Multi-Year Field Evaluation of Fluorinated Nematicides Against *Meloidogyne incognita* in Carrots

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Abstract

California grows approximately 80% of the U.S. carrot production. The primary production challenges derive from root-knot nematodes (*Meloidogyne* spp.). Between 2013 and 2016, we evaluated three novel fluorinated nonfumigant nematicides in five field trials. Fluensulfone, fluopyram, and fluzaindolizine were applied as product-ready formulations at various rates, dates, and formulations. They were rated for their efficacy against the Southern root-knot nematode (*M. incognita*), their ability to mitigate nematode-caused crop damage, and potential to produce marketable carrot yield under high disease pressure. All trials were conducted in randomized complete block designs in *M. incognita*-infested, sandy-loam fields. Soil population of *M. incognita* at seeding and harvest, midseason plant vigor and fibrous root galling, harvest taproot galling, and marketable carrot yield were analyzed by ANOVA.

Midseason gall ratings were indicative of disease ratings at harvest. All fluzaindolizine and fluensulfone treatments reduced at-harvest galling compared with the untreated controls. Fluopyram resulted in less galling but did not sufficiently protect the lower part of the taproot. Overall, fluzaindolizine at 2.24 kg/ha resulted in the most consistent and highest marketable carrot yield, followed by fluensulfone at 2.95 kg/ha. Both fluzaindolizine and fluensulfone will likely provide effective and target-selective crop protection against root-knot nematodes in fresh carrot production.

Keywords: nematodes, vegetables, disease management, chemical, root-knot nematodes, *Meloidogyne incognita*, fluensulfone, fluopyram, fluzaindolizine, carrot, nematicide

California fresh market carrots, valued at about \$600 million, are grown on about 25,000 ha, which represents approximately 80% of the U.S. acreage (USDA-NASS 2016). Root-knot nematodes (RKN; *Meloidogyne* spp.) are the primary cause of disease problems in California carrot production (Nunez et al. 2008, 2016). In 1999, the production loss was conservatively estimated at 5 to 8% despite the use of various soil fumigants (Koenning et al. 1999). In particular, the Southern RKN (*M. incognita*) and the Javanese RKN (*M. javanica*) are widespread throughout Central and Southern California. They are especially damaging in sandier soil types (Siddiqui et al. 1973), which are preferred for carrot production. As with other susceptible root and tuber crops, damage by RKN in carrot directly impacts the quality of the harvested product. Even low initial RKN levels can result in significant damage, and consequently, control strategies are recommended when RKN are detected from field soil samples where carrots are to be grown (Nunez et al. 2016). Symptoms in carrots include galling, bumpiness, and forking. Even moderate symptoms can render the carrots nonmarketable. Furthermore, distorted roots pick up excess soil that is transported to the processing carrot facilities. The additional cleaning effort further increases cost.

To mitigate RKN damage, crop rotation with nonhost crops is usually not sufficiently effective due to the broad host range, the large nematode reproduction potential, and the very low damage thresholds of carrot for RKN (Nunez et al. 2016). Although there is an ongoing long-term breeding effort aimed at developing RKN resistance

in carrot (Parsons et al. 2015), all current commercially available cultivars are susceptible to RKN. Another nonchemical management strategy in California was evaluated by Roberts (1987), who reported that delaying carrot seeding dates until the cooler periods when RKN activity is low provided substantial protection from RKN damage. This option, however, is not always feasible due to year-round market demands. Additionally, such management strategy bears the risk that extended rain periods leave fields too wet for the seeding equipment. Thus, management of RKN in California carrot production has typically relied on the use of broad-spectrum soil fumigants such as 1,3-dichloropropene, metam-sodium, or metam-potassium. In 2016, 38% of the California carrot acreage was treated with one of these chemicals, representing a total of 2.3 million kg fumigant applied (CDPR 2016). However, substantial portions of fields need to be excluded from fumigation because of buffer zone requirements (US EPA 2012) and township restrictions to reduce emissions of volatile organic compounds associated with fumigant use (Goodhue et al. 2016). Furthermore, the California Department of Pesticide Regulation indicated their intention to eliminate all fumigants eventually (CDPR 2013). Thus, there is an urgent need for effective, economically viable, and nonfumigant nematicides that can be used in carrot production.

Until recently, there was no effective nonfumigant nematicide registered for use in California fresh carrot production. Lately, fluensulfone (Nimitz) has received CalEPA registration for use on root and tuber crops including carrots. Two other contact nematicides are under development. Fluopyram (Velum One) has California registration for a multitude of crops, among them fruiting vegetables, strawberry, and tree nuts. Fluzaindolizine (Salibro) is expected to be registered in the United States soon. All of them are fluorinated compounds (Burriss et al. 2018; Kearn et al. 2014). One of the most intriguing attributes of these three novel nematicides, besides their efficacy against plant-parasitic nematodes, is their low acute toxicity to mammals and other nontarget organisms (EFSA 2011; Lahm et al. 2017; Oka et al. 2012; Thoden and Wiles 2019). Thus, compared with currently used fumigants, their use will not require extensive regulatory restrictions. Fluensulfone- and fluopyram-treated fields have a restricted-entry interval of 12 h, compared with at least 48 h for organophosphate or carbamate nematicides. In general, this group of fluorinated nematicides appears to be much safer for applicators,

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farm workers, and the general public than soil fumigants and previous generations of contact nematicides.

Fluensulfone had a rapid early impact on stylet thrusting and the motility of second-stage juveniles (J2) of *Globodera pallida*. It inhibited development, egg-laying, feeding, and locomotion (Kearn et al. 2014). Increasing tissue deterioration resulted ultimately in mortality (Kearn et al. 2017). The activity of fluensulfone and flua-zaindoline appeared specific to plant-parasitic nematodes, with little acute toxicity to other nematodes or microorganisms (Kearn et al. 2017; Lahm et al. 2017; Thoden and Wiles 2019). In comparison, fluopyram affected both plant-parasitic and free-living nematodes as well as certain fungi. It was initially developed as a potent fungicide that disrupts the citric acid cycle by inhibiting the succinate dehydrogenase at complex II of the fungi's respiratory chain (Avenot and Michailides 2010). All three nematicidal compounds have presumably novel modes of action compared with previous nematicides and work primarily by contact with the nematodes in soil pore water. With fluopyram, this inhibitory effect was reversible when *M. incognita* or *Rotylenchulus reniformis* was exposed to the compound for 1 h, then rinsed and kept for observation in distilled water (Faske and Hurd 2015). Both fluensulfone and flua-zaindoline had irreversible effects leading to death (Lahm et al. 2017; Oka 2014; Oka et al. 2009; Thoden and Wiles 2019). Fluensulfone was reported to have some systemic activity when applied as a foliar spray on pepper or tomato plants (Morris et al. 2015; Oka et al. 2012). Fluopyram exhibited some xylem mobility, which allowed acropetal transport after uptake by plant roots (Heiken 2017). Flua-zaindoline did not show systemic activity (Lahm et al. 2017).

There has been limited published field research on the efficacy of these products on RKN in vegetable crops in general, and in carrots in particular. The objectives of this project were to determine the potential for these novel nematicides to suppress the population density of the Southern RKN, reduce the nematode's disease-causing activity, and to increase the marketability of the fresh market carrots. In fields uniformly infested with the Southern RKN and under high disease pressure, the three nematicides were evaluated at various rates and application methods and compared with each other and a nontreated control.

Materials and Methods

Field preparations. Five field trials were performed from 2013 to 2016, with two trials in 2014 and one trial each in the other years. The trials were located in a field with a San Emigdio sandy loam soil (66% sand, 18% silt, 16% clay, 0.1% organic matter, pH 7.3) at the University of California South Coast Research and Extension Center (UC SCREC), Irvine, CA. The field had been infested 5 years previously with an egg suspension of a *M. incognita* race 3 population. It was isolated originally from a cotton root in the San Joaquin Valley, CA. The population was reared on tomatoes in a greenhouse, and the extracted eggs (Hussey and Barker 1973) were applied as a suspension through buried drip tubing (Becker et al. 1989). Several *M. incognita*-susceptible vegetable crops were grown in sequence during the spring/summer to increase and maintain an evenly distributed *M. incognita* infestation level before the carrot trials were initiated. Wheat (*Triticum aestivum*) 'Yecora Rojo' was grown every year during the winter.

Trial set-ups and treatments. In each year (2013–2016), the trials were conducted on different, but nearby areas of the field. Each May, 102-cm-wide (center to center) beds were prepared, and plots were laid out. Individual plots were 3-m-long sections of bed, separated along the beds by a 91-cm border section. The experiments were designed as randomized complete blocks with five replicates. In each year, treatments included an untreated control. The tested products were supplied each year by the manufacturers; the formulations remained the same during the years. The 2013 trial had six treatments: An untreated control, oxamyl (Vydate L, a.i. 24%, DuPont Crop Protection, Wilmington, DE) at 4.48 kg/ha, and flua-zaindoline (Salibro 500 SC, a.i. 50%, DuPont Crop Protection) treatments at 1.12, 2.24, and 4.48 kg/ha, as well as a split application at 1.12 kg/ha. All nematicides were applied in 3.8 liters of water and

watered evenly over the plot surface with a watering can. Additional 7.6 liters of water was applied over each plot, and all plots were tilled with a rototiller to a depth of 7 to 10 cm. The second application of flua-zaindoline was applied 21 days after carrot seeding similarly over the top of the newly germinated seedlings, but without tilling. In 2014, two trials were performed. Treatments in the first 2014 trial were an untreated control, metam sodium (Vapam HL; a.i. 42%, AMVAC Chemical Corporation, Los Angeles, CA) at 294 liters/ha, fluensulfone (Nimitz 480 EC; a.i. 48%, ADAMA Agricultural Solutions Ltd., Raleigh, NC) at 2.95 kg/ha and at 3.98 kg/ha, flua-zaindoline at 1.12 kg/ha and at 2.24 kg/ha, and fluopyram (Velum 400 SC; a.i. 40%, Bayer CropScience, Research Triangle Park, NC) at 256 g/ha. All treatments were applied as described before. Metam-sodium and fluensulfone were used 19 days before seeding to avoid potential phytotoxicity. The other treatments occurred 4 days before seeding. Treatments in the second 2014 trial included an untreated control, metam-sodium at 294 liters/ha 19 days before seeding, and flua-zaindoline at 1.12 kg/ha 4 days before seeding. There were three additional flua-zaindoline treatments. A split application was used at 1.12 kg/ha each, 4 days before and 21 days after seeding. Two different granular flua-zaindoline formulations (a.i. 5% flua-zaindoline formulated with (A) dolomite limestone pellets or (B) bentonite clay) each at 2.24 kg/ha were applied 4 days before seeding. The granular formulations were evenly distributed over the plots followed by rototilling and sprinkling 7.6 liters of water on top. Treatments in the 2015 trial included an untreated control, fluensulfone applications at 2.95 kg/ha and at 3.98 kg/ha 14 days before seeding, the liquid formulation of flua-zaindoline at 1.12 kg/ha and at 2.24 kg/ha 3 days before seeding, the granular bentonite formulation (B) of flua-zaindoline at 2.24 kg/ha 9 days before seeding, a split application of fluopyram at 256 g/ha each, 3 days before and 28 days after seeding, and a sequential treatment of fluensulfone at 2.95 kg/ha 14 days before seeding followed by fluopyram at 256 g/ha 28 days after seeding. The treatments were applied over the plots as described before. In 2016, there were six treatments; an untreated control, fluensulfone treatments at 2.95 kg/ha and at 3.98 kg/ha 14 days before seeding, the liquid formulation of flua-zaindoline at 2.24 kg/ha 3 days before seeding, the bentonite granular formulation (B) of flua-zaindoline at 2.24 kg/ha 9 days before seeding, and a split fluopyram application at 256 g/ha each 2 days before and 14 days after seeding. Treatments were applied over the plots as described before. Carrot (*Daucus carota* 'Imperator 58', Lockhart Seeds, Stockton, CA) were seeded with a hand-pushed seeder (JP-1, Jang, South Korea) using a carrot roller releasing approximately 0.6 g seed/plot in a single line over the center of the plots. Seeding dates were 6/26/2013, 6/9/2014 (both trial 1 and 2), 6/11/2015, and 6/8/2016. For weed control, linuron (Lorox DF; a.i. 50%, DuPont Crop Protection) and pendimethalin (ProwlH2O; a.i. 38.7%, BASF Corporation, Research Triangle Park, NC) were applied at 0.56 kg/ha and 1.08 kg/ha, respectively, 1 day after seeding. Mefenoxam (Ridomil Gold SL; a.i. 45.3%, Syngenta Crop Protection, Inc., Greensboro, NC) was applied for control of Pythium diseases at 0.636 liters/ha 1 day after seeding. Trials were watered as necessary with overhead sprinklers, and fertilization was according to standard practices.

Data collection. For RKN analysis, a composite sample consisting of six cores of soil (1.5 cm diameter, 5 to 30 cm depth) was collected from each plot just before applying the first treatment (initial population: P_i) and just before harvest (final population: P_f). Nematodes were extracted from 100 g of soil subsamples with the Baermann-funnel technique for 5 days incubation at 26°C (Southey 1970), and RKN J2 were counted at $\times 40$ magnification. Six to eight weeks after seeding, a vigor rating 0 to 10 (very poor to excellent) was visually assigned to each plot encompassing plant density, color, and height. At the same time, 10 plants were carefully removed from each plot and attached soil was rinsed off. The severity of the galling on the fibrous root system of each plant was visually assessed and assigned a galling index 0 to 10, where 0 = no galls and 10 = 100% of roots galled (Zeck 1971). At harvest, approximately 3 months after seeding, a 1-m section of carrots from the center of each plot was dug and the leaves removed. The attached soil was

rinsed off the roots which were blotted dry and weighed. The taproot was indexed for severity of galling 0 to 10, where 0 = no galls, 10 = roots completely galled, stunted and severely deformed (Fig. 1). The roots were categorized as marketable (galling index 0 to 3) or non-marketable (galling index ≥ 4). The weight of all carrots and those deemed marketable was determined for each plot. For each plot, the average galling index of all the harvested carrots was used as the plot galling index.

Data analysis. Treatment effects on nematode counts, midseason crop vigor, midseason galling index, total carrot yield, marketable yield, and at-harvest galling index were analyzed using an analysis of variance (ANOVA) procedure. The means were compared, if appropriate, using Fisher's protected least significant difference (LSD) test ($P \leq 0.05$) using SAS statistical software (SAS Institute, Cary, NC, U.S.A.). Vigor and galling data were arcsine-transformed, and nematode counts were $\log_{10}$ -transformed to normalize variances before statistical analysis.

Results

General growing conditions for the trials were excellent in all but one trial. In the 2015 trial, the carrot stand at harvest was too uneven for meaningful yield data (kg/m). Therefore, all carrots from each plot were harvested and only indexed for galling.

RKN levels. The average initial RKN J2 levels over all years ranged between 29 and 57 J2 per 100 g soil recovered by the Baermann funnel method. With the sandy loam at SCREC, the extraction efficacy was about 35%. In none of the trials were these initial levels significantly different among the treatments before applying the test product. Root-knot nematode levels increased under carrot, and in each trial, the levels at harvest were significantly affected by the treatments (data not shown). Fifteen treatments included fluzaindolizine, and 12 of those resulted in a significant reduction of the RKN J2 population at harvest relative to the untreated control. The three times that it did not result in a significant RKN J2 reduction were associated with the lower rate (1.12 kg/ha) of fluzaindolizine. Fluensulfone and fluopyram significantly reduced at-harvest RKN J2 levels in 2015, but not in 2014 or 2016. Oxamyl or metam-sodium treatments did not significantly lower RKN J2 levels compared with the untreated controls. The reproduction ratios (Pf/Pi) at harvest did not differ among treatments in any of the trials (data not shown).

Crop data. At midseason, galling on the young carrot plants was always significantly lower in fluzaindolizine-treated plots than in the untreated control plots (Table 1). In 10 out of the total of 15 fluzaindolizine treatments, carrots were also more vigorous at mid-season than in untreated plots. Similar positive effects (4 out of 6

standalone treatments) on midseason carrot vigor were achieved with fluensulfone. However, the reduction on midseason carrot galling associated with fluensulfone treatments was not as consistent (3 out of 6 standalone fluensulfone treatments). Fluopyram (3 out of 3 treatments) always resulted in a significantly higher midseason carrot vigor, but only reduced midseason galling in the 2014 trial. Metam-sodium also reduced midseason carrot galling (2014), but oxamyl (2013) did not. The galling at harvest was significantly affected by the treatments in each trial. All of the 15 fluzaindolizine treatments and the six standalone fluensulfone treatments significantly reduced at-harvest galling compared with the untreated controls. Two of the three standalone fluopyram treatments also resulted in significantly less galling. However, while the top 1/3 of the long taproots were nearly symptom-free, typically the lower 2/3 were insufficiently protected. In contrast, oxamyl and metam-sodium were not or only slightly effective in reducing at-harvest galling of carrot.

Effects of the treatments on the total yields (kg/m) were minor. Only in the 2014-trial 1, the yields from most nematicide-treated plots were significantly higher than from the untreated control plots. The marketable carrot yields, however, were strongly affected by the treatments in all of the trials. Fluzaindolizine resulted in the most consistent increase in marketable carrot yield, as in each trial its treatments always resulted in a significantly higher marketable carrot yield than in the untreated control. Both the liquid and the granular formulation performed equally well. Split application of 1.12 kg product/ha before seeding and 3 weeks later did not provide improved disease ratings or marketable yield compared with a single dose of 2.24 kg product/ha before seeding. Furthermore, among all nematicide treatments, fluzaindolizine generally resulted in the highest marketable carrot yields. Compared with fluzaindolizine, the effects of fluensulfone on marketable carrot yields were less consistent, and generally not as effective. Fluopyram, oxamyl, or metam-sodium treatments did not significantly increase marketable carrot yields over the untreated control treatments. When the three nonfumigants fluzaindolizine, fluensulfone, and fluopyram were included in the same trial (2014-trial 1, 2015, 2016), fluzaindolizine generally performed better than the other two compounds. (Table 1).

Discussion

Fluzaindolizine was highly effective in reducing damage to carrot caused by RKN. In each trial, each fluzaindolizine treatment significantly reduced carrot root galling. Averaged over all trials, the disease rating dropped from 6.2 in the untreated control to 2.4 in the fluzaindolizine treatment and substantially increased marketable yields compared with the untreated control (from 0.09 kg/m to 1.57 kg/m averaged over 2013, 2014, and 2016 trials). At the same a.i. rates, granular and liquid formulations of the product were equally effective. Doubling the rate of fluzaindolizine from 1.12 kg/ha to 2.24 kg/ha did not always lead to better vigor, higher marketable yields, or less galling. However, the higher rate did consistently lower the at-harvest soil RKN level relative to the untreated control. The hypothesis that a split application might result in better or longer lasting control was not validated. There were no significant differences in marketable yields, at-harvest galling, or final RKN levels between the treatments in 2013 and 2014-trial 2 where 2.24 kg/ha per season was applied either as a one-time preplant application or as a split pre- and postplant application of 1.12 kg/ha twice. A single high rate of 4.48 kg/ha was only tested in 2013 and did not lead to additional benefits over the 2.24 kg/ha rate. Thus, from these trials, it can be concluded that a one-time preplant incorporated drench application of fluzaindolizine at a rate of 2.24 kg/ha is effective to mitigate RKN damage in carrot and reduce population build-up when grown in infested fields. Our data confirm previous reports that fluzaindolizine was effective against RKN species in extensive development trials around the globe (Lahm et al. 2017; Thoden and Wiles 2019). In our trials, fluensulfone performed not quite as well as fluzaindolizine but still provided considerable reduction in RKN population and root galling. This good efficacy is supported by a number of published reports about its performance under high disease

Fig. 1. Carrot taproot gall rating guide (left to right, 0 to 10).

pressure in *M. incognita*-infested fields with tomato, sweetpotato, lima bean, and cucumber (Becker et al. 2012, 2013; Jones et al. 2017; Morris et al. 2015, 2016; Ploeg et al. 2019). Similar results were achieved against *M. javanica* in trials with carrot, cucumber, and cantaloupe (Westerdahl et al. 2014). However, in three UK field trials, the performance of fluensulfone against the potato cyst nematode *G. pallida* was less efficacious than oxamyl or fosthiazate (Norshe et al. 2016). This might indicate a difference in sensitivity between other plant-parasitic nematodes and RKN (Oka 2014) or less conducive soil conditions for the nematicide. Fluensulfone mobility was negatively affected by increasing clay content (Morris et al.

2018; Oka et al. 2013). Under our trial conditions, in warm, sandy loam soil, there was no advantage regarding efficacy against RKN by using the higher 3.98 kg/ha rate compared with 2.95 kg/ha. However, the nematicide needs to be applied one or more weeks before seeding as it potentially delays emergence and early seedling growth (unpublished results). For further crop safety, the Nimitz label recommends supplemental irrigation 3 to 5 days after application.

Initially, fluopyram was commercially used as a nematicidal seed treatment in soybean (Beeman and Tylka 2018; Beeman et al. 2019; Lawrence 2017) and cotton (ILeVO and COPeO Prime, respectively; Bayer CropScience) or in combination with imidacloprid (Velum

Table 1. Effect of nematicide applications on vigor, galling, and yield data in five *Meloidogyne incognita*-infested field trials at UC SCREC, Irvine, CA with carrot ‘Imperator 58’^s

Treatment	Midseason vigor ^t	Midseason galling ^u	Total yield kg/m ^v	Marketable yield kg/m ^w	At-harvest galling ^x
Year 2013					
Untreated	5.6 ± 0.5 b	3.5 ± 0.7 a	3.0 ± 0.4 a	0.1 ± 0.1 b	6.2 ± 0.4 a
Oxamyl 4.48 kg/ha, 4 dbs ^y	7.2 ± 0.7 ab	2.3 ± 0.4 a	2.9 ± 0.3 a	0.3 ± 0.1 b	5.6 ± 0.3 a
Fluazaindoline 1.12 kg/ha 4 dbs	8.6 ± 0.2 a	0.7 ± 0.2 b	3.5 ± 0.1 a	1.7 ± 0.4 a	2.9 ± 0.5 b
Fluazaindoline 1.12 kg/ha 4 dbs + 1.12 kg/ha 21 das ^z	8.2 ± 0.6 a	0.8 ± 0.3 b	3.5 ± 0.1 a	1.9 ± 0.4 a	2.8 ± 0.4 b
Fluazaindoline 2.24 kg/ha 4 dbs	8.4 ± 0.5 a	0.5 ± 0.3 b	3.3 ± 0.2 a	2.4 ± 0.4 a	2.1 ± 0.4 b
Fluazaindoline 4.48 kg/ha 4 dbs	7.4 ± 0.4 ab	0.5 ± 0.1 b	3.2 ± 0.1 a	2.4 ± 0.3 a	2.0 ± 0.4 b
Treatment <i>P</i> value	0.03	0.0001	0.29	0.0001	0.0001
Year 2014 – trial 1					
Untreated	3.7 ± 0.8 b	6.8 ± 0.6 a	1.7 ± 0.3 c	0.1 ± 0.0 d	6.7 ± 0.5 a
Metam-sodium 294 liters/ha 19 dbs	6.0 ± 1.1 a	3.7 ± 0.7 bc	2.3 ± 0.2 ab	0.3 ± 0.1 cd	5.0 ± 0.3 b
Fluensulfone 2.95 kg/ha 19 dbs	5.1 ± 0.9 ab	2.4 ± 0.3 cd	2.2 ± 0.3 ab	0.4 ± 0.1 cd	4.3 ± 0.2 bc
Fluensulfone 3.98 kg/ha 19 dbs	4.9 ± 0.5 ab	2.0 ± 0.3 de	2.3 ± 0.2 ab	0.8 ± 0.2 bc	3.6 ± 0.4 c
Fluazaindoline 1.12 kg/ha 4 dbs	5.8 ± 1.1 a	2.8 ± 0.6 bcd	2.2 ± 0.4 ab	1.2 ± 0.4 b	2.5 ± 0.4 d
Fluazaindoline 2.24 kg/ha 4 dbs	6.3 ± 0.8 a	1.0 ± 0.5 e	2.5 ± 0.2 a	1.7 ± 0.3 a	2.1 ± 0.4 d
Fluopyram 256 g/ha 4 dbs	5.3 ± 0.9 a	4.2 ± 0.6 b	1.9 ± 0.2 bc	0.3 ± 0.1 d	4.6 ± 0.1 b
Treatment <i>P</i> value	0.013	0.0001	0.029	0.0001	0.0001
Year 2014 – trial 2					
Untreated	4.3 ± 0.4 c	6.5 ± 0.3 a	2.0 ± 0.1 a	0.1 ± 0.0 c	5.6 ± 0.2 a
Metam-sodium 294 liters/ha 19 dbs	5.6 ± 0.8 abc	4.0 ± 0.4 b	2.1 ± 0.2 a	0.2 ± 0.1 c	5.1 ± 0.2 a
Fluazaindoline liquid 1.12 kg/ha 4 dbs	5.4 ± 0.3 bc	2.2 ± 0.5 c	1.9 ± 0.1 a	0.8 ± 0.2 b	3.1 ± 0.5 b
Fluazaindoline liquid 1.12 kg/ha 4 dbs + 1.12 kg/ha 21 das	4.9 ± 0.6 bc	0.4 ± 0.1 d	2.0 ± 0.1 a	1.8 ± 0.2 a	1.5 ± 0.2 c
Fluazaindoline granular A, 2.24 kg/ha 4 dbs	7.1 ± 0.7 a	0.7 ± 0.2 d	2.4 ± 0.1 a	1.8 ± 0.2 a	1.8 ± 0.3 c
Fluazaindoline granular B, 2.24 kg/ha 4 dbs	6.1 ± 0.4 ab	1.8 ± 0.5 c	2.2 ± 0.2 a	1.4 ± 0.4 a	2.2 ± 0.4 c
Treatment <i>P</i> value	0.04	0.0001	0.2	0.0001	0.0001
Year 2015					
Untreated	3.8 ± 0.5 c	3.8 ± 1.0 a			7.3 ± 0.1 a
Fluensulfone 2.95 kg/ha 14 dbs	7.6 ± 0.7 a	3.1 ± 0.8 a			4.9 ± 0.5 cd
Fluensulfone 3.98 kg/ha 14 dbs	6.2 ± 0.6 b	3.3 ± 1.1 a			5.0 ± 0.6 cd
Fluazaindoline liquid 1.12 kg/ha 3 dbs	5.4 ± 1.0 bc	0.9 ± 0.4 b			3.9 ± 0.5 de
Fluazaindoline liquid 2.24 kg/ha 3 dbs	5.8 ± 0.4 b	1.0 ± 0.5 b			3.3 ± 0.8 e
Fluazaindoline granular B, 2.24 kg/ha 9 dbs	5.2 ± 0.4 bc	0.9 ± 0.4 b			3.9 ± 0.6 de
Fluopyram 256 g/ha 3 dbs + 256 g/ha 28 das	7.0 ± 0.3 ab	2.4 ± 0.5 ab			6.5 ± 0.1 ab
Fluensulfone 2.95 kg/ha 14 dbs + Fluopyram 256 g/ha 28 das	5.6 ± 0.5 bc	3.4 ± 0.4 a			5.5 ± 0.3 bc
Treatment <i>P</i> value	0.004	0.008			0.0001
Year 2016					
Untreated	3.0 ± 0.3 c	5.6 ± 0.8 a	0.75 ± 0.13 a	0.07 ± 0.03 d	5.4 ± 0.4 a
Fluensulfone 2.95 kg/ha 14 dbs	8.0 ± 0.9 b	3.9 ± 1.0 ab	0.84 ± 0.12 a	0.41 ± 0.07 bc	3.1 ± 0.5 c
Fluensulfone 3.98 kg/ha 14 dbs	6.4 ± 0.4 b	2.9 ± 0.8 b	0.88 ± 0.13 a	0.50 ± 0.07 b	2.9 ± 0.2 c
Fluazaindoline liquid 2.24 kg/ha 3 dbs	6.8 ± 1.0 b	0.4 ± 0.1 c	0.97 ± 0.13 a	0.92 ± 0.12 a	1.0 ± 0.2 d
Fluazaindoline granular B, 2.24 kg/ha 9 dbs	7.8 ± 0.6 b	0.6 ± 0.1 c	0.90 ± 0.10 a	0.80 ± 0.07 a	1.1 ± 0.4 d
Fluopyram 196 g/ha 3 dbs + 196 g/ha 28 das	6.6 ± 0.2 b	4.5 ± 0.8 ab	0.84 ± 0.12 a	0.20 ± 0.11 cd	4.2 ± 0.5 b
Treatment <i>P</i> value	0.003	0.0001	0.7	0.0001	0.0001

^s All data are mean of five replicates ± standard error. Different letters within the same column and within the same year and trial represent significant differences at the 95% confidence level. Vigor and galling data were arcsine-transformed before statistical analysis, nontransformed data shown.

^t Visual plant vigor rating on scale 1 to 10 (worst to best).

^u Fibrous root system gall rating on scale 0 to 10 (roots without galls to root system stunted, completely galled, plant dying).

^v Weight of all harvested carrots per linear meter.

^w Weight of carrots per linear meter deemed marketable by disease rating 0 to 3.

^x Taproot gall rating on scale 0 to 10 (roots without galls to root system stunted, deformed, plant dying).

^y Days before seeding.

^z Days after seeding.

Total, Bayer CropScience) as an in-furrow spray against insects and nematodes (Faske et al. 2018). Later, in precommercial development field trials with fluopyram soil applications (Velum One) in processing tomatoes in California, good levels of RKN control were reported (Becker et al. 2012, 2013; Cabrera et al. 2015). In Florida trials, fluopyram suppressed sting nematodes, *Belonolaimus longicaudatus*, in an infested strawberry field (Watson and Desaegeer 2019) and *M. incognita* in microplot trials with lima beans (Jones et al. 2017). Although it is an effective nematicide at a very low rate in vitro and in greenhouse trials (Faske and Hurd 2015), its efficacy in the field is often limited by its poor mobility in soil. During the first few weeks of carrot growth, it provided good RKN protection but only to the depth of the mechanical incorporation. Consequently, at harvest, the top 6 to 8 cm of the taproots were often disease symptom-free, but the lower parts were disfigured by root forking, stunting, and severe galling. Further optimizing the application technology might improve the product's crop protection efficacy.

The presented data demonstrated that fluensulfone and fluazaindolizine are useful tools for mitigating RKN problems in carrot production. Under high RKN pressure and favorable conditions for disease development, both compounds showed good to excellent efficacy regarding root damage control and ensuring high marketable yield. Together with their positive toxicological and environmental dossiers, they are the first examples of a much improved next generation of nematicides.

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