Fluensulfone: A New "Tool in the Tool Box" to Manage Plant-parisitic Nematodes in Vegetable Production[1]

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Nematodes belong to the phylum Nematoda and can be defined as ubiquitous pseudocoelomates with unsegmented bodies found in fresh and salt water, soil, and as internal parasites of living organisms like animals and humans (Blaxter 2011). Over 25,000 nematode species have been identified (Zhang 2013), 10,000 of which have been described as parasites (Maggenti 1981). Plant-parasitic nematodes are of special importance in agricultural systems because they feed on the crop plant, affecting yield. Plant-parasitic nematodes may be divided into endoparasites (meaning inside the root) and ectoparasites (meaning living outside the root system). Among plant-parasitic nematodes, root-knot nematodes (RKNs; *Meloidogyne* spp.) have been considered severe plant pathogens affecting all types of crops worldwide (USDA 2013). Although nearly 100 species of RKNs have been identified, only five species have been labeled as "major plant-parasitic nematodes of economic importance" (Handoo 1998). These species are *M. arenaria, M. incognita, M. javanica, M. hapla, and M. chitwoodi* (Handoo 1998). When second-stage juveniles (J2) initiate feeding, they secrete proteins from their esophageal glands that transform parasitized cells into hypertrophic cells, also known as "giant cells" (Bird 1961). The surrounding cortex cells then rapidly proliferate, resulting in gall formation. Hypertrophic cells act as nutrient reservoirs for females. The large number of females feeding from inside the roots results in nutrient losses and water uptake malfunction, stressing the plant and causing aboveground symptoms such as chlorosis, stunting, and incipient wilting of the leaves (Karssen et al. 2013).

Current alternatives for RKN management may be divided into two categories: cultural practices and chemical management.

Cultural Practices

Cultural practices include crop rotation, resistant cultivars, clean fallowing, and flooding. For crop rotation to be successful, crops that are nonhosts or poor hosts of RKNs need to be included. For instance, Noling (2016) has listed cover crops such as iron clay cowpea (*V. unguiculata*), sunn hemp (*C. juncea),* and American jointvetch (*A. americana*) as poor host legumes that may be rotated with cash crops for RKN management during the summer off-season. Additionally, rotations can include RKN- resistant cultivars of crops like tomato (*Solanum lycopersicum* L.) in which RKN resistance is due to a single dominant gene known as the *Mi* gene (Medina-Filho and Tanksley 1983; Smith 1944; Williamson et al. 1994). However, some studies have documented gene instability (due to high temperatures) that causes resistance failure (Dropkin 1969; Hwang et al. 2000).

Fallowing refers to land left uncropped and weed-free for a determined period of time to induce starvation of RKNs;

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hence, fallowing is often considered to be one of the most effective cultural approaches (Noling 2016). Nonetheless, Krueger and McSorley (2014) explained that when fallowing is used, RKNs may enter into a less active stage that allows them to survive for extended periods of time without food. However, fallowing may be regarded as a poor practice because it can result in soil erosion and leaching of residual fertilizer (Krueger and McSorley 2014). Flooding could be employed as a means to suppress RKN population densities. By alternating flooding and drying cycles, RKNs undergo abiotic stress, resulting in population decline (Noling and Becker 1994). Nevertheless, the growing concern of water use efficiency and aquifer exhaustion has triggered a reduction in the use of flooding (Noling 2016).

Chemical Management

Fumigant Nematicides

Nematicides are pesticides that either kill or immobilize nematodes. Currently available nematicides may be grouped into two different categories based on their movement in the soil: fumigants and non-fumigants (Table 1) (Noling 2014). Fumigant nematicides are liquid formulations that rapidly volatilize once introduced into soil. These groups may be divided into halogenated hydrocarbons and those that release carbon disulfide or methyl isothiocyanate (Nyczepir and Thomas 2009; Morris 2015). Methyl bromide (Terr-O-Gas 98™, Great Lakes Corp., Middlebury, CT), chloropicrin (Chloropicrin 100™, Cardinal, Hollister, CA), and 1,3-dichloropene (Telone II™, Dow Agrosciences LLC, Indianapolis, IN) are considered halogenated hydrocarbons, whereas metam sodium (Vapam™, AMVAC Chemical Cop., New Port Beach, CA) or metam potassium (Kpam™, AMVAC Chemical Cop., New Port Beach, CA) and dimethyl disulfide (Paladin™, Arkema Inc., King of Prussia, PA) release methyl isothiocyanate in the soil (Nyczepir and Thomas 2009; Morris 2015).

In Florida, current fumigants that may be applied to manage RKN in tomato include chloropicrin, metam sodium, metam potassium, 1,3-dichloropropene, dimethyl disulfide, and allyl isothiocyanate (Dominus™, Isagro USA Inc., Morrisville, NC) (Dittmar et al. 2016). In 2011, Florida tomato growers identified metam sodium, metam potassium, and chloropicrin as the least effective for managing RKN (Snodgrass et al. 2013), whereas the remaining fumigants are known to provide an acceptable level of management of RKN (Dittmar et al. 2016). Despite the favorable RKN management that fumigants may offer, Florida tomato growers indicated that the use of fumigants involves a high cost and that product availability is not always certain (Snodgrass et al. 2013). Furthermore, soil fumigants commonly used in Florida are subject to emission from the soil to the atmosphere and pesticide drift that may have off-target adverse effects (Fishel and Ferrell 2010), presenting the need for buffer zones and/or barrier films to limit the likelihood of effects on occupants of structures adjacent to fumigated fields.

Non-Fumigant Nematicides

Non-fumigant nematicides are generally formulated as either granules or liquids, move in soil or water by downward percolation, and can be either carbamates or organophosphates acting as nematistats (paralyzing agents) by inhibiting acetylcholinesterase activity (Haydock et al. 2006; Morris 2015; Opperman and Chang 1990).

Vydate™ (Oxamyl, DuPont Crop Protection, Hayward, CA) is the only non-fumigant nematicide labeled in Florida for management of RKN in tomato that can be applied during the crop cycle (Noling 2016). Vydate is a liquid formulation capable of moving both downward and upward within plants and can be applied as a foliar spray, soil drench, broadcast, or through chemigation. Growers may use Vydate as a post-plant supplement throughout the tomato growing season in combination with fumigant nematicides, because it acts a nematistat by temporally paralyzing RKNs (Noling 2016; Morris et al. 2015).

Fluensulfone [5-chloro-2 (3,4,4-trifluoro-but-3-ene-1-sulfonyl)-thiazole] (ADAMA Agricultural Solutions Ltd., Raleigh, NC), brand name Nimitz™, belongs to a new class of chemicals—the fluoroalkenyl thioester group—that can be used to control root-knot, potato cyst (*Globodera* spp.), needle (*Longidorus africanus*), lance (*Hoplolaimus* spp.), sting (*Belonolaimus* spp.), stubby root (*Trichodorus and Paratrichodorus* spp.), and lesion nematodes (*Pratylenchus* spp.). Fluensulfone is formulated as a non-fumigant emulsifiable concentrate that causes nematode mortality within 24 to 48 hours of product application, but has low toxicity to non-target insects and other animals (Kearn et al. 2014; Navia 2014a; Oka et al. 2009; Oka et al. 2013). Unlike organophosphates and carbamates, which cause paralysis in nematodes, fluensulfone kills nematodes by inhibiting acetylcholinesterase activity (Kearn et al. 2014; Oka et al. 2009; Oka et al. 2013).

In 2014, fluensulfone received its initial registration from the EPA in accordance with the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) section 3(c)(5). In 2015, the registration was amended to include a section 24(c) label for direct-seeded cucumber (*C. sativus*), squash

(*Cucurbita* spp.), watermelon (*C. lanatus*), cantaloupe (*C. melo*), and okra (*A. esculentus*) in Florida counties (EPA 2015). Fluensulfone is currently labeled for the control of nematodes in fruiting vegetables, including tomato, okra, eggplant (*S. melongena*), and peppers (bell and non-bell; *Capsicum* spp.); cucurbit vegetables, including cucumbers, melons (cantaloupes, watermelon, honeydew), and squash; brassica and leafy vegetables; and low-growing berries, including strawberry (*Fragaria* × *ananassa*). The fluensulfone product label utilizes the signal word "caution", and the nematicide has a 12-hour re-entry interval, which means no handling restrictions and less complicated personal protective equipment requirements than for fumigant products (Navia 2014a). Therefore, there is no need for fumigant management plans, restrictive buffer zones, and long re-entry intervals (Navia 2014b).

Fluensulfone can be applied via drip irrigation, banded incorporation, or broadcast incorporation a minimum of seven days before planting at a rate of 3.5 to 7.0 pints/acre. The label recommends incorporation with 0.5 to 1 inch of water applied 2–5 days after fluensulfone application. Research on carrot (*Daucus carota* subsp. *sativus*), cucumber, eggplant, squash, potato (*Solanum tuberosum* L.), sweet potato (*Ipomoea batatas*), lettuce (*Lactuca sativa*), and tomato have shown that application of fluensulfone reduced RKN galling on plant roots and soil population densities of J2 compared with plants grown with no fluensulfone application (Dickson and Mendes 2013; Morris et al. 2015; Oka et al. 2009; Oka et al. 2013). In a tomato crop with high RKN infestation (3265 J2/cc soil), in which Pic-Clor 60 [1,3-dichloropropene plus chloropicrin (40:60, w/w)] was pre-plant shank-applied at mid-season and final harvest, Pic-Clor 60 followed by fluensulfone resulted in a lower galling index than Pic-Clor 60 alone, decreasing root galling by approximately 61% and 55%, respectively (Castillo et al. 2017). In addition, Pic-Clor 60 followed by fluensulfone decreased population densities of RKN J2 by 88% at final harvest (Castillo et al. 2017). Norshie et al. (2016) showed that fluensulfone decreased potato cyst nematode root infection by 43% and increased yield by 62%.

In conclusion, as a nonfumigant nematicide, fluensulfone can be considered as a recent additional "tool in the tool box" to manage plant-parasitic nematodes. Further studies and evaluations of fluensulfone taking into account different climates, soil types, and integrated pest management practices, such as broad spectrum pesticides, will add value to the current knowledge, considering the limited options and the challenge that nematodes represent.

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Table 1. Current fumigant and non-fumigant nematicides available in Florida to manage plant-parasitic nematodes on vegetables.

Nematicide category	Brand name	Active ingredient	Rate/acre
Fumigant	Chloropicrin	Chloropicrin	100–350 lb
	Dominus	Allyl isothiocyanate	10–40 gal
	Kpam	Potassium N methyldithiocarbamate	30–62 gal
	Paladin	Dimethyl disulfide	54.2–60.0 gal
	Pic-Clor 60	1,3-Dichloropropene/ chloropicrin 40/60 (w/w)	19.5–34.5 gal
	Telone II	1,3-Dichloropropene	9.0–12.0 gal
	Telone C17	1,3-Dichloropropene/ chloropicrin 81/17 (w/w)	10.8–17.1 gal
	Telone C35	1,3-Dichloropropene/ chloropicrin 63/35 (w/w)	13.0–20.5 gal
	Vapam	Metam sodium	37.5–75.0 gal
Non-fumigant	Counter 15G	Terbufos	6.0–8.0 oz/1000 ft of row, banded or in furrow
	Mocap 15G	Ethoprop	40–60 lb
	Nimitz	Fluensulfone	3.5–5.0 pint
	Vydate L	Oxamyl	2–4 pint
Adapted from Dittmar et al. 2016; Noling 2014.			