

## Research

# Evaluating Management Programs Utilizing Fumigation and Genetic Resistance for Control of Southern Root-Knot Nematode in a Pepper–Cucumber Rotation

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## Abstract

Root-knot nematodes (RKNs; *Meloidogyne* spp.) are the most prevalent and damaging nematode taxa on solanaceous and cucurbit vegetable crops in the southeastern United States. An RKN-resistant pepper hybrid was evaluated for its effects on root galling, RKN population density, and yield in a pepper–cucumber double crop system, relative to a susceptible hybrid and compared with factorial treatments of 1,3-dichloropropene (1,3-D) fumigation in Kinston, NC. The effects of these treatments were also evaluated on the subsequently planted cucumber. These results guided the selection of seven different nematicide and pepper hybrid combinations, as management programs, for a 3-year study in Elm City, NC. Treatment effects on yield, root damage, and population densities of free-living and plant-parasitic nematode species were examined. In Kinston, both 1,3-D fumigation and the RKN-resistant hybrid significantly reduced root galling and RKN densities. Use of the RKN-resistant pepper hybrid was the only factor to significantly improve pepper and

second crop cucumber yields ( $P < 0.05$ ). In Elm City, higher pepper and cucumber yields were observed in RKN management programs that included the RKN-resistant pepper hybrid combined with fluopyram application, regardless of fumigation application. No significant differences in the densities of free-living or plant-parasitic nematode species were observed across management programs, though RKN densities trended lower when using an RKN-resistant hybrid. These results highlight the potential for increasing yields and improving RKN management in pepper–cucumber rotations by using RKN-resistant pepper hybrids, combined with fluopyram application. Reducing dependence on 1,3-D fumigation improves both the economic and environmental sustainability of vegetable production.

**Keywords:** double cropping, host resistance, *Meloidogyne incognita*, southern root-knot nematode

The southeastern United States produces a diversity of vegetable crops. Solanaceous, cucurbit, and brassica species make up a large portion of this production area (USDA-NASS 2022) and are often intensively managed in conventional plasticulture systems across the region. A planting rotation or “double cropping” of cucumber, squash, or a brassica species after production of a solanaceous crop in the same calendar year, or even across multiple years, is common. This practice reduces farm input costs by enabling production of multiple crops on the same footprint but may also allow for an increased buildup of plant-parasitic nematodes between crop cycles (Thies et al. 2004). Lack of available land and the inability to move stationary irrigation infrastructure from field to field further limits the potential for effective crop rotation practices that could help reduce the buildup of plant-parasitic nematode species.

Southern root-knot nematode (RKN), *Meloidogyne incognita* (Kofoid and White, 1919) Chitwood, 1949, has a broad host range

and is often the most common and most devastating plant-parasitic nematode species on vegetables in the southeastern United States (Koenning et al. 1999). A comprehensive survey in Georgia found that 67% of vegetable fields were infested with RKNs (Marquez et al. 2021). A similar survey across the Carolinas and Tennessee found a similar incidence (60%) of RKNs in vegetable fields there (Gorny et al. 2024). Average densities above 250 RKNs per 100 cm<sup>3</sup> in both surveys dramatically surpass recommended treatment thresholds for vegetables in the region (Dickerson et al. 2000), highlighting the importance of identifying effective nematode management tools and practices.

Work in the early 2000s identified 1,3-dichloropropene (1,3-D) combined with chloropicrin as an effective control measure for RKNs and other soilborne pathogens as an alternative to the historically used methyl bromide (Roskopf et al. 2005; Webster et al. 2001). Today, preplant fumigant application of 1,3-D and chloropicrin is still a standard practice for managing plant-parasitic nematodes and other fungal soilborne pathogens in many solanaceous and cucurbit vegetable systems. Numerous studies have also demonstrated the effectiveness of RKN-resistant varieties at reducing galling severity and decreasing the population density of *M. incognita* both at harvest and in subsequent crops (Djian-Caporalino et al. 2014; Hajihassani et al. 2019b; Navarrete et al. 2016; Thies et al. 2005). Some studies, however, have reported a

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yield drag in the RKN-resistant varieties, as compared with susceptible varieties with a fumigant treatment (Nnamdi et al. 2022). It is possible that the RKN-resistant hybrids used in these studies lack inherent yield potential, high fruit quality, or other necessary disease traits relative to commercial standard varieties, which may account for some of these discrepancies.

This study consisted of two experiments, the first conducted in Kinston, NC, in 2021, and the second conducted in Elm City, NC, over 2022 to 2024. The objective of the first experiment was to evaluate, factorially, the efficacy of an RKN-resistant pepper hybrid (SVPB4241) and 1,3-D fumigation relative to untreated controls for each factor. Treatment effects on a subsequently planted cucumber were also observed, thus replicating the nature of a typical pepper–cucumber rotation. In the second experiment, varying RKN management programs consisting of pepper variety, fluopyram application, and fumigation treatment were evaluated for a 3-year period to assess effects of the different management programs over time. In this experiment, ‘Hammerhead’ was used as the RKN-resistant pepper variety. Hammerhead boasts intermediate resistance to *Phytophthora* blight and to races 0 to 10 of bacterial leaf spot, in addition to its RKN resistance. It has demonstrated competitive yield and fruit quality relative to current market standards (A. C. Scruggs, Bayer Crop Science, *unpublished data*), setting it apart agronomically from previously tested RKN-resistant pepper varieties. Therefore, an objective of this study was to evaluate the yield and efficacy of Hammerhead, in combination with fluopyram application, in a pepper–cucumber double crop rotation under varying fumigation practices, relative to that of a grower standard treatment of preplant fumigation of chloropicrin and 1,3-D coupled with an RKN-susceptible pepper variety. The effects on subsequent cucumber yield and vigor were also observed across management programs. Lastly, the population densities of both plant-parasitic and free-living nematode species were tracked over a 3-year period to evaluate the impacts of fumigant and non-fumigant treatments on diverse nematode taxa over time. The results from these experiments will be valuable for applying practical methods to help sustainably improve nematode control and better understand the impacts of production practices on crop productivity and the effects on nontarget nematode species.

## Materials and Methods

### Kinston trial location, design, and field preparation

Initial field trial experiments were conducted in 2021 at the Cunningham Research Station in Kinston, NC. The field trial site has a Lynchburg sandy loam soil type with established populations of *M. incognita* race 4. The trial design for this experiment was a split-plot design, with whole plots receiving either fumigant or no fumigant and the subplots receiving an RKN-resistant pepper hybrid (SVPB4241) or an RKN-susceptible pepper hybrid (SVPB7768). Six replicates of each treatment were included.

1,3-D (Telone II; Dow Chemical Company, Midland, MI) was shank-applied at a rate of 65.5 liters/ha in the bed to one whole plot of the trial and white plastic mulch laid in the field on 13 April 2021. A second whole plot was left unfumigated and laid with white plastic mulch at the same time. The RKN-resistant and susceptible hybrids were randomly assigned to subplots within the fumigant treatment whole plots so that each combination of fumigant and pepper hybrid was tested. Bell pepper seeds were sown in 98-cell trays in the greenhouse in mid-March and transplanted into the field on 14 May 2021. Plots were 3.7 m long with plants planted 30 cm apart on double rows per bed, for a total of 20 plants per plot. Beds were spaced 1.5 m apart. Other than treatment differences, plots

were managed as recommended for commercial practice (Kemble et al. 2024). Following pepper harvest and evaluation, pepper plants were pulled up and removed from the plots. ‘Peacemaker’ pickling cucumbers were direct seeded back into the same plots on 11 August 2021 at a rate of two seeds per planting hole, in a single row per bed. Stands were thinned to one plant per hole after germination, giving 10 plants per plot.

### Kinston harvest and evaluation

Peppers were harvested a single time on 30 July 2021. The weight of marketable fruit for each plot was collected and recorded. Six days after harvest, three plants per plot were carefully removed with the root mass intact and rinsed with tap water to remove soil particles. Galling severity was rated on an index ranging from 0 to 10, where 0 = no galls, 1 = 1 to 5%, 2 = 6 to 10%, 3 = 11 to 15%, 4 = 16 to 20%, 5 = 21 to 30%, 6 = 31 to 40%, 7 = 41 to 55%, 8 = 56 to 70%, 9 = 71 to 85%, and 10 = 86 to 100% of the root system galled (Bridge and Page 1980). Three soil cores per plot were collected at this same time for soil counts of *M. incognita* second-stage juveniles. Cores were taken through the planting hole to a depth of 20 cm and within 10 cm of the base of the plant to ensure consistent collection of rootzone soil. Cores were then bulked together per plot and transported back to the lab, where a modified Whitehead tray extraction was performed (Whitehead and Hemming 1965). Total RKN counts for the Kinston trial are reported per 100 g of soil.

Second crop cucumbers were harvested a single time on 30 September 2021. All pickling cucumbers at least 7.6 cm in length were harvested from each plot, weighed, and recorded. Immediately following cucumber harvest, three cucumber plants per plot were carefully removed with roots intact, rinsed, and rated for galling severity as described above for peppers.

### Kinston data analysis

Pepper and cucumber yield data were fit to a linear model with fumigation and pepper hybrid as fixed effects. Block and whole-plot effects from the split-plot design were determined to have a variance of random effect close to zero and were therefore excluded from the model for both crops. Yield data were subjected to an analysis of variance (ANOVA) using RStudio (R Core Team 2024). Due to the non-parametric nature of the data, the root galling data for both pepper and cucumber were subjected to a Kruskal–Wallis test in RStudio. Pepper root weight and RKN count data were log transformed prior to running an ANOVA using RStudio.

### Elm City trial location, design, and field preparation

Field trial experiments were conducted for three consecutive years from 2022 to 2024 on a research farm located in Wilson County, NC. The trial site is a Goldsboro sandy loam soil and contained natural populations of various plant-parasitic and free-living nematode species. The trial design was a randomized complete block design with varying management programs (labeled as management programs A to G) as treatments, which are detailed in Table 1. The trial was blocked by replicate, with five total replications. To assess any compounding treatment effects over time, each treatment returned to the same plot footprint for each year of testing. Plots were spaced with 9.1 m from the end of a plot to the beginning of the next plot within the same row and with rows spaced 3 m apart to limit any potential cross-contamination of nematodes during annual field preparation work. Drip tape was capped at the end of each plot to eliminate movement of nematodes through the irrigation lines. Specific dates of field activities can be found in Table 2.

Peppers were sown into 98-cell black plastic trays in a commercial greenhouse each year in late February with a target transplant date of mid- to late April. In this experiment, ‘Tarpon’ bell pepper was used as the RKN-susceptible variety, and Hammerhead was used as the RKN-resistant pepper hybrid. Plots were a single raised soil bed, 3 m in length, and covered with 1.25 mil white plastic mulch. Eggs of *M. incognita* race 2 were extracted from tomato culture plants grown in the greenhouse using the sodium hypochlorite extraction of Hussey and Barker (1973), quantified, and used as the field inoculum. Each plot was inoculated with 2,500 eggs at the beginning of the trial period in 2022. Peppers were transplanted on a double row per bed, with 30.5- × 30.5-cm spacing, giving 20 plants per plot. Fluopyram (Velum; Bayer Crop Science, Creve Coeur, MO) was drip-applied to the appropriate treatments as detailed in Table 2. Other than treatment differences, plots were managed as recommended for commercial practice (Kemble et al. 2024). Following the completion of the pepper harvests, pepper plants were removed, and metam sodium was applied (see Table 1). After a 14-day plant-back restriction, plots were direct seeded with ‘Brickyard’ slicing cucumbers with three seeds per hole on 30.5-cm spacing in a single row per bed. The stand was hand-thinned after germination to one plant per hole for a total of 10 plants per plot.

### Elm City pepper harvest and evaluation

Peppers were harvested three times in 2022 and 2023 and twice in 2024. At each harvest, both marketable peppers and peppers affected with blossom end rot were counted, weighed, and recorded for each plot. The number of plants per plot infected with a soilborne fungal disease was also noted. Following the completion of the final harvest, five pepper plants were carefully removed from each plot, rinsed with tap water, and scored for root vigor rating and a root galling index. Root vigor was rated with a visual index of 1 to 10, with 1 being no root development and 10 designating a full, vigorous plant root system. Roots were scored for root galling using an index ranging from 0 to 10, as described above.

### Elm City cucumber harvest and evaluation

Cucumbers with a minimum length of 17 cm were harvested, counted, and recorded for each plot. Cucumber plots were harvested twice in 2022 and 2023 and three times in 2024. Prior to making the final harvest, cucumber plots were visually rated on a scale from 1 to 10 for vine vigor, where 1 = poor vine vigor and 10 = high vine vigor. Following the completion of the final harvest, five cucumber plants per plot were removed and scored for root vigor rating and a root galling index as described above for peppers.

Twelve soil cores were collected as described above following completion of cucumber harvest. Cores from each plot were bulked into a clean, plastic bucket, gently mixed, and placed into a nematode assay sample bag/box provided by the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) Nematode Assay Section. Samples were promptly delivered to the NCDA&CS Nematode Assay Lab (Raleigh, NC) for plant-parasitic nematode genus identification and population density counts. Free-living nematodes were also identified and counted by feeding type (bacterivore, fungivore, omnivore, and predator). Nematode counts from the Elm City trial are reported per 500 g of soil.

### Elm City data analysis

Yield and vigor data for pepper and cucumber were fit to a linear mixed effects model using the *lme4* package (Bates et al. 2015) in R version 4.4.2 (R Core Team 2024). In the mixed effects model, data from all 3 years were combined and analyzed together, with management program considered a fixed effect in the model. Year and replication were each modeled as random effects. Yield and vigor data for both crops were subjected to a mixed ANOVA in R. Treatment effects were considered significant at  $P < 0.05$ . Multiple comparisons for significant main effects were conducted using the *emmeans* (Lenth 2025) package in R, and  $P$  values were adjusted using Tukey’s test.

Trial activity	2022	2023	2024
Peppers seeded	2/16/2022	2/21/2023	2/29/2024
Fumigation application	3/25/2022	3/31/2023	3/26/2024
Pepper transplanted	4/19/2022	4/21/2023	4/24/2024
Velum application (474 ml/ha)	4/21/2022	4/22/2023	4/25/2024
Pepper harvest 1	6/29/2022	7/6/2023	6/24/2024
Pepper harvest 2	7/12/2022	7/19/2023	7/10/2024
Pepper harvest 3	7/27/2022	8/2/2023	N/A
Metam sodium application	8/16/2022	8/4/2023	7/12/2024
Cucumbers seeded	9/10/2022	8/28/2023	8/2/2024
Velum application (237 ml/ha)	9/22/2022	9/12/2023	8/20/2024
Velum application (237 ml/ha)	10/7/2022	9/19/2023	9/3/2024
Cucumber harvest 1	11/3/2022	10/13/2023	9/26/2024
Cucumber harvest 2	11/7/2022	10/20/2023	10/2/2024
Cucumber harvest 3	N/A	N/A	10/7/2024

**TABLE 1**  
Management programs (as treatments) tested in Elm City, NC, in 2022, 2023, and 2024 for root-knot nematode control in a pepper–cucumber double crop rotation

Program	Pepper preplant fumigant	Variety	Fluopyram <sup>y</sup>	Cucumber preplant fumigant
A	Chloropicrin + 1,3-D <sup>z</sup> (Pic60) at 136 liters/ha	Tarpon (Susc.)	None	Metam sodium at 327 liters/ha
B	Chloropicrin + 1,3-D (Pic60) at 136 liters/ha	Hammerhead (Res.)	948 ml/ha	Metam sodium at 327 liters/ha
C	Chloropicrin + 1,3-D (Pic60) at 136 liters/ha	Hammerhead (Res.)	948 ml/ha	None
D	Chloropicrin (Pic100) at 72 liters/ha	Hammerhead (Res.)	948 ml/ha	None
E	Chloropicrin (Pic100) at 72 liters/ha	Hammerhead (Res.)	948 ml/ha	Metam sodium at 327 liters/ha
F	None	Hammerhead (Res.)	948 ml/ha	None
G	None	Tarpon (Susc.)	None	None

<sup>y</sup> Fluopyram was split applications with the timing and rates specified in Table 2.

<sup>z</sup> 1,3-dichloropropene.

Root galling data for both peppers and cucumbers were fit to a cumulative link mixed model using R package *ordinal* (Christensen 2023) due to the non-parametric nature of the data. Management program was modeled as the only fixed effect, and year and replication were considered random effects. Multiple comparisons were conducted using the *emmeans* (Lenth 2025) package in R, and *P* values were adjusted using Tukey's test.

Nematode count data were combined across years and fit to a linear mixed effects model using the packages described above. Year and plot ID were fit as random effects to increase power in observing differences in nematode counts between management programs. In instances in which the variance of a random effect was close to zero, the random effect was excluded from the model. These data were subjected to an aligned rank transformation ANOVA using the *ARTool* package (Kay et al. 2025) in R as a non-parametric test due to a lack of normality.

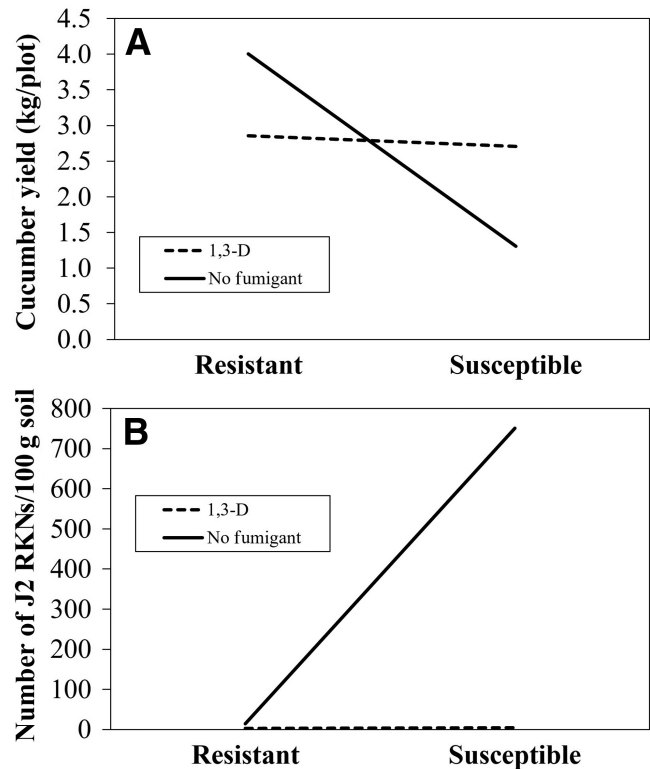
## Results

### Kinston harvest and evaluations

Preplant fumigation of 1,3-D did not significantly improve bell pepper yield in the Kinston trial location in 2021 (Table 3), nor was there a significant difference in fresh root weights after harvest. Mean counts of RKN second-stage juveniles after harvest demonstrated that 1,3-D fumigation significantly reduced the RKN population density, with 99% fewer RKNs in the fumigated plots versus the unfumigated plots. There was a significant interaction effect between fumigation and pepper hybrid with RKN density as the response variable (Fig. 1). The absence of either treatment (RKN-resistant pepper hybrid or 1,3-D fumigation) resulted in an RKN density of 750 RKNs per 100 g of soil, versus treatment with the resistant pepper hybrid or 1,3-D fumigation alone, which reduced densities to below 15 RKNs per 100 g of soil and 5 RKNs per 100 g of soil, respectively. The combination of a resistant pepper hybrid and 1,3-D fumigation resulted in a slightly lower postharvest RKN density of 4 RKNs per 100 g of soil. Furthermore, 1,3-D fumigation reduced root galling severity on the peppers by an average of 65% and reduced root galling on the subsequent cucumber crop by 73%. Cucumber yield was not significantly affected by preseason fumigation with 1,3-D.

Planting the RKN-resistant pepper hybrid SVPB4241 was the only treatment factor that resulted in a significant increase in pepper yield in the Kinston trial in 2021 (Table 3). The yield with the

resistant hybrid was 42% greater than that of the susceptible hybrid. SVPB4241 also significantly reduced the root galling severity by 70% and the RKN density after harvest by 98%. Planting of the RKN-resistant hybrid had a significant effect on the yield of the subsequent cucumber crop in the absence of 1,3-D fumigation. Cucumber yield was 41% higher by planting behind the RKN-resistant versus the susceptible pepper hybrid. Galling severity on cucumber roots was also significantly reduced by 85% when planted following the resistant pepper hybrid (Table 3).



**FIGURE 1**

Interaction effects of fumigant treatment and variety treatment that were significant at the 0.05 significance level at the Kinston, NC, trial in 2021 for **A**, cucumber yield and **B**, the number of second-stage juvenile (J2) root-knot nematodes (RKNs) per 100 g of soil.

**TABLE 3**  
Effect of 1,3-dichloropropene (1,3-D) fumigation and root-knot nematode (RKN)-resistant bell pepper hybrid on pepper and cucumber in Kinston, NC, in 2021

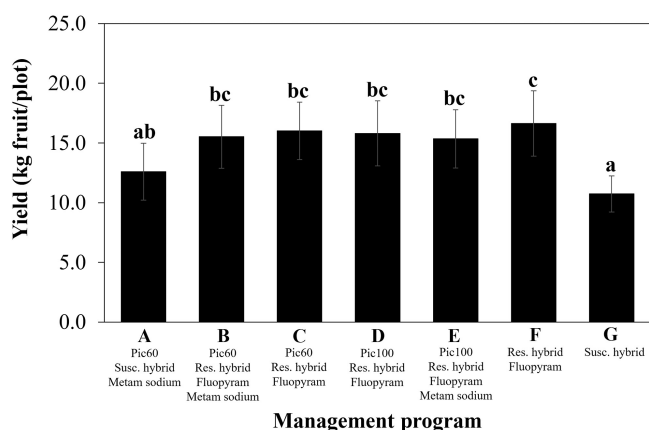
Parameter	Pepper yield (kg/plot) <sup>y</sup>	Pepper galling severity <sup>y</sup>	RKN count (J2s/100 g of soil) <sup>y</sup>	Cucumber yield (kg/plot) <sup>y</sup>	Cucumber galling severity <sup>y</sup>
Fumigation (F)					
1,3-D	8.74 ± 0.53	0.24 ± 0.05	3.80 ± 1.44	2.78 ± 0.33	0.78 ± 0.13
None	8.78 ± 0.56	0.68 ± 0.08	382.45 ± 126.02	2.66 ± 0.37	2.94 ± 0.39
<i>P</i> value	0.9442	<0.0001	<0.0001	0.7709	0.0003
Pepper hybrid (H)					
SVPB4241 (Res.)	10.30 ± 0.47	0.21 ± 0.05	8.65 ± 1.95	3.43 ± 0.32	0.49
SVPB7768 (Sus.)	7.22 ± 0.41	0.71 ± 0.08	377.60 ± 126.63	2.01 ± 0.31	3.24
<i>P</i> value	<0.0001	<0.0001	<0.0001	0.0019	<0.0001
F × H <sup>z</sup>	0.7456	N/A	<0.0001	0.0050	N/A

<sup>y</sup> Data are presented as the mean ± standard error.

<sup>z</sup> Interaction terms labeled F and H refer to fumigation and pepper hybrid, respectively.

## Elm City pepper harvest and evaluations

Pepper yield over the 3-year experiment in Elm City was numerically highest in each plot that was planted with the RKN-resistant pepper hybrid Hammerhead and combined with fluopyram application (management programs B to F), though these did not differ statistically from each other. Of these, only management program F was significantly higher than the grower standard treatment, program A (Fig. 2). Pepper yield in each treatment containing both Hammerhead and fluopyram application was significantly higher than the untreated control program, G. Pepper root vigor was numerically highest for management program B that received 1,3-D and chloropicrin fumigation, Hammerhead, and fluopyram application (Table 4). This did not statistically differ from management programs C and D but was significantly higher than other treatments. The untreated management program (G) had the lowest root vigor, significantly lower than any other management program. All management programs with the Hammerhead and fluopyram com-



**FIGURE 2**

Average bell pepper yield in kilograms per plot across a 3-year trial in Elm City, NC, from 2022 to 2024 for seven root-knot nematode (RKN) management programs. Programs that share a similar letter above the bar are not significant at the 0.05 significance level based on separation of means using Tukey's honestly significant difference. Error bars represent the standard error of the mean.

bination had higher root vigor than the grower standard program (A), though management program F did not differ significantly ( $P > 0.05$ ). Overall, low levels of root galling were observed on peppers across the Elm City experiment, but some differences were observed (Table 4). The highest galling indexes occurred on the untreated control program (G) and the grower standard program (A). These were statistically similar and did not differ from management program F. All other programs had significantly less root galling than the untreated and grower standard programs. There was no significant difference in the amount of blossom end rot-affected pepper fruits or plant mortality due to soilborne fungal disease between management programs (data not shown).

## Elm City cucumber harvest and evaluations

Cucumber yields averaged across the 3-year study in Elm City demonstrated numerically higher yields for each management program that included Hammerhead combined with fluopyram application (Fig. 3). These yields did not differ significantly from the grower standard program (A), but all these programs did result in significantly higher yields than the untreated control program (G), except for management program D, which was statistically similar to all other programs. The grower standard program (A) also did not differ from the untreated control, though it demonstrated numerically higher yields (Fig. 3). The untreated control management program (G) had the lowest vine vigor and was significantly lower than all other programs, except management program F (Table 4). No significant difference in cucumber vine vigor was observed between programs A, B, C, D, and E. Root vigor ratings after harvest were somewhat similar, with the lowest root vigor being in the untreated control program (G). This was statistically similar to program F but was significantly lower than all other tested management programs. Programs A, B, C, D, and E were all statistically similar for cucumber root vigor. Lastly, overall root galling severity was low on cucumbers each year of this experiment in Elm City. The most root galling was observed in the untreated control program (G), with a root gall index of 1.47 on a scale of 0 to 10. This was significantly higher than all other management programs, except program F, which had an index of 1.08. The lowest root galling was observed in management program E, and this was significantly lower than both programs F and G. Root galling in the standard grower management program (A) was similar to that of programs B, C, D, and F (Table 4).

**TABLE 4**  
Effect of nematode management program on pepper and cucumber in the Elm City, NC, experiments from 2022 to 2024

Program	Fumigant(s) <sup>w</sup>	Hybrid <sup>x,y</sup>	Pepper root vigor (1–10 index) <sup>z</sup>	Pepper root galling (0–10 index) <sup>z</sup>	Cucumber vine vigor (1–10 index) <sup>z</sup>	Cucumber root vigor (1–10 index) <sup>z</sup>	Cucumber root galling (0–10 index) <sup>z</sup>
A	Pic60 + metam sodium	Susc.	7.36 ± 0.11 b	1.69 ± 0.08 d	7.67 ± 0.25 bc	7.60 ± 0.09 bc	0.63 ± 0.09 ab
B	Pic60 + metam sodium	Res.	8.72 ± 0.14 e	0.85 ± 0.10 ab	8.07 ± 0.24 c	7.85 ± 0.11 bc	0.73 ± 0.10 ab
C	Pic60	Res.	8.37 ± 0.20 de	0.65 ± 0.09 a	8.07 ± 0.22 c	7.94 ± 0.11 bc	0.88 ± 0.11 ab
D	Pic100	Res.	8.19 ± 0.25 ce	1.16 ± 0.13 bc	7.43 ± 0.24 bc	7.80 ± 0.10 bc	0.81 ± 0.10 ab
E	Pic100 + metam sodium	Res.	7.98 ± 0.21 cd	0.76 ± 0.10 a	8.23 ± 0.16 c	8.16 ± 0.12 c	0.59 ± 0.10 a
F	None	Res.	7.79 ± 0.18 bc	1.37 ± 0.13 cd	7.07 ± 0.25 ab	7.27 ± 0.09 ab	1.08 ± 0.13 bc
G	None	Susc.	6.71 ± 0.08 a	1.72 ± 0.12 d	6.37 ± 0.19 a	6.56 ± 0.07 a	1.47 ± 0.13 c

<sup>w</sup> Pic60 and Pic100 applications were made at least 21 days prior to bell pepper transplanting, and metam sodium applications were made after the final pepper harvest and at least 14 days prior to seeding cucumbers.

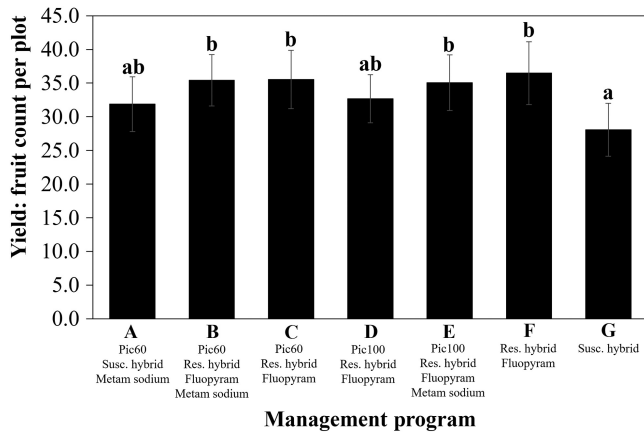
<sup>x</sup> Susc. refers to the root-knot nematode (RKN)-susceptible hybrid 'Tarpon', and Res. refers to the RKN-resistant hybrid 'Hammerhead'.

<sup>y</sup> Fluopyram applications were made to programs receiving the RKN-resistant hybrid.

<sup>z</sup> Vigor and galling index values are reported as mean ± standard error. Means followed by the same letter do not differ significantly ( $P = 0.05$ )

## Elm City nematode diversity and density

Bacterivore, fungivore, omnivore, and predator nematodes were present in the experimental trial field in Elm City during the trial period (2022 to 2024). There were no significant differences in population densities between management programs for each feeding type or the total number of free-living nematodes at the end of the season (Table 5). There were also no significant differences in the densities of spiral (*Helicotylenchus* spp.), stunt (*Tylenchorhynchus* spp.), stubby root (*Paratrichodorus* spp.), and ring (Criconematinae) nematodes between management programs (Table 6). RKNs (*Meloidogyne* spp.) were found at the highest densities in management programs A and G, the two programs planted with the RKN-susceptible pepper hybrid, but still did not differ significantly from the other management programs, which found zero or near zero RKNs after cucumber harvest (Table 6).



**FIGURE 3**

Average cucumber yield in number of fruits per plot across a 3-year trial in Elm City, NC, from 2022 to 2024 for seven root-knot nematode (RKN) management programs. Programs that share a similar letter above the bar are not significant at the 0.05 significance level based on separation of means using Tukey's honestly significant difference. Error bars represent the standard error of the mean.

## Discussion

The experiments presented here demonstrate the value of planting RKN-resistant pepper hybrids and the potential to reduce or eliminate reliance on 1,3-D fumigation. Higher pepper yields, improved vigor, reduced galling, and lower RKN densities were observed with the RKN-resistant varieties in the Kinston and Elm City experiments. These same observations, relative to susceptible varieties, have previously been well documented (Nnamdi et al. 2022; Thies and Fery 2002; Thies et al. 1998, 2004; Webster et al. 2001). For example, Nnamdi et al. (2022) found that the lowest root galling ratings were observed on the unfumigated RKN-resistant pepper hybrid versus the susceptible hybrid treated with 1,3-D fumigation. Similarly, Webster et al. (2001) observed that 1,3-D fumigation did not further reduce root galling on RKN-resistant hybrids when the treatments were combined. In the current Elm City study, combining the RKN-resistant pepper variety with 1,3-D and/or chloropicrin fumigation did not demonstrate any additional increase in pepper yield (Fig. 2), signaling no benefit of utilizing both RKN treatment methods. This is consistent with previous work by Thies and Fery (2002), who concluded that when planting a highly resistant pepper variety such as 'Carolina Cayenne', fumigation would not be needed even in heavily infested soils due to the RKN population suppression effect of resistant varieties (Thies and Fery 2002). Though the benefits of 1,3-D fumigation are well understood when planting a susceptible variety into an infested field, the option of eliminating this 1,3-D application through use of an RKN-resistant variety has many positive implications. The observations from the studies in Kinston and Elm City validate these previous conclusions that fumigation with 1,3-D may not be warranted when utilizing an RKN-resistant hybrid.

Continued use of chloropicrin fumigation, however, should still be considered for control of soilborne fungal pathogens in some fields. In the Elm City trial, combining chloropicrin fumigation with the RKN-resistant variety Hammerhead resulted in slightly improved pepper root vigor ratings and reduced root galling (Table 4), signaling a benefit to pepper root health. In a separate, preliminary on-farm experiment, Pythium root rot severely infected pepper plants in plots that received no chloropicrin treatment (data not shown). However, preliminary experiments in other fields suffered no disease from soilborne fungal pathogens in the absence of fumigation. This finding is consistent with what Webster et al. (2001)

**TABLE 5**  
Effect of nematode management program on free-living nematode populations in the Elm City, NC, experiments from 2022 to 2024

Program	Fumigant(s) <sup>w</sup>	Hybrid <sup>x,y</sup>	Bacterivore <sup>z</sup>	Fungivore <sup>z</sup>	Omnivore <sup>z</sup>	Predator <sup>z</sup>	Total free-living <sup>z</sup>
A	Pic60 + metam sodium	Susc.	1,187 ± 215	206 ± 53	12 ± 2	0	1,405 ± 219
B	Pic60 + metam sodium	Res.	1,195 ± 182	146 ± 75	13 ± 6	6 ± 6	1,360 ± 195
C	Pic60	Res.	1,294 ± 219	276 ± 125	14 ± 4	3 ± 3	1,587 ± 277
D	Pic100	Res.	1,648 ± 387	256 ± 84	9 ± 4	1 ± 1	1,914 ± 399
E	Pic100 + metam sodium	Res.	1,408 ± 388	144 ± 36	22 ± 10	1 ± 1	1,574 ± 392
F	None	Res.	1,340 ± 287	163 ± 57	22 ± 5	1 ± 1	1,526 ± 289
G	None	Susc.	1,443 ± 348	330 ± 117	10 ± 5	1 ± 1	1,784 ± 358
P value			0.96216	0.41243	0.22289	0.93302	0.91223

<sup>w</sup> Pic60 and Pic100 applications were made at least 21 days prior to bell pepper transplanting, and metam sodium applications were made after the final pepper harvest and at least 14 days prior to seeding cucumbers.

<sup>x</sup> Susc. refers to the root-knot nematode (RKN)-susceptible hybrid 'Tarpon', and Res. refers to the RKN-resistant hybrid 'Hammerhead'.

<sup>y</sup> Fluopyram applications were made to programs receiving the RKN-resistant hybrid.

<sup>z</sup> Nematode densities are given as mean count per 500 g of soil ± standard error.

observed in their field experiments in 1998. They noted significant losses in pepper plants due to *Pythium* in the absence of methyl bromide, methyl iodide, or chisel-applied 1,3-D with chloropicrin. It should be noted that the fungicidal activity of chloropicrin will remain valuable in a reduced fumigation system in fields with high levels of phytopathogenic fungi and oomycetes.

Southern RKNs may complete up to three or four life cycles on peppers in the southeast United States in a single crop season (Hajihassani et al. 2019a). Therefore, populations may rebound rapidly on a susceptible host after an initial fumigation treatment, as 1,3-D provides no residual control. In Kinston, a 98% reduction in RKN density was observed in plots planted with the RKN-resistant pepper hybrid versus the untreated control. In Elm City, density counts of RKN were relatively low across the 3 years of trialing. Despite this limitation, however, RKN densities above the treatment threshold (Dickerson et al. 2000) were found in both management programs utilizing the RKN-susceptible hybrid, with no real numerical difference between the fumigated and unfumigated plots. Few RKNs were found in any treatments containing the RKN-resistant pepper Hammerhead, but there was no significant difference in RKN density between any management programs due to high variability in densities between trial replications. The similarity in RKN density between management programs A and G suggests that 1,3-D and chloropicrin fumigation had little to no impact on RKN density by the end of the season. Plots planted with Hammerhead and treated with fluopyram maintained low levels of RKNs at the end of each season, even after planting a susceptible cucumber behind the resistant peppers.

Both the Kinston and Elm City trials demonstrated a positive effect on cucumber yield and cucumber root galling in plots following the RKN-resistant pepper hybrid. This effect on subsequent crops following an RKN-resistant variety has been well documented (Colyer et al. 1998; Djian-Caporalino et al. 2014; Hanna 2000; Navarrete et al. 2016; Thies et al. 2004). For example, Colyer et al. (1998) found that planting cucumbers after an RKN-resistant tomato variety resulted in higher cucumber yields, reduced root galling, and lower RKN densities than cucumbers grown after a susceptible tomato variety. Similarly, melons grown after an RKN-resistant tomato also resulted in higher yields and less root galling as opposed to those grown after a susceptible tomato (Hanna 2000). Lastly, Thies et al. (2004) demonstrated that squash grown behind

the RKN-resistant pepper ‘Charleston Belle’ yielded 55% higher and cucumbers 87% higher compared with those planted following a susceptible pepper hybrid. Root galling severity on the squash and cucumbers were also significantly lower when planted behind the RKN-resistant variety, with fewer eggs per gram of root, signifying reduced reproduction on resistant hybrids (Thies et al. 2004).

A second goal of the Elm City study was to examine the change in plant-parasitic and free-living nematode taxa over time under the different management programs. To our knowledge, this has never been evaluated over multiple years in a pepper-cucumber rotation with varying fumigation practices. An initial hypothesis was that eliminating the 1,3-D fumigation component would potentially result in an increase of non-RKN plant-parasitic nematodes and of free-living nematodes over time. However, analysis across the 3 years of trialing in which management programs were repeated in the same plot footprint year after year revealed no significant differences in spiral, stunt, stubby root, or ring nematode population densities between management programs. Similarly, there was no difference in bacterivore, fungivore, omnivore, or predator nematode types between management programs. This differs from work by Grabau et al. (2020), who found that 1,3-D fumigation negatively impacted the population density of fungivores. Furthermore, Collins et al. (2006) found that fumigation with metam sodium and 1,3-D resulted in a significant decline in total free-living nematode populations. However, soil samples from that study were collected prior to planting and much closer to the time of fumigant application than what was performed at the current Elm City study. This may account for some of the differences, as the Elm City study was sampled for nematode density at the end of the season, 7 to 8 months after the initial fumigant treatments were applied, which may have allowed time for populations to rebound. Previous work has shown that fumigation negatively impacts microbial and nematode communities in the short term, but they may quickly recover (Wang et al. 2006; Yeates et al. 1991). Other studies, however, have demonstrated that nematode populations may not fully recover even over 4 years after the fumigation application (Yeates and van der Meulen 1996).

Proper selection of RKN management practices is critical for the effective and sustainable production of vegetable crops. Rising input costs, regulatory hurdles, and supply constraints highlight the importance of examining alternative RKN management programs.

**TABLE 6**  
Effect of nematode management program on plant-parasitic nematode (PPN) populations in the Elm City, NC, experiments from 2022 to 2024

Program	Fumigant(s) <sup>w</sup>	Hybrid <sup>x,y</sup>	Spiral <sup>z</sup>	Stubby root <sup>z</sup>	Stunt <sup>z</sup>	Ring <sup>z</sup>	RKN <sup>z</sup>	Total PPN <sup>z</sup>
A	Pic60 + metam sodium	Susc.	83 ± 30	1 ± 1	0	1 ± 1	45 ± 45	130 ± 62
B	Pic60 + metam sodium	Res.	85 ± 36	4 ± 1	3 ± 3	0	1 ± 1	93 ± 38
C	Pic60	Res.	59 ± 20	7 ± 2	3 ± 3	3 ± 3	1 ± 1	72 ± 21
D	Pic100	Res.	69 ± 29	4 ± 2	3 ± 3	0	0	76 ± 29
E	Pic100 + metam sodium	Res.	40 ± 12	2 ± 1	0	28 ± 25	0	70 ± 28
F	None	Res.	112 ± 48	3 ± 2	0	10 ± 7	0	125 ± 48
G	None	Susc.	136 ± 47	3 ± 2	0	0	49 ± 37	188 ± 58
<i>P</i> value			0.98782	0.13513	0.67713	0.74496	0.16907	0.97833

<sup>w</sup> Pic60 and Pic100 applications were made at least 21 days prior to bell pepper transplanting, and metam sodium applications were made after the final pepper harvest and at least 14 days prior to seeding cucumbers.

<sup>x</sup> Susc. refers to the root-knot nematode (RKN)-susceptible hybrid ‘Tarpon’, and Res. refers to the RKN-resistant hybrid ‘Hammerhead’.

<sup>y</sup> Fluopyram applications were made to programs receiving the RKN-resistant hybrid.

<sup>z</sup> Nematode densities are given as mean count per 500 g of soil ± standard error.

The negative impacts that fumigants such as 1,3-D may have on soil microbial communities and soil health are becoming better understood (Dangi et al. 2017; Grabau et al. 2020), and growers are facing increasing pressure for more environmentally sustainable production practices. RKN management becomes even more important in double crop systems, where RKN populations may reach devastating levels prior to planting the second crop (Desaeger and Csinos 2006). In these situations, shank-applied fumigation is impossible due to plastic mulch covering the planting beds, and drip-applied fumigants are often ineffective in these systems due to uneven distribution of the chemical in the bed, rapid volatilization out of the planting holes, or plant-back date restrictions (Desaeger and Csinos 2006). Previous work to evaluate the effectiveness of RKN-resistant varieties in reducing RKN damage and controlling RKN populations in the soil, relative to traditional approaches of soil fumigation, have concluded that RKN-resistant vegetable varieties provide a safe and cost-effective method for managing RKNs and should be a part of integrated pest management programs in vegetables (Thies and Fery 2002; Webster et al. 2001). Commercially, use of RKN-resistant pepper varieties has not been widely adopted, as these varieties have occasionally resulted in lower yields (Nnamdi et al. 2022) and may lack other desirable disease resistance traits or fruit quality traits. The current study demonstrates the ability of an advanced pepper hybrid, Hammerhead, when combined with fluopyram application, to reduce nematode damage, lower soil RKN populations, and maintain or increase yield potential above the current standard grower practices for both the pepper itself and a subsequently planted cucumber, regardless of fumigation application. These results highlight the potential to eliminate some fumigant components from a grower management program and replace them with RKN-resistant varieties and effective non-fumigant nematicides such as fluopyram. Inclusion of a non-fumigant nematicide, such as fluopyram, in a reduced fumigant program is important for genetic resistance management and control of non-RKN plant-parasitic nematode species. Fluopyram has demonstrated efficacy against a broad spectrum of plant-parasitic nematode species (Desaeger et al. 2020) while having a reduced impact on beneficial and free-living microorganisms (Grabau et al. 2020; Watson and Desaeger 2019). Chloropicrin will certainly remain an important piece of an integrated disease management program moving forward for many production fields in which control of soilborne fungal pathogens is needed. Similarly, although metam sodium application did not appear to have a significant impact on root galling, RKN density, or crop yield in this study, it is commonly applied between crop cycles for weed control (Dayton et al. 2017). In the absence of other weed control options, this may continue to be a necessary application for that purpose but poses no observed benefits for RKN management based on the current study. However, elimination of 1,3-D in favor of RKN-resistant varieties seems like a viable option given the results of the current study and that of previous work discussed here.

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