\)). The \(P_i\) did not differ among the fluensulfone and fosthiazate treatments. In experiment 2, the EC fluensulfone and the oxamyl treatments gave lower numbers of cysts (\(P = 0.009\)), lower \(P_i\) values (\(P = 0.003\)) and lower \(P_i/P_r\) ratios (\(P = 0.0013\)) when compared with the plot left untreated (Table 3). No other significant differences were found among the treatments.

### 3.2 Experiment 3 (Howle, 2011)

#### 3.2.1 Plant biomass and tuber yield

The fresh shoot weight was affected by the nematicide treatment at 28 DAP (\(P = 0.016\)) and at 42 DAP (\(P = 0.008\)) (Table 4). The fluensulfone treatment did not increase fresh shoot weight relative to the untreated plot at 28 DAP, but at 42 DAP fluensulfone had effects similar to oxamyl or fosthiazate. Only the oxamyl treatment gave greater fresh shoot weight than the plot left untreated at both sampling times. Santé had greater shoot weights than Vales Everest and Estima at 28 DAP (\(P = 0.015\)) and at 42 DAP (\(P = 0.027\)).

Integrating either Santé or Vales Everest with a nematicide treatment did not enhance the plant biomass. Both the ware and total yields were affected by the nematicide treatments (\(P = 0.002\)) and by variety (\(P = 0.004\)), but not by nematicide \(\times\) variety interaction. The fluensulfone treatment did not affect the yields when compared with the untreated plots and the two standard nematicide treatments.

#### 3.2.2 Root infection

Like the two standard nematicides, the fluensulfone treatment did not reduce root infection at 28 DAP but did at 42 DAP (\(P < 0.001\)). The varieties differed in root infection at 28 DAP but not at 42 DAP (\(P = 0.028\)); Vales Everest was infected more than Santé or Estima. The fluensulfone \(\times\) Santé or fluensulfone \(\times\) Vales Everest integration did not result in lower root infection than growing either variety in the plot left untreated. Oxamyl integration with both varieties reduced infection at 42 DAP (\(P < 0.001\)), while fosthiazate integration with Vales Everest lowered infection at 42 DAP (\(P < 0.05\)). The fluensulfone treatment reduced the infection of Estima when compared with the plot left untreated (\(P < 0.01\)), but significantly greater reductions were obtained from the oxamyl and fosthiazate treatments than from the fluensulfone treatment (\(P < 0.05\)).

#### 3.2.3 Multiplication rate and final population density

The \(P_i/P_r\) ratio and the \(P_f\) (Table 5) differed among the nematicide treatments (\(P < 0.001\)), the varieties (\(P < 0.001\)) and the variety \(\times\) nematicide integrations (\(P < 0.001\)). The fluensulfone treatment did not affect the \(P_i\) and \(P_i/P_r\) ratio when compared with the untreated plot. The treatment compared similarly with the fosthiazate treatment, but less so with the oxamyl treatment. Santé and Vales Everest lowered the \(P_f\) and \(P_i/P_f\) ratio in comparison with Estima. Integrating Santé with fluensulfone gave lower \(P_f\) than growing Santé untreated, and the effect was similar to integration with oxamyl. The \(P_f\) after Estima was lowered by the oxamyl treatment (\(P < 0.001\)). None of the nematicide treatments integrated with Vales Everest lowered the \(P_f\) and \(P_i/P_f\) ratio. The fluensulfone treatment did not lower the \(P_f\) and \(P_i/P_f\) ratio on Estima as did the oxamyl and fosthiazate treatments (\(P < 0.001\)).

---

**Table 3.** Initial population density (\(P_i\), in number of eggs g\(^{-1}\) soil), final population (\(P_f\), in number of eggs g\(^{-1}\) soil) and multiplication rate (\(P_i/P_f\), ratio) of *Globodera pallida* in soils treated with fluensulfone (as Nimitz 15G or as Nimitz 480EC) in comparison with fosthiazate (as Nemathorin G), oxamyl (as Vydate G) or a plot left untreated at Woodcote and Howle in Shropshire, England\(^{a}\)

| Treatment (kg Al ha\(^{-1}\)) | Woodcote | Howle |
|-----------------------------|----------|-------|
|                            | \(P_i\)  | \(\log_{10}(P_i)\) | \(\log_{10}(P_i/P_f + 1)\) | \(P_i\)  | \(\log_{10}(P_i)\) | \(\log_{10}(P_i/P_f + 1)\) |
| Untreated at 0.00           | 18.2a    | 4.5 (149.1)a        | 2.6 (9.2)b                  | 10.9a    | 4.9 (147.5)a        | 2.6 (14.2)b                  |
| Fluensulfone G at 1.95      | 17.6a    | 4.3 (137.2)a        | 2.1 (25.6)a                 | 11.9a    | 4.3 (85.2)ab        | 2.1 (8.8)ab                  |
| Fluensulfone G at 3.00      | 13.2a    | 4.5 (123.8)ab       | 2.2 (17.7)a                 | 7.7a     | 4.3 (88.1)a         | 2.2 (10.6)ab                 |
| Fluensulfone G at 4.05      | 16.0a    | 4.2 (92.4)ab        | 2.2 (5.2)bcd                | 9.1a     | 4.2 (71.5)a         | 2.2 (9.9)ab                  |
| Fluensulfone G at 5.05      | 15.6a    | 4.1 (60.6)bc        | 2.0 (3.5)cd                 | 9.2a     | 4.1 (75.5)a         | 2.0 (8.9)ab                  |
| Fluensulfone G at 6.00      | 18.2a    | 4.1 (128.2)ab       | 1.9 (5.7)bcdf               | 10.1a    | 4.1 (66.5)ab        | 2.0 (8.0)ab                  |
| Fluensulfone EC at 4.05     | 13.2a    | 3.6 (107.6)bc       | 1.5 (5.5)bc                 | 8.2a     | 3.6 (40.5)a         | 1.5 (5.5)a                   |
| Fosthiazate at 3.00         | 18.0a    | 3.5 (94.8)abc       | 1.4 (7.8)bc                 | 10.7a    | 4.2 (66.6)ab        | 2.1 (8.6)ab                  |
| Oxamyl at 5.50              | 16.2a    | 4.1 (30.5)c         | 2.1 (2.4)d                  | 8.2a     | 3.5 (38.3)a         | 1.4 (5.6)a                   |

\(^{a}\) Experiments 1 and 2, respectively, at Woodcote (2010) and Howle (2011). Back-transformed means are in parentheses. Means followed by the same letter within a column as per cultivar, nematicide and cultivar \(\times\) nematicide interaction are not different according to Tukey's post hoc test at \(P < 0.05\).
that population development can also be suppressed. Previous studies have shown that fluensulfone can inhibit nematode hatching and movement. Reducing the size of potential inoculum with respect to the number of J2 that infect a host crop is one, if not the main, principle underlying soil treatments with nematicides, the rationale being the direct relationship between the infection activities of the J2 and crop yield loss.\(^1\)\(^{2}\)\(^{\text{a}}\)\(^{\text{b}}\)\(^{\text{c}}\) If fluensulfone is able to reduce J2 hatching and movement, then it can reduce the inoculum load, and therefore its application could provide some protection to the potato from damage associated with root infection. Overall, fluensulfone treatments reduced the infection of Estima roots by about 43 and 44% in experiments 2 and 3 (Howle), corresponding to increases in ware yields of 61.5 and 57.7%, respectively. The infection of Santé in experiment 2 was reduced by 52.5%, and the ware yield was more than double that of the untreated Santé. There is, therefore, evidence to suggest that fluensulfone soil treatments can protect potato plants from *G. pallida* infection. The reasons for the lack of plant responses to the treatments in experiment 1 at Woodcote are not clear. Other studies\(^\text{13,30–32}\) have demonstrated that soil treatment with nematicides is not always accompanied with improved potato growth and yield parameters. The *P_.*\(^\text{33}\) soil pH\(^\text{34}\) and plant nutrition\(^\text{53,34}\) are some of the factors suggested to influence responses of potatoes to nematicide treatments. The field at Woodcote was infested by *G. pallida* at ca 16 eggs g\(^{-1}\) soil, which is well above the damage threshold suggested for this species in the United Kingdom.\(^\text{17}\) As damage was probable at this *P_.*\(^\text{3}\) the crop was expected to benefit from the reductions in the root infection by the nematicide treatments. However, this was not the case under the conditions at the Woodcote site in 2010. Perhaps, the yield responses at Howle in 2011 could be ascribed to the greater infection (1125.8 juveniles g\(^{-1}\) root) than had occurred at Woodcote (444.2 juveniles g\(^{-1}\) root). It was possible that Estima suffered greater damage at Howle and therefore was more likely to reflect the benefits of the nematicide treatment on the root infection.

Generally, the effects of fluensulfone were dose independent. However, the full-rate application in granular form appeared to be a more robust treatment than the lower rates of 1.95 and 3.00 kg Al ha\(^{-1}\). As no evidence was shown for greater efficacy at application rates higher than the full rate, the 3.05 and 6.00 kg Al ha\(^{-1}\) treatments cannot be justified. Overall, comparisons between full-rate treatment with fluensulfone and with the two currently commercially available nematicides for PCNs in the United Kingdom indicated that fluensulfone may give far less control than oxamyl and a somewhat parallel performance when compared with fosthiazate. UK potato production strongly relies upon the availability of nematicides where fields are known to be infested with PCNs.\(^\text{10}\) The uncertainty surrounding the future availabilities of oxamyl and fosthiazate, as per EU reviews regarding health and environment hazards associated with their usage,\(^\text{37}\) coupled with the fact that there are not yet alternative treatments to protect the potato from *G. pallida* damage, will increase demand for new treatments.

### Table 4. Plant biomass (g) and number of *G. pallida* (g\(^{-1}\) root) at 28 and 42 days of planting (DAP) and tuber yield of potatoes Estima, Santé and Vales Everest (t ha\(^{-1}\)) at 138 DAP in soil treated with fluensulfone (as Nimitz 15G) in comparison with fosthiazate (as Nemathorin G), oxamyl (as Vydate G) or soil left untreated at Howle in Shropshire, England, 2011\(^\text{a}\)

| Nematicide | Treatment | 28 DAP | 42 DAP | Root weight (g) | Shoot weight (g) | Yield (t ha\(^{-1}\)) |
|------------|-----------|--------|--------|----------------|-----------------|-------------------|
| **Untreated** |          |        |        |                |                 |                   |
| Fluensulfone G at 4.05 kg Al ha\(^{-1}\) |          |        |        |                |                 |                   |
| Fosthiazate at 3.0 kg Al ha\(^{-1}\) |          |        |        |                |                 |                   |
| Oxamyl at 5.5 kg Al ha\(^{-1}\) |          |        |        |                |                 |                   |
| **Variety** |          |        |        |                |                 |                   |
| Estima |          |        |        |                |                 |                   |
| Santé |          |        |        |                |                 |                   |
| Vales Everest |          |        |        |                |                 |                   |
| **Nematicide × variety interaction** |          |        |        |                |                 |                   |
| Untreated Estima |          |        |        |                |                 |                   |
| Fluensulfone G @ 4.05 kg Al ha\(^{-1}\) + Estima |          |        |        |                |                 |                   |
| Fosthiazate G @ 3.0 kg Al ha\(^{-1}\) + Estima |          |        |        |                |                 |                   |
| Oxamyl G @ 5.5 kg Al ha\(^{-1}\) + Estima |          |        |        |                |                 |                   |
| Untreated Santé |          |        |        |                |                 |                   |
| Fluensulfone G @ 4.05 kg Al ha\(^{-1}\) + Santé |          |        |        |                |                 |                   |
| Fosthiazate G @ 3.0 kg Al ha\(^{-1}\) + Santé |          |        |        |                |                 |                   |
| Oxamyl G @ 5.5 kg Al ha\(^{-1}\) + Santé |          |        |        |                |                 |                   |
| Untreated Vales Everest |          |        |        |                |                 |                   |
| Fluensulfone G @ 4.05 kg Al ha\(^{-1}\) + Vales Everest |          |        |        |                |                 |                   |
| Fosthiazate G @ 3.0 kg Al ha\(^{-1}\) + Vales Everest |          |        |        |                |                 |                   |
| Oxamyl G @ 5.5 kg Al ha\(^{-1}\) + Vales Everest |          |        |        |                |                 |                   |

\(^\text{a}\) Experiment 3 at Howle in 2011. Back-transformed means are in parentheses. Means followed by the same letters within a column as per variety, nematicide and variety × nematicide interaction are not different according to Tukey’s post hoc test at \(P < 0.05\).
Molecules. Even though the research into the nematicidal efficacy of fluensulfone relative to the control of PCNs is at its early stages, there is evidence in this study to suggest that soil treatment with fluensulfone for control of *G. pallida* may be feasible. Even if fosthiazate and oxamyl remain in use, the addition of fluensulfone to the list of nematicides for PCNs would provide growers with more options, and could perhaps help in curtailing the problem of accelerated degradation. However, at its current level of efficacy, fluensulfone may not be reliably integrated with short potato rotations (e.g., 1:4), as efficacy needs to be at approximately 80% for sustainable crop protection.7

Santé and Vales Everest gave good control of both *G. pallida* multiplication rate and final population density, and were found to have provided greater control than growing the susceptible Estima in a nematicide-treated soil. Nonetheless, there was evidence of enhanced control and improved plant biomass and tuber yields where either variety received a nematicide treatment. Santé, in particular, gave better control when combined with fluensulfone. Integration of non-fumigant and varietal resistance has long been a management option for *G. pallida* in the United Kingdom. Such integration is based on the principle that resistant varieties, like their susceptible counterparts, stimulate hatching of the J2 and thus must be protected from infection damage. The responses of their susceptible counterparts, stimulate hatching of the J2 and thus must be protected from infection damage. The responses of Santé, perhaps, could be related to Santé having a more extensive root system and thus making better use of available water and nutrients. Therefore, integration of fluensulfone with this variety is feasible and may be worth considering for long-term management of *G. pallida* populations. Even though Vales Everest has a higher resistance score of 6, as against 4 for Santé (http://potatoes.ahdb.org.uk/), and had more pronounced effects on population development, it did not respond to the fluensulfone treatment as well as the oxamyl and fosthiazate treatments.

The evidence shown here suggests fluensulfone soil application as a potential control option for *G. pallida*. The 3.0 kg Al ha⁻¹ treatment could be the minimum dosage for control of root infestation, but a higher rate may be required for a more robust effect. The incorporation of the 15% granular formulation at the full rate of 4.05 kg Al ha⁻¹ at 15–20 cm depth at planting could provide control of root infection and may lower population development. Nonetheless, at these dose rates, fluensulfone may not be a substitute for either oxamyl or fosthiazate treatment, which have given better control in this study. Additional studies are needed though, particularly in soils other than a sandy clay loam, to provide further evidence to substantiate these claims.

**ACKNOWLEDGEMENTS**

The authors would like to acknowledge the help provided by the staff at the Crop and Environment Research Centre at Harper Adams University, and Mr Matthew Rodenhurst, in particular, for locating field sites and applying nematicides during the field experiments. A special mention is made of Dr PPJ Haydock, who initiated the work reported in this paper but has since passed away. The first author was in receipt of a PhD studentship from ADAMA Agricultural Solutions Ltd, Airport City, Golan Street, Israel.

**REFERENCES**

1 Urwin PE, Troth KM, Zubko EI and Atkinson HJ, Effective transgenic resistance to *Globodera pallida* in potato field trials. *Mol Breed* 8:95–101 (2001).

---

| Treatment | $P_i$ | log$_e$ ($P_i$) | log$_e$ ($P_i/P_{i+1}$) |
|-----------|------|----------------|-------------------------|
| Untreated | 11.2a | 2.8 (40.3)a | 1.2 (3.7)a |
| Fluensulfone G at 4.05 kg Al ha⁻¹ | 12.2a | 2.6 (32.9)b | 1.0 (2.8)b |
| Fosthiazate at 3.0 kg Al ha⁻¹ | 12.9a | 3.1 (34.0)a | 1.1 (2.7)a |
| Oxamyl at 5.5 kg Al ha⁻¹ | 11.9a | 1.8 (7.7)a | 0.5 (0.7)a |
| Variety | | | |
| Estima | 12.1a | 4.3 (75.9)a | 2.1 (6.5)a |
| Santé | 12.1a | 1.6 (6.3)b | 0.4 (0.5)b |
| Vales Everest | 12.1a | 1.8 (3.9)c | 0.4 (0.4)b |
| Nematicide × variety interaction | | | |
| Estima untreated | 11.2a | 5.1 (109.9)a | 2.4 (10.1)a |
| Fluensulfone G at 4.05 kg Al ha⁻¹ + Estima | 11.9a | 4.6 (91.1)a | 2.1 (7.6)b |
| Fosthiazate at 3.0 kg Al ha⁻¹ + Estima | 12.9a | 4.9 (86.3)a | 2.0 (6.8)b |
| Oxamyl at 5.5 kg Al ha⁻¹ + Estima | 12.2a | 2.8 (16.5)b | 0.9 (1.4)c |
| Untreated Santé | 11.2a | 1.9 (6.7)c | 0.5 (0.6)cd |
| Fluensulfone G at 4.05 kg Al ha⁻¹ + Santé | 11.9a | 1.1 (4.5)cd | 0.2 (0.3)d |
| Fosthiazate at 3.0 kg Al ha⁻¹ + Santé | 12.9a | 2.5 (3.3)b | 0.7 (1.0)cd |
| Oxamyl at 5.5 kg Al ha⁻¹ + Santé | 12.2a | 0.9 (2.8)d | 0.2 (0.2)d |
| Vales Everest untreated | 11.2a | 1.4 (4.1)cd | 0.3 (0.4)cd |
| Fluensulfone G at 4.05 kg Al ha⁻¹ + Vales Everest | 11.9a | 2.1 (4.5)cd | 0.3 (0.4)cd |
| Fosthiazate at 3.0 kg Al ha⁻¹ + Vales Everest | 12.9a | 1.9 (3.3)cd | 0.2 (0.3)d |
| Oxamyl at 5.5 kg Al ha⁻¹ + Vales Everest | 12.2a | 1.7 (3.9)cd | 0.2 (0.3)d |

*Experiment 3, Howle 2011. Back-transformed means are in parentheses. Means followed by the same letter within a column as per variety, nematicide and variety × nematicide interaction are not different according to Tukey’s post hoc test at $P < 0.05$.*
Control of potato cyst nematodes with the nematicide fluensulfone

2 Bates JA, Taylor EJA, Gans PT and Thomas JE, Determination of relative proportions of Globodera species in mixed populations of potato cyst nematodes using PCR product melting peak analysis. Mol Plant Pathol 3:153–161 (2002).

3 Turner SJ and Rowe A, Cyst nematodes, in Plant Nematology, ed. by Perry RN and Moens M. CABI Publishing, Wallingford, Oxon, UK, pp. 91–122 (2006).

4 Twining S, Clarke J, Cook S, Ellis S, Gladders P, Ritchie F et al., Pesticide availability for potatoes following revision of Directive 91/414/EEC: impact assessments and identification of research priorities. Project Report 2009/2. (2009).

5 Gatwick M, Crop Pests in the UK. Collected Edition of MAFF Leaflets. Chapman and Hall, London, UK, 490 pp. (1992).

6 Minnis ST, Haydock PPJ, Ibrahim SK, Grove IG, Evans K and Russell MD, Potato cyst nematodes in England and Wales – occurrence and distribution. Ann Appl Biol 140:187 – 195 (2002).

7 Trudgill DL, Elliott MJ, Evans K and Phillips MS, The white potato cyst nematode (Globodera pallida) – a critical analysis of the threat in Britain. Ann Appl Biol 143:73 – 80 (2003).

8 Haydock PPJ, Woods SR, Grove IG and Hare MC, Chemical control of nematodes, in Plant Nematology, 2nd edition, ed. by Perry RN and Moens M. CABI, Wallingford, Oxon, UK, pp. 259 – 279 (2013).

9 Hillocks RJ, Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. Crop Prot 31:85 – 93 (2012).

10 Clayton R, Parker B, Ballingall M and Davies K, Impact of reduced pesticide availability on control of potato cyst nematodes and weeds in potato crops. Agriculture and Horticulture Development Board, Kenilworth, Warks, UK (2008).

11 Whitehead AG, Emergence of juvenile potato cyst-nematodes Globodera rostochiensis and Globodera pallida and the control of G. pallida. Ann Appl Biol 120:471 – 486 (1992).

12 Evans K, New approaches for potato cyst nematode management. Nematropica 23:221 – 231 (1993).

13 Whitehead AG, Nichols AJF and Senior JC, The control of potato pale cyst-nematode (Globodera pallida) by chemical and cultural methods in different soils. J Agric Sci 123:207 – 218 (1994).

14 Karpouzas DG, Giannakou IO, Walker A and Gown SR, Reduction in biological efficacy of ethoprophos in a soil from Greece due to enhanced biodegradation: comparing bioassay with laboratory incubation data. Pestic Sci 55:1089 – 1094 (1999).

15 Karpouzas DG and Walker A, Aspects of the enhanced biodegradation and metabolism of ethophosphos in soil. Pest Manag Sci 56:540 – 548 (2000).

16 Osborn RK, Edwards SG, Wilcox A and Haydock PPJ, Potential enhancement of degradation of the nematicides aldicarb, oxamyl and fosathiazate in UK agricultural soils through repeated applications. Pest Manag Sci 66:235 – 261 (2010).

17 Haydock PPJ, Woods SR, Grove IG and Hare MC, Chemical control of nematodes, in Plant Nematology, ed. by Perry RN and Moens M. CABI Publishing, Wallingford, Oxon, UK, pp. 393 – 431 (2006).

18 Oka Y, Shuker S and Tkachi N, Nematicidal efficacy of MCW-2, a new nematicide of the fluoroalkenyl group, against the root-knot nematode, Meloidogyne javanica. Pest Manag Sci 65:1082 – 1089 (2009).

19 Oka Y, Shuker S and Tkachi N, Systemic nematicidal activity of fluensulfone against the root-knot nematode Meloidogyne incognita on pepper. Pest Manag Sci 68:268 – 275 (2012).

20 Oka Y, Shuker S and Tkachi N, Influence of soil environments on nematicidal activity of fluensulfone against Meloidogyne javanica. Pest Manag Sci 69:1225 – 1234 (2013).

21 Kearn J, Ludlow E, Dillon J, O’Connor V and Holden-Dye L, Fluensulfone is a nematicide with a mode of action distinct from anticholinesterases and macrocyclic lactones. Pestic Biochem Physiol 109:44 – 57 (2014).

22 Fenwick DW, Methods for the recovery and counting of cysts of Heterodera schachtii from soil. J Helminthol 18:155 – 172 (1940).

23 Shepherd AM, Extraction and estimation of cyst nematodes, in Laboratory Methods for Work with Plant and Soil Nematodes. Ministry of Agriculture, Fisheries and Food, Reference Book No. 402, ed. by Southey JF. HMSO, London, UK, pp. 31 – 50 (1986).

24 The Analysis of Agricultural Materials, 3rd edition. Ministry of Agriculture, Fisheries and Food (MAFF), Reference Book No. 427. HMSO, London, UK (1986).

25 Woods SR and Haydock PPJ, The effect of granular nematicide incorporation depth and potato planting depth on potatoes grown in land infested with the potato cyst nematodes Globodera rostochiensis and G. pallida. Ann Appl Biol 136:27 – 33 (2000).

26 Burstall L and Harris PM, The estimation of percentage light interception from leaf area index and percentage ground cover in potatoes. J Agric Sci 100:241 – 244 (1983).

27 Hooper DJ, Extraction of free-living stages from soil, in Laboratory Methods for Work with Plant and Soil Nematodes, Ministry of Agriculture, Fisheries and Food, Reference Book No. 402, ed. by Southey JF. HMSO, London, UK, pp. 5 – 30 (1986).

28 Elston DA, Phillips MS and Trudgill DL, The relationship between initial population density of potato cyst nematode Globodera pallida and the yield of partially resistant potatoes. Rev Nématol 14:213 – 219 (1991).

29 Whitehead AG and Turner SJ, Plant Nematode Control. CABI Publishing, Wallingford, Oxon, UK, 383 pp. (1998).

30 Whitehead AG, Tite DJ, Fraser JE and Nichols AJF, Differential control of potato cyst nematodes, Globodera rostochiensis and G. pallida, by oxamyl and the yields of resistant and susceptible potatoes in treated and untreated soils. Ann Appl Biol 105:231 – 244 (1984).

31 Whitehead AG, Nichols AJF and Senior JC, Control of potato pale cyst-nematode, Globodera pallida, with a granular nematicide and partially resistant potatoes. Ann Appl Biol 118:623 – 636 (1991).

32 Evans K, Webster R, Barker A, Halford P, Russell M, Stafford J et al., Mapping infestations of potato cyst nematodes and the potential for spatially varying application of nematicides. Precis Agric 4:149 – 162 (2003).

33 Trudgill DL, Yield losses caused by potato cyst nematodes: a review of the current position in Britain and prospects for improvements. Ann Appl Biol 108:181 – 198 (1986).

34 Haverkort AJ, Mulder A and Van De Waart M, The effect of soil pH on yield losses caused by the potato cyst nematode Globodera pallida. Potato Res 36:219 – 226 (1993).

35 Grove IG, Haydock PPJ, Evans K and Lewis DJ, Supplementary foliar N, P and K, applied individually or in combinations, and the tolerance of potatoes to infection by the potato cyst nematodes Globodera rostochiensis and G. pallida. Ann Appl Biol 134:193 – 204 (1999).

36 Grove IG, Haydock PPJ, Evans K and Lewis DJ, Basal fertiliser application method, tuber initiation nitrogen, foliar NPK and the tolerance of potatoes to infection by the potato cyst nematodes Globodera rostochiensis and Globodera pallida. Ann Appl Biol 134:205 – 214 (1999).

37 EC Regulation No. 1107/2009 Concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC. OJ 52:1 – 50 (2009).