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

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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.

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.[6]

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 PCNs[7] 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 legislation[9] 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]

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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 nematicidal activities of fluensulfone against the root-knot nematode (*Meloidogyne* species) on tomato (*Solanum lycopersicum* L.),[18,19] on peppers (*Capsicum annuum* cv. Hazera 1195)[20] and on *Caenorhabditis elegans in vitro*.[21]

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 nematicidal 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 m^2 grid. Soil cores were extracted using a 2.5 by 30 cm 'cheese corer'-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 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 Greenvale GP (Telford, UK). The tubers were sprouted for 3 weeks in plastic trays under natural lighting. Planting was done manually to 10–15 cm depth using a hand-held potato planter and at 25 cm within-row spacing. Progeny tubers were harvested after the plants had senesced naturally, which involved mechanical lifting followed by hand forking of the plots to collect all potatoes. The yield was expressed in tonnes per hectare (t ha^{-1}). Soil temperature was recorded at 15 cm depth using a pair of Tinytag Plus 2 temperature data loggers (Gemini Data Loggers, Chichester, UK) positioned at 50 m apart. Rainfall records were taken at Harper Adams University, Newport, Shropshire, approximately 6.0 km from the experiments. The growers managed the crops according to commercial practice.

2.1.2 *PCN population densities and soil properties*

The population densities of PCNs were first determined prior to application of nematicides and planting of tubers (P_i) and then again 24 h after harvest (P_f). Soil samples for P_i and P_f determination (ca 2.5 kg) consisted of 50 cores (2.5 cm diameter × 20 cm deep) taken from each plot, placed in a secured cotton bag and transferred to a drying cabinet at 25 °C for at least 7 days. Cysts were extracted from a 200 g subsample using the Fenwick can,[22] and egg/juvenile counts followed procedures described by Shepherd.[23] The multiplication rates of *G. pallida* during the experiments were expressed as the P_f/P_i ratio. The soils were analysed for texture, pH and organic matter contents as per the procedures outlined in MAFF.[24] Soil moisture [field capacity (FC)] was determined using a model 1600 Pressure Plate Extractor (ELE International, Leighton Buzzard, UK).

2.1.3 *Experimental design and analysis*

Experiments 1 and 2 were randomised complete block designs, the model for which is given as $y_{ij} = \mu + \alpha_i + \beta_j + e_{ij}$, where y_{ij} is the observed value for block j of treatment i, μ is the population mean, α_i is the effect of treatment i, β_j is the effect of block j and e_{ij} is the experimental error resulting from block j of treatment i. Experiment 3 was a split-plot design, with nematicide treatments as whole plots and potato varieties as subplots. It is modelled by $y_{ijk} = \mu + \alpha_i + \beta_j + \delta_k + e_{ijk}$, where y_{ijk} is the observed value from row j and column k receiving treatment i, μ is the overall mean, α_i is the effect of treatment i, β_j is the effect of row j, δ_k is the effect of row k and e_{ijk} is the random error component for row j and column k receiving treatment i. The treatments were replicated 5 times. Blocking was informed by the P_i, and was formed by grouping plots with similar P_i, and the treatments were assigned to these plots randomly. The blocking effect was checked with analysis of variance (ANOVA) in GenStat for Windows® v15 (VSN International Ltd, Hemel Hempstead, UK), where the P_i was entered as treatments and replications as blocks; treatment arrangements were accepted only at $P > 0.05$. All plant growth and tuber yield data were checked for normality before ANOVA in GenStat. All nematode counts were transformed to $\log_e(x)$ or $\log_e(x + 1)$ to establish normality before ANOVA. Means were compared using Tukey's test.

2.1.4 *Application of nematicides and plant measurements*

All granular nematicides were metered onto preformed beds using a calibrated Rickshaw-type granule applicator, and incorporated into the topmost 20 cm depth[25] by a tractor-mounted spike rotavator (Jones Engineering, 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 the grid method.[26] 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.[27] 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 P_i 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 AI ha^{-1}, in comparison with fosthiazate (as Nemathorin 10G; Syngenta Crop Protection Ltd., Cambridge, UK) and oxamyl (as Vydate 10G; Du Pont Protection Ltd. Stevenage, UK) treatments at 3.00 and 5.50 kg AI 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[26] starting at 25 days after planting (DAP), then at 7 day intervals until 53 DAP, by which time there was

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 Vydate 10G) or soils left untreated at Woodcote in Shropshire, England, 2010[a]

		Juveniles (g^{-1} root)		Root weights (g)		Shoot weights (g)		Tuber yield (t ha^{-1})	
Nematicide	Rate (kg AI ha^{-1})	29 DAP	44 DAP	29 DAP	44 DAP	29 DAP	44DAP	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 (68.8)bc	5.3 (277.5)ab	6.3a	5.5a	110.2a	368.8a	49.1a	52.7a
Fluensulfone G	3.00	4.4 (81.6)bc	4.3 (104.2)bc	9.1a	5.5a	94.0a	438.0a	41.0a	44.3a
Fluensulfone G	4.05	4.1 (61.6)bc	4.1 (95.6)bc	6.7a	4.9a	97.4a	446.3a	51.2a	54.5a
Fluensulfone G	5.05	4.6 (91.4)b	4.2 (72.2)bc	8.3a	4.4a	91.0a	422.5a	50.9a	54.6a
Fluensulfone G	6.00	4.6 (97.4)b	4.2 (89.2)bc	6.4a	4.0a	94.1a	379.1a	36.3a	39.3a
Fluensulfone EC	4.05	4.5 (79.7)bc	4.5 (157.5)bc	5.0a	5.1a	92.7a	380.3a	40.5a	43.7a
Fosthiazate	3.00	4.5 (95.6)c	4.3 (135.8)bc	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	379.5a	52.2a	57.2a

[a] 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 Vydate G) or soils left untreated at Howle in Shropshire, England, 2011[a]

		Juveniles (g^{-1} root)		Root weight (g)		Shoot weight (g)		Tuber yield (t ha^{-1})	
Nematicide	Rate (kg AI ha^{-1})	28 DAP	42 DAP	28 DAP	42 DAP	28DAP	42 DAP	Ware	Total
Untreated	–	5.8 (358.3)a	7.6 (1893.3)a	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 (156.7)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)ab	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)ab	6.0 (600.0)bc	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)bc	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

[a] 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 379 mm, 29.8% of which was irrigated during May (8 mm), June (60 mm) and July (45 mm).

2.3 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).

2.4 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_i ranged 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 was 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 AI ha^{-1},

Table 3. Initial population density (P_i in number of eggs g^{-1} soil), final population (P_f in number of eggs g^{-1}) and multiplication rate (P_f/P_i 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]

	Woodcote			Howle		
Treatment (kg AI ha^{-1})	*Pi*	$\log_e(P_f)$	$\log_e(P_f/P_i+1)$	P_i	$\log_e(P_f)$	$\log_e(P_f/P_i+1)$
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)ab	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)ab	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)ab	2.0 (8.9)ab
Fluensulfone G at 6.00	18.2a	4.1 (128.2)ab	1.9 (5.7)bcd	10.1a	4.1 (66.5)ab	2.0 (8.0)ab
Fluensulfone EC at 4.05	13.2a	3.6 (107.6)ab	1.5 (5.5)bcd	8.2a	3.6 (40.5)a	1.5 (5.5)a
Fosthiazate at 3.00	18.0a	3.5 (94.8)ab	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 × nematicide interaction are not different according to Tukey's post hoc test at $P < 0.05$.

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 AI ha^{-1} at 28 DAP, and 1.95 kg AI 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 AI 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 AI ha^{-1} at 28 DAP, and then at 1.95, 3.00 and 4.05 kg AI ha^{-1} at 42 DAP ($P < 0.05$). The fosthiazate treatment had greater effects than fluensulfone at 1.95 kg AI ha^{-1} at 28 DAP ($P = 0.038$), and at 1.95, 3.00 and 4.05 kg AI 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_f/P_i ratio ($P < 0.001$) and P_f ($P = 0.006$) only after the fluensulfone treatment at 5.05 kg AI ha^{-1} when compared with the plot left untreated (Table 3). Fluensulfone at 1.95 and 3.00 kg AI ha^{-1} gave a higher P_f/P_i ratio than either of the standard nematicide treatments ($P < 0.05$). The P_f/P_i ratio after the granular fluensulfone treatments was dosage dependent ($r^2 = -0.761$; $P < 0.001$). Except for the 5.05 kg AI ha^{-1} application, the fluensulfone treatments had lesser effects on the P_f than the oxamyl treatment ($P < 0.05$). The P_f 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_f values ($P = 0.003$) and lower P_f/P_i 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 × 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 × Santé or fluensulfone × 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 effects 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_f/P_i ratio and the P_f (Table 5) differed among the nematicide treatments ($P < 0.001$), the varieties ($P < 0.001$) and the variety × nematicide integrations ($P < 0.001$). The fluensulfone treatment did not affect the P_f and P_f/P_i 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_f/P_i 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_f/P_i ratio. The fluensulfone treatment did not lower the *Pf* and *Pf*/*Pi* ratio on Estima as did the oxamyl and fosthiazate treatments ($P < 0.001$).

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[a]

	$\log_e$ (juveniles g^{-1} root)		Root weight (g)		Shoot weight (g)		Yield ($t\ ha^{-1}$)	
Treatment	28 DAP	42 DAP	28 DAP	42DAP	28 DAP	42 DAP	Ware	Total
Nematicide								
Untreated	6.2 (523)a	6.9 (984)c	7.0a	7.8a	40.4a	81.9a	12.2a	13.2a
Fluensulfone G at 4.05 kg AI ha^{-1}	5.5 (256)b	6.4 (600)b	8.9a	10.9a	50.7ab	109.8b	16.4a	17.8b
Fosthiazate at 3.0 kg AI ha^{-1}	5.3 (227)b	6.1 (493)a	7.0a	11.6a	61.5ab	100.0 b	19.7a	20.6b
Oxamyl at 5.5 kg AI ha^{-1}	5.1 (189)b	6.0 (421)a	9.0a	7.8a	73.9c	167.2b	18.3a	19.4b
Variety								
Estima	5.7 (376)a	6.3 (628)a	7.3a	9.0ab	58.9b	122.7b	13.2a	14.3a
Santé	5.4 (268)a	6.5 (686)b	9.1a	12.3b	71.1b	134.3b	16.0a	17.0a
Vales Everest	5.4 (252)a	6.3 (560)a	7.6a	7.3a	39.9a	87.2a	20.7b	21.7b
Nematicide × variety interaction								
Untreated Estima	6.6 (712)a	7.1 (1224) f	7.7a	6.3a	38.4a	82.0a	7.5a	8.0a
Fluensulfone G @ 4.05 kg AI ha^{-1} + Estima	5.8 (320)a	6.4 (584)cd	4.4a	11.5a	47.3a	120.3a	11.9a	13.3a
Fosthiazate G @ 3.0 kg AI ha^{-1} + Estima	5.5 (288)a	5.7 (344)a	7.1a	9.3a	73.8a	101.9a	15.1a	16.3a
Oxamyl G @ 5.5 kg AI ha^{-1} + Estima	5.1 (184)a	5.9 (360)ab	9.9a	8.7a	76.2a	186.5a	18.5a	19.5a
Untreated Santé	6.2 (472)a	6.8 (912)ef	5.7a	9.9a	50.1a	93.4a	9.0a	10.3a
Fluensulfone G @ 4.05 kg AI ha^{-1} + Santé	5.3 (224)a	6.5 (680) cde	8.3a	13.3a	60.5a	120.8a	18.4a	19.2a
Fosthiazate G @ 3.0 kg AI ha^{-1} + Santé	5.1 (160)a	6.4 (624) cde	12.9a	17.7a	77.2a	115.7a	23.0a	23.7a
Oxamyl G @ 5.5 kg AI ha^{-1} + Santé	5.2 (216)a	6.3 (528)bc	9.4a	8.2a	96.5a	207.2a	13.6a	14.7a
Untreated Vales Everest	6.0 (384)a	6.7 (816) def	7.7a	7.2a	32.6a	70.2a	20.2a	21.2a
Fluensulfone G @ 4.05 kg AI ha^{-1} + Santé	5.4 (224)a	6.3 (536)bcd	8.3a	7.9a	44.4a	88.2a	18.8a	19.9a
Fosthiazate G @ 3.0 kg AI ha^{-1} + Santé	5.3 (232)a	6.2 (512)bc	6.8a	7.7a	33.4a	82.4a	20.9a	21.8a
Oxamyl G @ 5.5 kg AI ha^{-1} + Santé	4.9 (168)a	5.9 (376)ab	7.5a	6.5a	49.1a	108.0a	22.7a	23.9a

[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 $P < 0.05$.

4 DISCUSSION

In general, the results from these studies show that fluensulfone soil treatments applied at planting can reduce the infection of potato roots by *G. pallida*, at least during the first 44 DAP, and that population development can also be suppressed. Previous *in vitro* experiments[18–21] have indicated 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.[28,29] 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[13,30–32] have demonstrated that soil treatment with nematicides is not always accompanied with improved potato growth and yield parameters. The P_i,[33] soil pH[34] and plant nutrition[35,36] 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.[17] As damage was probable at this P_i, 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 AI ha^{-1}. As no evidence was shown for greater efficacy at application rates higher than the full rate, the 5.05 and 6.00 kg AI 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.[10] The uncertainty surrounding the future availabilities of oxamyl and fosthiazate, as per EU reviews regarding health and environment hazards associated with their usage,[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

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Table 5. Increase of *G. pallida* on potato varieties Estima, Santé and Vales Everest grown in soil treated with fluensulfone as Nimitz 15G or Nimitz 480EC in comparison with fosthiazate (as Nemathorin G), oxamyl (as Vydate G) or soil left untreated at Howle, 2011.[a] Untransformed data are in parentheses

Treatment	P_i	$\log_e (P_f)$	$\log_e (P_f/P_i + 1)$
Nematicide			
Untreated	11.2a	2.8 (40.3)a	1.2 (3.7)a
Fluensulfone G at 4.05 kg AI ha^{-1}	12.2a	2.6 (32.9)b	1.0 (2.8)b
Fosthiazate at 3.0 kg AI ha^{-1}	12.9a	3.1 (34.0)a	1.1 (2.7)a
Oxamyl at 5.5 kg AI 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 AI ha^{-1} + Estima	11.9a	4.6 (91.1)a	2.1 (7.6)b
Fosthiazate at 3.0 kg AI ha^{-1} + Estima	12.9a	4.9 (86.3)a	2.0 (6.8)b
Oxamyl at 5.5 kg AI 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 AI ha^{-1} + Santé	11.9a	1.1 (4.5)cd	0.2 (0.3)d
Fosthiazate at 3.0 kg AI ha^{-1} + Santé	12.9a	2.5 (3.3)b	0.7 (1.0)cd
Oxamyl at 5.5 kg AI 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 AI ha^{-1} + Vales Everest	11.9a	2.1 (4.5)cd	0.3 (0.4)cd
Fosthiazate at 3.0 kg AI ha^{-1} + Vales Everest	12.9a	1.9 (3.3)cd	0.2 (0.3)d
Oxamyl at 5.5 kg AI ha^{-1} + Vales Everest	12.2a	1.7 (3.9)cd	0.2 (0.3)d

[a] 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 $P < 0.05$.

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 curbing 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 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 AI ha^{-1} treatment could be the minimum dosage for control of root infection, 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 AI 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.

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