Crop Losses in Corn Induced by *Rhizoctonia solani* AG-2-2 and Nematodes

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ABSTRACT

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Field corn was grown for 3 yr in a Fuquay loamy sand soil infested with *Rhizoctonia solani* AG-2-2. Grain yields averaged 6,890 and 8,760 kg/ha, with high and low inoculum levels, respectively, compared with 9,890 kg/ha for noninfested plots. Yields were reduced 47, 42, and 8% in soil infested with the high inoculum level and 15, 19, and 1% with the low inoculum level from the first through the third years, respectively, compared with noninfested soil. The percentage of crown and brace roots with terminal decay 7–8 wk after planting had a highly significant effect on grain yield each year. The root disease index, the total number of crown and brace roots per plant, the number of roots without lesions, and nematodes explained 44–47% of the variation in yield each year.

Additional keywords: Criconemella ornata, Meloidogyne incognita, Paratrichodorus minor, Pratylenchus spp.

Crown and brace root rot of corn (*Zea mays* L.) is induced by isolates of anastomosis group (AG)-2-2 of *Rhizoctonia solani* Kühn (5,15,21,22). The fungus causes reddish-brown lesions on the roots and may kill the apices. Seedlings may be killed or stunted, and mature plants may lodge because of lack of support. In the Georgia coastal plain, the fungus is widely distributed and has been isolated from diseased corn roots in 17 counties. The disease occurs commonly in both sand and loamy sand in rotations with peanut and soybean, and in continuous corn. The pathogen may survive several months in fallow soil (2).

Numerous nematodes and fungi induce corn root diseases in Georgia, but the role of specific fungi in yield losses has not been investigated (13,14,23,25,27). This research was undertaken to determine the influence of *R. solani* AG-2-2 on grain yield in corn, and to determine if nematodes interact with the fungus to increase yield losses.

MATERIALS AND METHODS

Density and placement of AG-2-2 inoculum. A split-split plot design with four replicates was used to determine the influence of inoculum density and placement on root disease severity and plant growth. Each experimental unit was a 9.6-L plastic container filled with heat-treated (82 C for 2 hr with aerated steam) Tifton loamy sand soil infested with *R. solani* AG-2-2 (isolate Rhs-36 from diseased corn roots in Baker County, GA) and planted with three seeds of cultivar Funks G-4507 hybrid corn. Inoculum, grown on a cornmeal-sand mixture (3%, w/w) for 4 wk, was mixed with soil at 1:400 or 1:2,000 (v/v; subplots) by blending in a concrete mixer along with 33, 67, and 100 μg/g of N, P, and K, respectively. Infested soil was placed in the containers in layers 0–7.5, 7.5–15, or 0–15 cm deep before planting (sub-subplots); the remainder of the soil was noninfested. Seeds were planted 3 cm deep 3–5 days after infestation. Whole plots in each replicate either were not treated, or were treated with pencycuron 75WP (14.4 μg a.i./ml) applied as a drench after planting. Pencycuron is a nonsystemic fungicide effective against *R. solani* (20). Two other similar experiments were conducted with infested peanut hulls as inoculum, but not including a pencycuron treatment.

Soil samples (three cores, 2.5 cm in diameter) were taken 0–7.5 and 7.5–15 cm deep in two replicates of each subplot 1 wk after pencycuron was applied. Soil was assayed on tannic-acid benomyl agar (TABA) (21) with a multiple-pellet soil sampler (7) for *R. solani* AG-2-2. Pots were fertilized weekly with NH_4NO_3 beginning 3 wk after planting (a total of 112 μg of N/g of soil was applied). Plants were harvested 6 wk after planting and roots were rated for root disease severity on a scale of 1–5 where 1 = <2, 2 = 2–10, 3 = 11–50, 4 = >50% discoloration and decay, and 5 = dead plant. The total number of crown and brace roots and the number with lesions or terminal decay were counted 0–5, 5–10, and >10 cm below the soil surface, and fibrous root and mesocotyl lesions were counted. The average daily increase in height was calculated 11–42 days after planting.

Field experiments. Experiments were conducted for 3 yr on the same site (1984–1986) in a field of Fuquay sand (loamy, siliceous, thermic, Arenic Plinthic Paleuduts) naturally infested with the nematodes, *Meloidogyne incognita* (Kofoid & White) Chitwood, *Criconemella ornata* (Raski) Luc & Raski, *Pratylenchus* spp., and *Paratrichodorus minor* (Colbran) Siddiqi, but not with *R. solani* AG-2-2 at the Coastal Plain Station. The experimental area was prepared in March by disk-harrowing and plowing 20–25 cm deep with a moldboard turning plow. Each year, soil was tested and fertilizer (K_2SO_4, $MgSO_4$, and NH_4NO_3) at recommended rates for producing 13,000 kg/ha (29) of grain was spread and incorporated by disking before planting, and by side-dressings 6–10 wk after planting. In the last 2 yr of the study, soil was subsoiled 40–45 cm deep under the row just before planting to reduce soil compaction and promote root growth. Corn was irrigated with overhead sprinklers as necessary.

Inoculum. Inoculum of *R. solani* AG-2-2 was grown on 3% cornmeal sand (w/w) for 2–3 wk. Inoculum was spread by hand in a band 60 cm wide over the row at 1,430 kg/ha (high inoculum density) or 238 kg/ha (low inoculum density) in 1984 and 1985. In 1986, inoculum was distributed over entire plots at 1,144 kg/ha and 143 kg/ha, respectively. Controls were noninfested and nonamended. Corn was planted on the same site each year, but treatments were randomized separately in each experiment. Immediately after application, inoculum was incorporated 5 cm deep with a tractor-driven roto-tiller, and the corn planted by machine in rows 0.91 m apart at approximately 79,000 seeds/ha. Cultivar Pioneer 3320 was planted in 1984 and Funks G-4614 in 1985 and 1986. Both were susceptible to *R. solani* AG-2-2. In a greenhouse experiment with nine commercial field corn hybrids and one sweet corn hybrid, all hybrids were susceptible

to *R. solani* AG-2-2.

Pesticides. Immediately after planting each year, each inoculum density level was treated with pencycuron (9.14 kg a.i./ha) (18) applied as a drench over the row in a band 60 cm wide (690 ml water/m^2) or not treated. Experiments were irrigated with 1.2 cm of water after treatment. In the last 2 yr, fenamiphos, a systemic, broad-spectrum nematicide, was included to ascertain the role of nematodes in the root-rot complex. Fenamiphos (6.72 kg a.i./ha) was applied in a band 60 cm wide over the row as a drench (6,900 L/ha) in 1985. The nematicide was applied as a spray (935 L/ha) in 1986 before the inoculum was spread, and the fenamiphos and inoculum were incorporated simultaneously.

Randomized complete block designs were used for all experiments. In the first 2 yr, experiments were arranged in a factorial with five replicates. Plots were 0.9 × 11.4 m. In 1986, a split-plot design was used with levels of inoculum density as whole plots (four replicates) and chemical treatments as subplots. Whole plots were 11 × 23 m, and subplots were 3.7 × 7.6 m.

In 1984, a mixture of alachlor (2.1 kg a.i./ha) plus atrazine (1.26 kg a.i./ha) was applied preemergence 4 days after planting, and in 1985 alachlor (2.47 kg a.i./ha) plus atrazine (1.47 kg a.i./ha) was applied the day after planting for weed control. In 1986, tridiphane (0.56 kg a.i./ha) plus atrazine (1.68 kg a.i./ha) was applied postemergence when the corn was in the V2–V3 (16) stage.

Nematodes. Soil samples (10 cores/plot, 2.5 cm diameter, 30 cm deep) were collected 12 June 1984; 13 March (1 day before application of inoculum and pesticides), 19 April, and 8 July 1985; and 11 March, 1 May, and 24 July 1986. Nematodes were extracted from 150 cm of soil by centrifugal-sugar flotation (9). Roots were examined for injury by stubby-root or root-knot nematodes, but nematodes were not extracted from roots.

Root disease severity. Plants were harvested (5–10 plants per plot) 7–8 wk after planting (V5–V7 stage) (16), and crown, brace, and lateral roots (10) were washed and rated for crown and brace root rot on a scale of 1–5, as previously described. Also, five plants per plot were harvested and rated after harvest (17 wk) in 1984. The total number of crown and brace roots, the number without lesions (white), and the number of roots with lesions or terminal decay 0–5, 5–10, and >10 cm below the soil surface were counted.

Tissue sections (5–10 mm) from 30–50 root lesions were selected at random in different treatments, surface-disinfested for 15–30 sec in 70% ethanol, blotted dry on sterile filter paper, and incubated on water agar in Petri dishes. Hyphal tips were transferred to potato-dextrose agar (PDA), and cultures of *R. solani* were identified to AG by pairing with known tester isolates (21).

Soil assays. Ten soil cores (2.5 cm diameter) 5–7 cm deep were taken in the row in each plot 16 and 39 days after planting in 1984 and 1985, respectively. Soil cores from each plot were mixed and assayed on TABA with a multiple-pellet soil sampler. Colonies of fungi that resembled *R. solani* were transferred to PDA, and cultures of *R. solani* were identified to AG by pairing with known tester isolates (21).

Plant growth and grain yield. Average plant height in each plot was recorded weekly or biweekly from 4–5 wk after planting until tasseling, and the average daily gain in height was computed for each plot. Grain in each plot was harvested as high moisture corn (26–30% moisture), dried in an oven, and shelled. Grain was weighed, and weights were adjusted to 15.5% moisture.

Greenhouse experiments with fenamiphos. In February 1986 and November 1988, moist Tifton loamy sand soil was collected from the field site and was used to study the interaction of fenamiphos with *R. solani* AG-2-2 in the greenhouse. Factorial experiments in randomized complete block designs with four replicates were conducted. From each collection, four experiments were prepared during a 2-day period. Soil was blended in a concrete mixer with 58, 71, 40, 44, and 44 μg/g of N, P, K, S, and Mg, respectively, and placed into 2-L plastic containers to 6 cm below the rim. Soil treated with fenamiphos or infested with cornmeal-sand cultures of *R. solani* AG-2-2, or both, was layered 5 cm deep over the nontreated soil to simulate the treatments that were 5 cm deep in applications in field soils. Fenamiphos (360 mg a.i./ml) was sprayed on soil during mixing at 0, 1.1, 2.2, or 4.3 mg a.i./L (equivalent of 1.68, 3.36, and 6.72 kg/ha) and *R. solani* AG-2-2 (cornmeal-sand cultures) was mixed at 0, 1:400, 1:2,000, or 1:4,000 (v/v). In each container, half of the treated soil was placed over the nontreated soil, four seeds of the corn cultivar Funks G4614 were planted, and the seeds covered 2.5 cm deep with the remainder of the soil. The soil in the containers was watered to bring the soil to the water holding capacity (approximately 8%). Each year, plants were removed from one complete experiment and the roots washed and evaluated for root disease severity 3, 7, 14, or 28 days after planting to observe the affects of treatments with time. The variances in the root disease index were compared in 1986 and 1988 with the *F*-ratio test (18).

Data were analyzed with least squares analysis of variance linear regression and stepwise multiple regression statistical procedures. Various linear comparisons were tested with the *F*-test (18).

RESULTS

Greenhouse experiment with inoculum of *R. solani* AG-2T2. Neither the inoculum level nor the depth of placement of the inoculum influenced significantly the number of lesions in the 0–5 cm depth of topsoil, or the total number of lesions on the crown and brace roots (Table 1). The higher inoculum level reduced the average daily growth and the dry foliage weight, compared with the lower inoculum level, but depth of soil infestation did not influence growth. Results were similar in other tests where infested peanut shells were used as inoculum (data not shown). The number of roots with lesions in the top 5 cm of soil was reduced by 93% in soil treated with pencycuron compared with nontreated soil, and the average daily growth and dry foliage weight were similar in pencycuron-treated soil and noninfested soil. However, there were no differences in the number of lesions on roots 5–10 cm deep between nontreated soil and soil treated with pencycuron (data not shown), and treatment with pencycuron increased the number of lesions on roots 10–15 cm deep (Table 1). The regression of dry foliage weight on the number of crown and brace roots that developed normally (no lesions) was highly significant ($P = 0.01$), $R^2 = 0.31$) (Fig. 1). In a multiple regression analysis, the root disease severity rating plus the total number of crown and brace roots with lesions explained 53% of the variation in dry foliage weight. The average dry foliage weight was 41% less in infested soil not treated with the fungicide than in noninfested soil.

Lesions in soil treated with pencycuron frequently were fewer and smaller in soil 0–5 cm deep, and more abundant below 7.5 cm deep than in nontreated soil. Root volume appeared to be two- to three-fold greater in soil treated with pencycuron, especially at the 7.5–15 cm depth.

Colony-forming units (cfu) of *R. solani* AG-2-2 were not detected in pencycuron-treated soil assayed on TABA. Population densities in nontreated, infested soil averaged 4.7 cfu/100 g of oven-dried soil 0–7.5 cm deep, but the pathogen was not detected in soil 7.5–15.0 cm deep.

Field experiments. The percentage of crown and brace roots with terminal decay 7–8 wk after planting had a highly significant ($P = 0.01$) effect on grain yield each year; $R^2 = 0.28$, 0.37, and 0.34 for 1984, 1985, and 1986, respectively (Fig. 2). Each year, 44–47% of the variation in yield could be explained with a multiple regression analysis that included the root-disease index, the total number of crown and brace roots per plant, the number of roots with no lesions, and population densities of *M. incognita, P. minor,* and *Pratylenchus* spp. in soil in May and July.

In 1984, roots were evaluated for root disease severity at both 7 and 17 wk after planting (Table 2). An average of 86, 77, and 0% of the crown and brace roots had lesions (of any kind) on plants grown in soil infested with high and low inoculum levels and in noninfested soil, respectively, 7 wk after planting. In contrast, all of the crown and brace roots had lesions 17 wk after planting on plants grown in infested soil, whereas only 14%

TABLE 1. Root disease severity, growth rate, and dry foliage weight of corn grown 6 wk in soil infested with *Rhizoctonia solani* AG-2-2 in a greenhouse[a]

		Crown and brace roots[b]						
			With lesions (depth, cm)					
		Without lesions	0–5	10–15	0–15	RDI[c]	Average daily growth (cm/day)	Dry foliage weight (g)
Fungicide								
Pencycuron		8.4	0.7	11.6	15.3	1.9	1.70	11.50
None		4.2	10.5	2.8	18.2	3.0	1.48	7.78
Soil treatments								
Inoculum[d] level	Depth of infestation (cm)							
1:400	0–7.5	4.2	5.6	4.5	13.4	2.8	1.44	7.78
	7.5–15	3.8	7.9	3.7	16.0	2.8	1.54	7.53
	0–15	4.8	6.6	11.2	21.9	2.5	1.46	8.31
1:2,000	0–7.5	4.9	7.6	8.0	20.4	2.5	1.58	11.03
	7.5–15	4.8	6.0	9.7	22.0	2.5	1.72	11.46
	0–15	5.4	5.1	5.3	14.8	2.5	1.66	9.29
None	None	16.1	0.4	7.8	7.9	1.8	1.73	12.21
Comparisons of interest[e]								
Pencycuron vs. no fungicide		0.01	0.01	0.01	0.05	0.01	0.01	0.01
Inoculum level		NS	NS	NS	NS	NS	0.05	0.01
Depth of infestation								
0–7.5 vs. 7.5–15 cm		NS	NS	NS	NS	NS	NS	NS
7–5-15 vs. 0–15 cm		NS	NS	0.01	NS	NS	NS	NS
Control vs. infested soil		0.01	0.01	NS	0.01	0.01	NS	0.01

[a]Soil treated with aerated steam for 2 hr at 82 C before infestation.
[b]Total roots on three plants.
[c]Root disease index: 1 = <2, 2 = 2–10, 3 = 11–50, and 4 = >50% root discoloration and decay, and 5 = plant dead.
[d]Ratio of cornmeal-sand (3%, w/w) to heat-treated soil.
[e]$P = 0.01$ or 0.05; NS = no significant differences, according to least squares analysis of variance linear comparisons tested with the F-test.

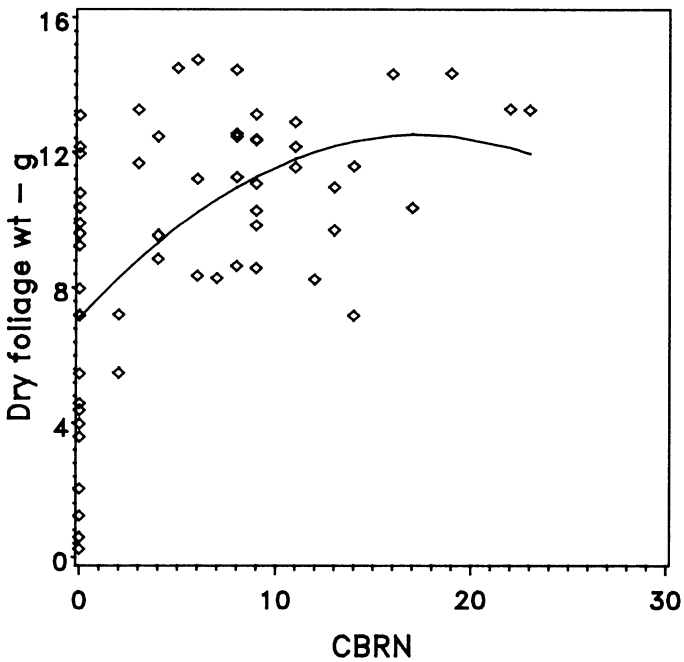

Fig. 1. Oven-dry foliage weight of corn regressed against crown and brace roots without lesions (normal) (CBRN) induced by *Rhizoctonia solani* AG-2-2. Each observation represents three 6-wk-old plants in the V8 to V9 stage (16).

had lesions in noninfested soil. In soil infested with high and low inoculum levels and treated with pencycuron, 4 and 0% of the crown and brace roots had lesions at 7 wk and 19 and 38% at 17 wk, respectively. At 17 wk in infested soil, terminal decay was most severe in the top 5 cm of soil, whereas in infested soil treated with pencycuron the terminal decay was greatest at the 5–10 cm depth.

There were no significant differences in plant emergence, and postemergent plant death averaged 8%. In soil infested with the highest inoculum level, numerous plants were chlorotic and stunted soon after emergence, and remained stunted throughout the growing season. Two weeks after mid-silk, 47, 11, and 1% of the plants were <170 cm tall in soil infested with high and low inoculum levels and noninfested, respectively. A few plants in soil infested with a high level of inoculum never grew taller than 30 cm. In infested soil treated with pencycuron, stunting and chlorosis were rare, and plants were similar to those in noninfested soil.

In 1985, fenamiphos interacted with the high inoculum level of *R. solani* AG-2-2 to decrease plant stand 85% compared with noninfested soil. When pencycuron was included with fenamiphos, plant stand was decreased only 35% (Table 3). There was no reduction in plant stand by fenamiphos, pencycuron, or fenamiphos + pencycuron treatments in noninfested soil compared with plants in nontreated, noninfested soils.

Crown and brace roots with dead, decayed root apices were most frequent in the top 5 cm of soil infested with *R. solani* AG-2-2, with or without fenamiphos (Table 3). In infested soil treated with pencycuron or pencycuron + fenamiphos, crown and brace roots with killed apices were more numerous at the 5–10 cm depth than at the 0–5 cm depth.

The average daily gain in height was greatest in pencycuron + fenamiphos treated noninfested soil (Table 3). Multiple regression analysis indicated that 67% of the variation in height 7 wk after planting and 57% of the growth rate from 6 wk after planting through silking were explained by the number of crown and brace roots with apical decay in the top 5 cm of soil plus the total number of crown and brace roots per plant.

Grain yield was greater in 1985 than 1984 (average of 10,044 kg/ha vs. 5,295 kg/ha), but the difference in yield between infested and noninfested soil was similar each year. Fenamiphos applied to plots infested with *R. solani* AG-2-2 reduced yield, but

pencycuron increased yield in infested soil (Table 3). In contrast, in soil not infested with *R. solani* AG-2-2, nematicide and fungicide treatments had negligible influence on yield.

Nematode populations of all nematode species were low in 1985 and not related significantly to root disease severity or grain yield (Table 4). In 1986, population densities of *M. incognita* in the soil on 24 July, plus the number of crown and brace roots without lesions, explained 46% of the variation in grain yield.

In 1986, there was no significant difference in emergence or plant stand between infested and noninfested soil. There were more stunted plants in infested soil than in noninfested soil through 4–5 wk after planting, but there were no significant differences in height among treatments at midsilk. Fenamiphos did not reduce plant stand in soil infested with a high level of inoculum of AG-2-2, but grain yield was reduced 30% compared with noninfested soil treated with nematicide. Crown and brace root rot and overall root disease severity were most severe in soil infested with AG-2-2 treated with fenamiphos, especially on roots in the top 10 cm of soil (Table 5). In soil infested with a low level of AG-2-2 inoculum and treated with fenamiphos, root disease was not severe enough to cause a yield loss, and yield was significantly greater in soil treated with fenamiphos than in infested soil not treated with fenamiphos. In noninfested soil, pencycuron + fenamiphos increased yield compared with pencycuron alone, but yield in the fenamiphos treated soil was not different from yield in the control.

Soil assays. In 1984, colonies of *R. solani* AG-2-2 were detected in soil from only three of 10 infested plots and never from soil in plots treated with pencycuron or noninfested plots. Populations averaged 2.6 cfu/100 g of oven-dried soil in infested, nontreated plots. In 1985, the pathogen was detected in soil from two of 10 plots each in infested soil and infested soil treated with fenamiphos, and in only one of 20 plots from infested soil treated with pencycuron or pencycuron + fenamiphos. Population

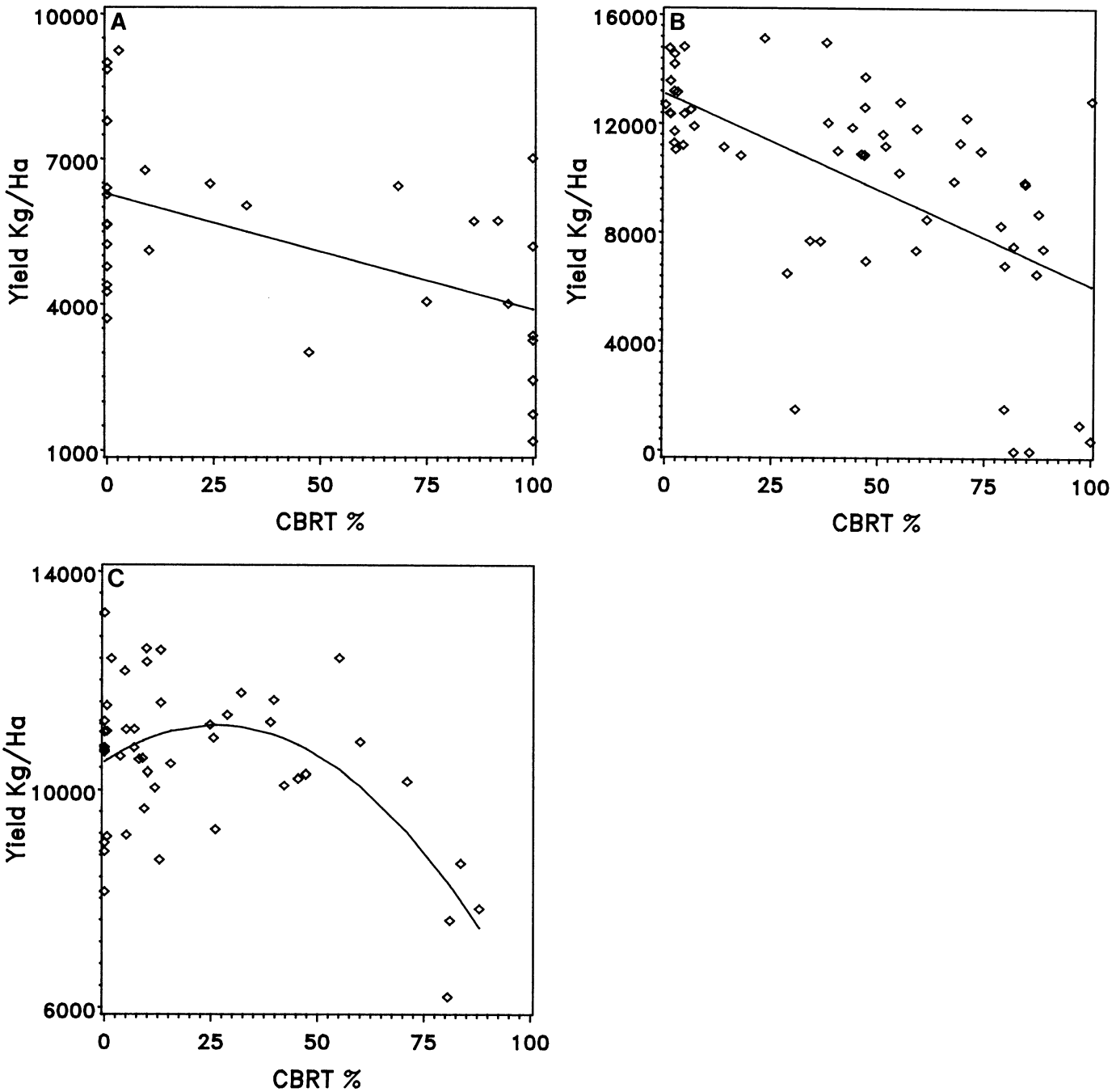

Fig. 2. Yield of corn grain regressed against percentage of the crown and brace roots with apices terminated (CBRT%) by *Rhizoctonia solani* AG-2-2 in **A**, 1984, **B**, 1985, and **C**, 1986. $R^2 = 0.28$, 0.37, and 0.34 during 1984–1986, respectively.

densities in infested plots with no pesticide treatment averaged 1.9 cfu/100 g of oven-dried soil.

Isolations from roots. The pathogen was isolated from 10, 9, and 33% of the lesions on crown and brace roots from 3- to 8-wk-old plants grown in infested soil during 1984–1986, respectively. In noninfested soil, the fungus was not isolated in 1984, but was isolated from 21 and 31% of lesions in 1985 and 1986. Because the plots were rerandomized each year, the noninfested plots may have been infested the previous year. The fungus could not be reisolated from lesions on 17-wk-old plants in 1984, and no attempt was made to isolate the fungus from root lesions late in the season in the last 2 yr.

Greenhouse experiments with fenamiphos. Diurnal soil temperatures ranged from 4 to 39 C in 1986 and from 9 to 41 C in 1988 during the eight experiments grown 3, 7, 14, and 28 days, respectively. Variances were homogenous in 1986 and 1988 in experiments harvested at 3 days, but were different in experiments harvested at 7, 14, and 28 days after planting. For the harvests at 7 and 14 days, the variances were greater in 1988 than in 1986, but the reverse was true for experiments harvested at 28 days. Means of root disease severity with different inoculum levels and rates of fenamiphos at 7, 14, and 28 days are shown in Table 6. Two days after seeding, epicotyls were 1 cm long and radicals were 7–15 mm long. Three days after planting radicals and

TABLE 2. Plant stand, height, root disease severity, and grain yield of corn grown in soil infested with different levels of inoculum of *Rhizoctonia solani* AG-2-2 and treated with a fungicide, 1984

				Crown and brace roots[c], 7 wk				Crown and brace roots[d], 17 wk			
	Plants/3 m of row 17 wk	Height (cm) 13 wk	RDI[b] 7 wk	Without lesions	With lesions (depth, cm) 0–5	5–10	RDI 17 wk	Without lesions	With lesions (depth, cm) 0–5	5–10	Grain yield (kg/ha)
Treatment[a]											
HIL	14.4	178	3.7	6.6	39.4	3.4	4.0	0.0	35.0	19.0	3,050
LIL	15.4	194	3.0	11.0	30.8	6.8	4.0	0.0	44.2	15.6	4,870
None	15.0	214	1.0	49.2	0.0	0.0	1.6	59.2	3.4	3.6	5,740
HIL + P	17.2	225	1.1	43.2	0.0	3.0	2.2	44.0	4.8	13.6	6,740
LIL + P	14.8	216	1.1	43.6	0.0	1.6	2.1	40.0	6.0	13.8	6,210
P	17.2	223	1.0	44.8	0.0	0.0	1.2	48.2	0.6	2.4	6,460
Comparisons of interest[e]											
Inoculum level (I)	NS	NS	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	NS
Fungicide (F)	0.05	0.01	0.01	0.01	0.01	0.05	0.01	0.01	0.01	NS	0.01
I × F	NS	NS	0.01	0.01	0.01	NS	0.01	0.01	0.01	0.01	0.05

[a] HIL = High inoculum level, 1,430 kg/ha; LIL = low inoculum level, 238 kg/ha; P = pencycuron.
[b] RDI = Root disease index: 1 = <2, 2 = 2–10, 3 = 11–50, 4 = >50% discoloration and decay; 5 = dead.
[c] Total roots on four plants.
[d] Total roots on five plants.
[e] $P = 0.0$ or 0.05; NS = no significant differences, according to least squares analysis of variance linear comparisons tested with the *F*-test.

TABLE 3. Emergence, plant growth, root disease severity, and grain yield in corn grown in soil infested with different inoculum levels of *Rhizoctonia solani* AG-2-2, and treated with pesticides, 1985

					Crown and brace roots[d]					
	Plants per 4.6-m row 19 days	Stunted plants (<15 cm tall) 6 wk	ADG[b] cm/day	RDI[c] 8 wk	Without lesions	With lesions (depth, cm) 0–5	5–10	>10	Root apices killed	Grain yield (kg/ha)
Treatment[a]										
HIL	28.6	3.2	3.82	3.8	9.8	67.4	20.2	2.8	65.2	7,610
LIL	32.2	1.2	4.09	4.0	12.8	64.0	20.2	4.2	55.0	10,640
None	31.6	0.2	4.54	1.5	76.2	0.6	2.6	2.2	2.8	13,070
HIL + P	30.2	0.4	4.38	3.3	28.8	28.4	23.4	5.8	39.6	12,030
LIL + P	31.2	1.0	4.54	3.1	27.4	28.6	22.6	6.2	43.4	12,350
P	31.4	0.4	4.47	1.7	79.2	2.2	5.0	1.6	5.0	11,980
HIL + F	4.8	2.4	0.77	3.9	3.8	46.6	7.8	1.2	48.8	2,850
LIL + F	23.4	2.0	3.68	4.0	6.6	68.0	19.6	3.0	70.6	6,930
F	30.2	0.2	4.52	1.7	87.4	7.2	3.2	1.2	4.0	12.760
HIL + P + F	20.6	3.0	4.29	3.1	47.0	20.0	24.0	6.4	33.8	7,680
LIL + P + F	30.6	1.0	4.62	3.0	36.2	22.8	25.8	5.2	41.4	10,630
P + F	32.2	0	4.70	1.4	86.6	0.8	2.0	1.4	3.8	12,790
Comparisons of interest[e]										
Inoculum level (I)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Pencycuron (P)	0.01	0.05	0.01	0.01	0.01	0.01	0.05	0.01	0.01	0.01
Fenamiphos (F)	0.01	NS	0.01	NS	NS	NS	NS	NS	NS	0.01
I × P	0.05	NS	0.01	NS	0.01	0.01	NS	NS	0.01	0.05
I × F	0.01	0.05	0.01	NS	NS	0.05	NS	NS	0.05	0.01
P × F	0.01	NS	0.01	0.05	0.05	NS	NS	NS	NS	NS
I × P × F	NS	0.05	0.01	NS	NS	NS	NS	NS	NS	NS

[a] HIL = High inoculum level, 1,430 kg/ha; LIL = low inoculum level, 238 kg/ha; P = pencycuron; F = fenamiphos.
[b] Average daily gain in height (slope).
[c] Root disease index: 1 = <2, 2 = 2–10, 3 = 11–50, and 4 = >50% discoloration and decay; 5 = plant dead.
[d] Total roots on four plants.
[e] $P = 0.01$ or 0.05; NS = no significant differences, according to least squares analysis of variance linear comparisons tested with the *F*-test.

epicotyls averaged 48 and 10 mm long, respectively, and there was no discoloration or decay. Fenamiphos significantly reduced epicotyl length from 4 to 19% as rates were increased from 1.1 to 4.3 mg a.i./L of soil in 1986, but there were no differences in 1988. There were no differences in growth between infested and noninfested soil. Plants began emerging 5 days after planting, and root discoloration and decay was observed 7 days after planting when an average of 5, 16, 24, and 72% of the seminal roots had lesions in the 0, 1:4,000, 1:2,000, and 1:400 inoculum levels, respectively. There were no significant differences in root disease severity between the plants grown in soil treated with fenamiphos and nontreated soil at 7 and 14 days. Fenamiphos did not influence plant height significantly in plants dug 14 and 28 days after planting in the V3 and V5 to V6 leaf stages, respectively. At 28 days, fresh and dry foliage weight was reduced significantly by an average of 12% in infested soil versus noninfested soil. Fenamiphos increased fresh weight significantly by an average of 9%, but did not increase dry foliage weight, compared with nontreated soil. Fenamiphos increased root disease severity 28 days after planting in 1988 but not in 1986. In 1988, there was a significant ($P = 0.05$) interaction between inoculum levels and rates of fenamiphos. The most severe disease was at the highest inoculum level and the highest rate of fenamiphos.

DISCUSSION

Destruction of crown and brace roots by *R. solani* AG-2-2 caused substantial reductions in grain yield, suggesting that those roots probably contribute greatly to the production of forage and grain. Only 40–50% of the variation in yield, however, was explained by crown and brace root disease. For several reasons, such variability could be expected when research with this

TABLE 4. Populations of nematodes in corn grown in soil infested with different levels of *Rhizoctonia solani* AG-2-2 and treated with pesticides in 1985 and 1986[a]

	8 July 1985				24 July 1986			
	Co	Mi	Pm	Pspp	Co	Mi	Pm	Pspp
Treatment[b]								
HIL	130	172	56	46	40	478	122	142
LIL	62	158	70	24	42	450	35	125
None	126	242	68	48	30	2,212	80	160
HIL + P	132	132	42	124	38	418	60	318
LIL + P	168	234	50	30	122	560	65	500
P	114	92	34	144	85	3,642	58	42
HIL + F	20	8	22	0	230	848	78	18
LIL + F	64	18	22	2	135	302	58	210
F	122	10	36	4	112	580	45	40
HIL + P + F	112	14	42	2	82	78	30	12
LIL + P + F	126	4	26	6	65	152	25	30
P + F	132	8	18	22	58	98	18	68
Comparisons of interest[c]								
Inoculum level (I)	NS	NS	NS	NS	NS	NS	NS	NS
Pencycuron (P)	0.05	NS	NS	NS	NS	NS	NS	NS
Fenamiphos (F)	NS	0.01	0.05	0.01	NS	NS	NS	NS
P × F	NS	NS	NS	NS	NS	0.01	NS	0.01

[a] Nematodes/150 cm^3 of soil; Co = *Criconemella ornata*, Mi = *Meloidogyne incognita*, Pm = *Paratrichodorus minor*, Pspp = *Pratylenchus* spp.
[b] HIL = high inoculum level; LIL = low inoculum level of *Rhizoctonia solani* AG-2-2; P = pencycuron; F = fenamiphos.
[c] $P = 0.01$ or 0.05; NS = no significant differences, according to least squares analysis of variance linear comparisons tested with the *F*-test.

TABLE 5. Plant stand, root disease severity, and yield in corn grown in soil infested with different inoculum levels of *Rhizoctonia solani* AG-2-2 and treated with pesticides, 1986

			Crown and brace roots, 8 wk[b]					
				With lesions (soil depth, cm)			Root apices killed 0–5 cm depth (%)	Grain yield (kg/ha)
	Chemical (C)	RDI[a]	Without lesions	0–5	5–10	>10		
Inoculum level (I)								
High	Pencycuron (P)	1.6	164	13	8	4	7	10,920
	Fenamiphos (F)	3.9	44	133	29	4	60	7,910
	P + F	2.2	118	45	25	9	20	10,980
	None	3.0	70	86	33	11	38	10,230
Low	P	1.6	157	8	10	6	3	11,050
	F	2.8	110	57	26	11	25	11,670
	P + F	1.8	148	31	13	9	11	10,550
	None	1.5	144	13	7	5	5	9,850
None	P	1.0	162	2	1	0	0	9,917
	F	1.6	159	16	15	10	4	11,240
	P + F	1.3	176	2	7	6	0	11,800
	None	1.3	163	14	9	4	3	10,420
Comparisons of interest[c]								
	I	0.01	0.01	0.01	0.01	NS	0.01	NS
	C	0.01	0.01	0.01	0.01	NS	0.01	NS
	I × C	0.01	0.01	0.05	NS	NS	0.01	0.01

[a] Root disease index: 1 = <2, 2 = 2–10, 3 = 11–50, 4 = >50% discoloration and decay; 5 = plant dead.
[b] Total roots on 10 plants.
[c] $P = 0.01$ or 0.05; NS = no significant differences, according to least squares analysis of variance linear comparisons tested with the *F*-test.

TABLE 6. Root disease severity in corn grown in a greenhouse in soil infested with different inoculum levels of *Rhizoctonia solani* AG-2-2 and treated with fenamiphos

	Root disease severity[b] days after planting					
	7		14		28	
	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2
Inoculum level (I)[a]						
0	1.00	1.00	1.00	1.00	1.00	1.12
1:4,000	1.00	1.37	1.23	1.24	1.12	1.08
1:2,000	1.08	1.62	1.42	1.42	2.36	1.31
1:400	2.35	3.56	2.60	2.67	2.95	1.76
Fenamiphos (mg/L) (F)						
0	1.30	1.89	1.56	1.52	1.69	1.19
1.08	1.40	1.83	1.61	1.65	1.85	1.32
2.16	1.40	2.00	1.56	1.65	2.00	1.20
4.31	1.33	1.83	1.57	1.50	1.89	1.55
Contrasts of interest[c]						
I-linear	0.01	0.01	0.01	0.01	0.01	0.01
I-quadratic	NS	NS	NS	NS	0.01	NS
I-cubic	0.01	NS	NS	NS	0.01	NS
F	NS	NS	NS	NS	NS	0.01
I × F	NS	NS	NS	NS	NS	0.05

[a] Ratio of cornmeal-sand (3%, w/w) inoculum to Fuquay loamy sand field soil.
[b] 1 = <2, 2 = 2–10, 3 = 11–50, 4 = >50% discoloration and decay; 5 = plant dead.
[c] $P = 0.01$ or 0.05; NS = no significant differences, according to least squares analysis of variance tested with the *F*-test.

pathosystem is conducted. Studies conducted with young corn plants in nutrient solution indicate that up to 62% of the crown roots may be excised before reductions in shoot weight are detected (3). Although crown and lateral roots are concentrated in the row directly under the plant during the first 5–6 wk of vegetative growth, and most of the horizontal growth between rows and vertical growth below 30 cm occurs 1–2 wk before and after tasseling (1,4), root distribution and depth may vary year by year, and may influence nutrient uptake and yield (11). In addition, yield losses induced by crown and brace root rot might be even greater in nonirrigated than in irrigated corn because of reduced root systems and increased plant stress (27).

The number of crown and brace roots with terminal decay appeared to affect grain yield more than any other root system parameter, and termination of roots in the top 5 cm of soil was more injurious than termination below that depth. Roots in our tests and in grower fields frequently had new lateral, tertiary roots emerging above the terminal decay. The deeper roots penetrate the soil before being decayed, the more surface area is available for emergence of new roots above the decay. However, it was not uncommon to see new lateral branch roots terminated by decay a few centimeters from their juncture with crown or brace roots. Mengel and Barber (12) observed that few roots died during vegetative growth, but roots began to die after tasseling and new roots continued to form. They assumed that roots were dying from natural causes, but the role of root pathogens was not determined.

Our studies indicate that nematodes could contribute to yield loss by *R. solani* AG-2-2, possibly because of reduced nutrient and water uptake by fibrous roots. Nematode population densities in soil were not assayed at planting in 1984 and a nematicide treatment was not included, so it was not possible to determine if nematodes contributed to yield loss. The 1984 experiment followed cowpea the previous year, and yields were much lower than in subsequent years in continuous corn.

It is not clear why recovery of the pathogen from lesions was so low during field studies (9–31%). Destruction of corn root apices and the subsequent reduction in yield may be related to the pathogen's ability to produce pectic lyase and polygalacturonase (17), or the production by the pathogen of toxins that inhibit corn growth (6) (although recent evidence suggests that toxin production may not be related to pathogenicity in *R. solani* [8]). Thus, difficulty in isolating the fungus from rotted crown and brace roots in the field may be due to the fungus killing host tissue well in advance of the mycelium, autolysing soon after the root tissues are destroyed, or being replaced by other fungi.

The location and density of *R. solani* AG-2-2 in soil may influence yield reduction. Our research indicates that there is a direct relationship between inoculum density and the amount of disease on roots, and that the extent of disease on roots is related directly to grain yield. Greenhouse experiments in which inoculum was placed 0–7.5 cm, 7.5–15 cm, or 0–15 cm deep in soil did not influence the location of lesions on roots or the number of diseased roots. On some 6-wk-old plants, roots were terminated at the crown in soil where inoculum was buried 7.5–15 cm deep. In field tests where inoculum was placed in the top 5 cm of soil, lesions rarely were observed below 10 cm 7 wk after planting, but were observed frequently 15–20 cm deep 17 wk after planting. Symptoms of crown and brace root rot have not been observed in pathogenicity tests with other fungi in Georgia (21,22,24), and *R. solani* AG-2-2 apparently grows through soil or roots to lower depths.

Our research indicates that fenamiphos increases root rot and reduces yield in field soil infested with *R. solani* AG-2-2, but the results could not be duplicated in greenhouse experiments with the pathogen. Soil temperatures were warmer in the greenhouse experiments than the 5–20 C that may occur in fields in late March and early April in the Georgia coastal plain. *R. solani* AG-2-2 causes more severe root disease on corn at temperature ranges of 8–21 and 16–28 C than at 20–34 C (22). Previous research has shown that the herbicides pendimethalin and metolachlor increased root disease severity in soil infested with *R. solani* AG-2-2 in a greenhouse experiment, and pendimethalin increased root disease severity on a sandy soil in the field (24). In other research, the nematicide ethoprop increased root disease severity in snap bean and turnip in field experiments (26,28) and in snap bean in soil infested with *Pythium myriotylum* (19). Pendimethalin is a dinitroanaline, and fenamiphos and ethoprop are organophosphates. It is not known if the chemicals affect the host, the pathogen, or both.

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