

Response of Soybean to *Heterodera glycines* Races 1 and 2 in Different Soil Types¹

D. P. SCHMITT,² H. FERRIS,³ AND K. R. BARKER²

Abstract: Experiments were conducted for 3 years at four locations and 1 year with six soil types at a common location in North Carolina to determine damage and control-cost functions for *Heterodera glycines* races 1 and 2 on soybean. In the experiments on native loamy sand and sandy soils, tolerance limits for initial population densities were 0 or very low, whereas in a muck, the tolerance limit was 315 eggs/500 cm³ soil. The aggressive race 2 was more damaging than race 1 in Lakeland sand and Norfolk loamy sand. The crop response was not different between races in the Appling sandy clay loam and Belhaven muck. Soybean yield responses to *H. glycines* were linear in six soil types in microplots at a common site. The amount of damage varied among these soil types, with lowest yields in the muck because of severe drought stress in this soil. An exponential function adequately described soybean yield response relative to nematode control with increasing rates of aldicarb in Norfolk loamy sand. Treatment with aldicarb in the Lakeland sand decreased the effective egg population of *H. glycines* but had only a minor effect in the muck.

Key words: aldicarb, chemical control, control-cost function, damage function, *Glycine max*, *Heterodera glycines*, soybean, soybean cyst nematode, damage threshold.

The high cost and difficulty of controlling *Heterodera glycines* Ichinohe make it economically desirable to develop reliable damage thresholds. The quantitative relationship between plant-parasitic nematodes and yield of annual crops is primarily a function of initial nematode population densities (2,4). As the pest population increases, the impact per individual nematode decreases (5,12,16,21). Within a range of initial population densities (P_i), the relationship between crop yield or value and log-transformed counts approximates linearity. At low P_i , the plant may be able to tolerate the nematode damage (5,16). This basic relationship exists with *H. glycines* in soybeans, although stress from high population densities during the reproductive phase of plant growth may have additional subtle effects (19).

Various types of regressions have been used to describe the relationship between

initial population density and plant damage (2,10,11,14,15,23). Damage-function models form a basis for economic threshold decisions, but their use for nematodes could be expanded. Seinhorst (21) developed a logistic exponential model to describe the relationship between yield and initial population density. The model includes the concepts of tolerance limit and minimum yield (21,22). A theoretical economic model for determining nematode economic thresholds has been developed (9). Such models have value for predicting crop losses, provided that nematode-count data are reliable and the relationships are not overly influenced by the environment. Soil texture and rainfall, however, have important impacts on these relationships. Therefore, to assure reliable predictions of crop response to nematode damage, the influence of edaphic, environmental, and cultural effects of the nematodes on crop yield must be established.

Some systems currently in use to predict crop damage by *H. glycines* are based on cyst, egg, or second-stage juvenile (J2) counts (6,20; J. N. Sasser, pers. comm.; J. L. Imbriani, pers. comm.). Numbers of eggs plus J2 at planting have given fair-to-good prediction of seed yields. These models have been developed by least squares regression techniques and are generally linear (6) or quadratic (15). Meaningful es-

Received for publication 18 June 1986.

¹ Paper No. 10518 of the Journal Series of the North Carolina Agriculture Research Service, Raleigh. Use of trade names in this publication does not imply endorsement by the North Carolina Agriculture Research Service of the products named nor criticism of similar ones not mentioned.

² Associate professor and professor, Department of Plant Pathology, North Carolina State University, Raleigh, NC 27695.

³ Professor, Division of Nematology, University of California, Davis, CA 95616.

We thank C. P. Alston, J. A. Phillips, D. W. Byrd, Jr., D. W. Corbett, and the staff at Central Crops Research Station for technical assistance.

timates also have been derived by using other empirical approaches (1).

Prevention of crop loss due to *H. glycines* and other nematodes has been accomplished with resistant cultivars, nematicides, and (or) rotation. Aldicarb, which is used frequently to control *H. glycines*, has been tested on a large number of crops and has given significant yield increases (7,8,13). It gave approximately a 10% yield increase over the untreated control at all Pi in Illinois (15). Such nonfumigant nematicides require precise application (17,18). The optimal rate for control is needed and requires knowledge of nematicide dosage-response relationships (22).

The objectives of this research were to 1) determine the yield responses of soybean to race 1 and an aggressive race 2 of *H. glycines* in different soil types, 2) characterize the responses of soybeans to different dosages of aldicarb in relationship to *H. glycines* population densities, and 3) develop predictive models of crop damage.

MATERIALS AND METHODS

Three types of microplot experiments were established to determine the impact of soil type and *H. glycines* on soybean yield losses. Two series of tests involved 76-cm-d microplots established at four locations (minimal disturbance of soil profile). The third design involved six soil types at a common site (Central Crops Research Station near Clayton, NC).

Soybean yield responses at four locations: The soils at the four test locations were Appling sandy clay loam (53% sand, 17% silt, 30% clay, at Research Farm Unit 2, Raleigh, NC), Norfolk loamy sand (87% sand, 9% silt, 4% clay, at Central Crops Research Station, Clayton, NC), Lakeland sand (93% sand, 3% silt, 4% clay, at Grifton, NC), and Belhaven Muck (71% sand, 22% silt, 7% clay, > 35% organic matter, at Wenona Community, NC).

Microplots were fumigated with methyl bromide at 98 g/m². Central Crops Research Station and Unit 2 locations were fumigated on 4 April, Grifton on 21 April, and Wenona on 22 April 1980. The plots

were fertilized, limed, inoculated with *H. glycines* eggs and the mycorrhizal fungus *Glomus macrocarpus* Tul. and Tul., and planted on 7 May 1980. Lime and fertilizer were applied according to soil test recommendations for optimal soybean growth (pH 6.0 for the Lakeland, Norfolk, and Appling soils and pH 5.0 for Belhaven). Cysts from race 1 or 2 were crushed to extract eggs. Initial numbers of 0, 10, 100, 1,000, or 10,000 eggs per 500 cm³ soil for each race separately were mixed into the top 15 cm of soil, then 500 zygospores of *G. macrocarpus* were placed in the seed furrow of each plot. *Glycine max* (L.) Merr. cv. Ransom seeds inoculated with *Bradyrhizobium japonicum* were planted at a density of one seed/5 cm of row.

Plots were harvested and sampled for nematodes on 12 December at Clayton and Raleigh and 15 December at Grifton and Wenona. Composite soil samples consisting of 10–12 2.5-cm-d cores taken 15–20 cm deep were processed by a combination of elutriation and centrifugation (3).

The experiment was repeated at Wenona in 1981. The soil was fumigated on 12 April and infested and planted on 2 June. At Grifton, Clayton, and Raleigh, the experiments used residual population densities that developed on the crop grown in 1980. The Pi in each microplot was determined, and plots were planted with *B. japonicum*-inoculated Ransom soybeans on 22 May at Raleigh, 26 May at Clayton, and 10 June at Grifton. Seeds were harvested 13 November at Grifton and Wenona and 3 November at Clayton. Shoots were harvested 16 September at Raleigh. Nematode counts were obtained as in 1980. This test used a randomized complete block design with treatments arranged in a 2 × 5 factorial replicated five times.

Soybean yields in six soils at a common site: A factorial experiment with four inoculum levels of *H. glycines* race 1 and six soil types was used to determine the effects of these parameters on the yield of Lee 68 soybean. Soils used and their respective percentages of sand, silt, clay, and organic matter (where available) were Fuquay sand (native soil at

this site—91, 6, 3, 0.6), Cecil sandy clay (48, 13, 39), Cecil clay loam (43, 18, 29), muck (58, 33, 9, > 30), Norfolk loamy sand (84, 12, 4, 1.4), and Portsmouth sand (72, 18, 10, 2.7). These soils were placed in microplots to a depth of 30 cm. All plots were treated with methyl bromide as described for the 1980 experiments.

Cysts of race 1 of *H. glycines* produced on Lee 68 soybeans were crushed with a glass tissue grinder to free the eggs for use as inoculum. Each inoculum level (0, 100, 400, and 1,600 eggs/500 cm³ soil) was replicated five times per soil type. Nematode inoculum and other treatments were placed in the plots in mid-May 1982, 2 months after fumigation. *Bradyrhizobium japonicum*-coated seeds were planted on the same day, and about 1,500 spores of *G. macrocarpus* were added to each plot.

Supplemental plant nutrients for optimal plant growth and supplemental irrigation when plants were under severe water stress were provided. Residual methyl bromide caused some plant injury in the muck soil (partially responsible for lower yields). Plants in this soil also required more irrigation than in others because the muck removed from its native site tended to dry quickly.

Aldicarb efficacy: Microplots at Clayton and Wenona were used in 1982 to develop aldicarb dosage response curves and at Grifton to determine response of a Pi range to a standard rate of aldicarb. For the dosage-response curve experiments, the Pi were those nematodes surviving from the previous year and were determined by soil sampling (composite of ten 2.5-cm-d cores per plot), elutriation, and centrifugation (3). Plots were divided into six blocks by population density and race. Randomly selected plots within population levels were treated with low to excessively high rates of aldicarb: 0, 0.28, 0.56, 1.12, 2.24, 4.48, or 8.97 kg a.i./ha. Plots were sampled, treated, and planted 19 May at Wenona and 1 June at Clayton.

The soil in the microplots and the surrounding area at Grifton was fumigated with methyl bromide (48 g/9 m²) on 24

March. Low to high Pi, replicated eight times, were 0, 85, 170, 510, 2,040, and 10,200 *H. glycines* eggs per 500 cm³ soil. Aldicarb was broadcast at 6.78 kg a.i./ha and incorporated slightly by mechanical mixing in four randomly selected replicates of each inoculum level. Zygospores of *G. macrocarpus* (1,000/plot) were dispersed over *B. japonicum*-inoculated Ransom soybeans before they were covered. The experiment was established on 25 May, sampled for nematode assay on 7 July and 3 November, and harvested on 3 November.

Model development and data analysis: Models were developed to provide conceptual descriptions of two types: 1) damage functions, the relationship between numbers of nematodes and crop yield; and 2) dosage-response functions, the relationship between pesticide dosage or cost and level of management achieved. Concepts considered for the model were crop yield, quality, and (or) value decreases as the pest population density increases and the impact per pest individual decreases, usually approximating linearity on log-transformed data (12,16,21). The possibility of different tolerance limits in the models to be developed for *H. glycines* on soybean in different environments was recognized. Since yield or value were not depressed until the tolerance limit was reached, maximum yield or value was considered to be the average of all observations where nematode population densities were between 0 and the apparent tolerance limit. Yield was expressed on a relative basis for standardization by dividing the observations by the maximum value at each site (average of all yield observations where the population was below the tolerance limit). Then, the basic damage function model in these studies is:

$$y = 1.0 \text{ for } P \leq T,$$

$$y = c + b \log_{10}(P + 1) \text{ for } P \geq T,$$

where P is the nematode population density, T is the tolerance limit, y is crop yield in response to the nematode populations, c is the intercept of the regression line with

the yield axis, and b , a negative quantity, is the regression coefficient (damage per nematode using \log_{10} -transformed data).

Soybean yield response to aldicarb dosage in the presence of *H. glycines* was presumed to be one of diminishing returns. There was some minimum yield in the absence of treatment. The impact per unit increase of aldicarb dosage diminished as the yield approximated the maximum potential in the field. A natural growth function was used to describe the relationship between yield and aldicarb dosage for a given population density:

$$y = y_{\min} + a(1 - e^{bd})$$

where y is the crop yield in response to the nematode populations and aldicarb, d is the dosage, $(y_{\min} + a)$ is the maximum expected yield after aldicarb treatment, y_{\min} is the yield at the current population level without nematicide treatment, a is the yield difference between no treatment and the maximum expected with treatment, and b is a regression constant.

Effects of initial numbers of *H. glycines* on soybean yield in six soil types were analyzed using orthogonal and other linear contrasts. Mean differences across soil types were separated using a Waller-Duncan K-ratio t -test. Responses of soybean to the different P_i within soil types were described using linear regression models.

RESULTS

Soybean yield responses at four locations:

There was no difference between the impacts of races 1 and 2 of *H. glycines* on Ransom soybean yields in the Norfolk loamy sand when relative yields for 1980 were plotted against initial egg densities. There was not a measurable tolerance limit and yields were suppressed by 57% at the highest P_i (10,000 eggs/cm³ soil) (Fig. 1).

In 1981, relative yields from the same microplots were plotted against P_i measured as either J2, cysts, or eggs per 500 cm³ soil (Fig. 2). A tolerance threshold was calculated for cysts and eggs from fall counts and for egg counts at-planting (Fig. 2A, C, D, F). No tolerance threshold for

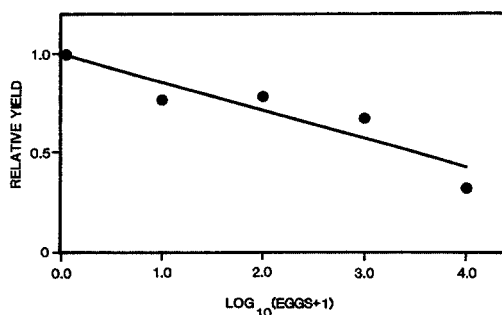


FIG. 1. Relationship of initial egg densities of *Heterodera glycines* (races 1 and 2 combined) to relative soybean yield in 1980 in a Norfolk loamy sand. $y = 1.0 - 0.143[\log_{10}(P_i + 1)]$, $r^2 = 0.86$, $y_{\max} = 279.0$.

cysts and J2 P_i determined at-plant was evident (Fig. 2A, B, D, E). Even though Ransom soybeans appear to be more tolerant to low numbers of race 2 than race 1 based on the calculated T value, any interpretation of T needs to be made cautiously because of the sparsity of observations at the low population densities (overall there are too many data points to be shown clearly on the figures). Regression coefficients for races 1 and 2 were cysts (-0.24 and -0.29) (Fig. 2A, D), J2 (-0.23 and -0.28) (Fig. 2B, E), and eggs (-0.19 and -0.28) (Fig. 2C, F).

Race 2 was more damaging than race 1 to soybean at the higher P_i during 1980 in the Lakeland sand (Fig. 3). Maximum yield suppression of 59% for race 2 vs. 32% for race 1 occurred at the highest P_i (Fig. 3). The regression coefficient for race 1 (-0.08) indicated less damage per \log_{10} nematode in the Lakeland sand than in Norfolk loamy sand (-0.14) (Fig. 1). Soybean yields on Lakeland sand in 1981 were low because of a 6-week drought during the pod filling period. Only plots with no or low residual nematode population densities from the 1980 season had any measurable yields.

There were no significant differences in crop responses to races 1 and 2 in the Belhaven soil. Measurable damage occurred at relatively high population densities ($T = 315$ eggs/500 cm³ soil) (Fig. 4). Yields were suppressed by 52% at the highest population density.

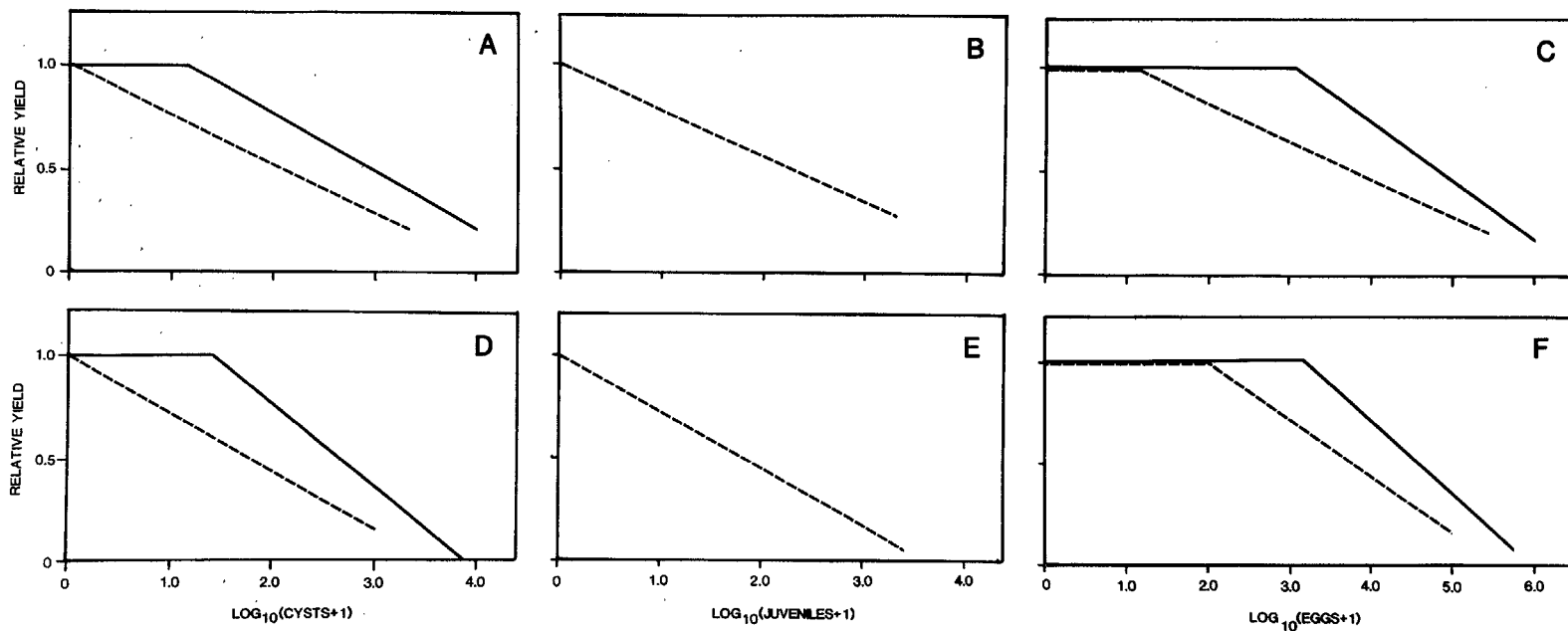


FIG. 2. Relative Ransom soybean yield in 1981 in relation to fall 1980 (Pi80) (—) and at plant 1981 (Pi81) (---) numbers of *Heterodera glycines* in a Norfolk loamy sand. A) Cysts of race 1, Pi80: $y = 1.342 - 0.285[\log_{10}(x + 1)]$ for $x > 15.0$; $y = 1.0$ for $x \leq 15.0$, $r^2 = 0.76$, $y_{\max} = 600.0$; Pi81: $y = 1.0 - 0.238[\log_{10}(x + 1)]$, $r^2 = 0.67$, $y_{\max} = 660.0$. B) Pi81 juveniles of race 1, $y = 1.0 - 0.227[\log_{10}(x + 1)]$, $r^2 = 0.70$, $y_{\max} = 600.0$. C) Eggs of race 1, Pi80: $y = 1.881 - 0.284[\log_{10}(x + 1)]$ for $x > 1,250$, $y = 1.0$ for $x \leq 1,250.0$, $r^2 = 0.70$, $y_{\max} = 597.0$; Pi81: $y = 1.226 - 0.188[\log_{10}(x + 1)]$ for $x > 15.0$, $y = 1.0$ for $x \leq 15.0$, $r^2 = 0.58$, $y_{\max} = 720.0$. D) cysts of race 2, Pi80: $y = 1.568 - 0.406[\log_{10}(x + 1)]$ for $x > 25.0$, $y = 1.0$ for $x \leq 25.0$, $r^2 = 0.88$, $y_{\max} = 573$; Pi81: $y = 1.0 - 0.285[\log_{10}(x + 1)]$, $r^2 = 0.86$, $y_{\max} = 590$. E) Pi81 juveniles of race 2, $y = 1.0 - 0.278[\log_{10}(x + 1)]$, $r^2 = 0.87$, $y_{\max} = 574.0$. F) Eggs of race 2, Pi80: $y = 2.17 - 0.366[\log_{10}(x + 1)]$ for $x > 1,600.0$, $y = 1$ for $x \leq 1,600$; Pi81: $y = 1.562 - 0.281[\log_{10}(x + 1)]$ for $x > 10.0$, $y = 1.0$ for $x \leq 10.0$, $r^2 = 0.85$, $y_{\max} = 593$.

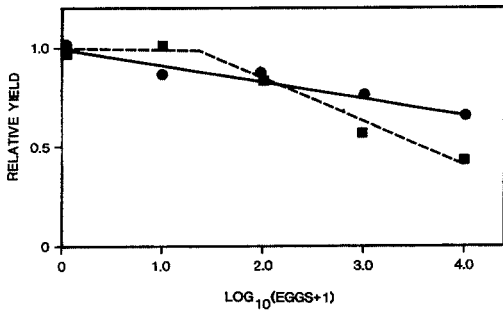


FIG. 3. Effects of *Heterodera glycines* on Ransom soybean yield in 1980 in a Lakeland sand. Race 1 (—): $y = 1.0 - 0.079[\log_{10}(x + 1)]$, $r^2 = 0.94$, $y_{\max} = 284$. Race 2 (---): $y = 1.288 - 0.221[\log_{10}(x + 1)]$ for $x > 19.0$, $y = 1.0$ for $x \leq 19.0$, $r^2 = 0.98$, $y_{\max} = 263$.

Yields of Ransom soybean were extremely low in the Appling sandy clay loam soil in 1980 and did not differ between races or among inoculum densities. In 1981, all pods aborted during an extremely hot period in August. Consequently, only weights of vegetative biomass could be determined for the experiment. Shoot weight generally decreased as inoculum density increased, but differences due to race were not significant (Table 1).

Soybean yields in six soils at a common site: Linear regression models fit most of the data for the six soil types: Fuquay sand, Cecil sandy clay, Cecil clay loam, muck, Norfolk loamy sand, and Portsmouth sandy loam (Table 2). The lowest Pi (100 eggs/500 cm³ soil) suppressed yield by 23–38% in the Portsmouth sandy loam. No further loss occurred in this soil up to a Pi of 1,600 eggs. Suppressions from 44% to 75% occurred in the other five soils, with the greatest loss occurring in the muck.

Nematicide efficacy in different soils: A natural growth model ($y = 0.067 + 0.721[1 - e^{-0.3793d}]$) described Ransom soybean yield responses to nematode control with increasing rates of aldicarb in the Norfolk loamy sand at Clayton (Fig. 5A). Races responded similarly to aldicarb treatment. The maximum yield achieved at high rates of aldicarb was 79% of that in noninfested soil (Fig. 5A). The yield differential between the nematode-free situation and the yield where no aldicarb was applied (y_{\min})

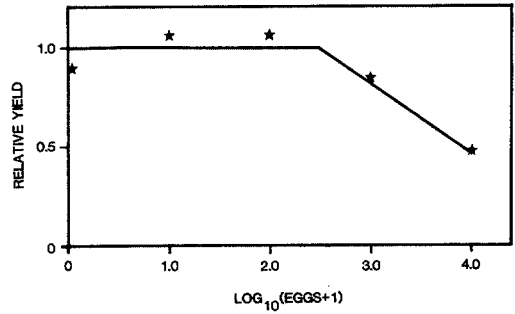


FIG. 4. The combined effect of *Heterodera glycines* races 1 and 2 on the relative yield of soybean grown in Belhaven muck soil. $y = 1.872 - 0.349[\log_{10}(x + 1)]$ for $x \geq 315$, $y = 1.0$ for $x \leq 315$, $r^2 = 0.92$, $y_{\max} = 253.0$.

was 0.721. Soybean yields were 4% greater in noninfested soil treated with aldicarb than in noninfested nontreated soil.

There was little response to aldicarb treatment in the muck soil at Wenona (Fig. 5B). The differences in yield between races in plots treated with aldicarb were not significant. Maximum yields in aldicarb treated soil were 87% of those in noninfested, nontreated soil. Soybean yields were 8% higher in noninfested plots treated with aldicarb than in nontreated, noninfested plots.

Soybean yield suppression by *H. glycines* in untreated plots in the Lakeland sand near Grifton was greater in 1982 (Fig. 6) than in 1980 (Fig. 3). Aldicarb treatment provided sufficient control so that yield in treated soil with 250 eggs/500 cm³ soil was equivalent to the yield with four eggs in untreated soil. Maximum yield suppressions were 100% in the untreated plots and

TABLE 1. Shoot weight of Ransom soybean as affected by *Heterodera glycines* in an Appling sandy clay loam soil at Research Farm Unit 2 in 1981.

Eggs	Inoculum density/500 cm ³ soil			Fresh shoot wt (g/microplot)
	Cysts	J2		
0	0.0	0		2,243 a
30	0.4	8		2,065 ab
230	3.8	4		1,294 bc
2,630	19.2	4		1,186 c
3,900	21.4	12		1,405 bc

Means followed by the same letter are not significantly different ($P = 0.05$) according to the Waller-Duncan K-ratio *t*-test.

TABLE 2. Yields of Ransom soybeans grown on six soils infested at different population densities of *Heterodera glycines*.

Initial no. eggs/500 cm ² soil	Yield (g/microplot)					
	Cecil sandy clay	Cecil clay loam	Fuquay	Muck	Norfolk	Portsmouth
0	332	595	513	364	635	575
100	207	401	372	277	486	434
400	173	456	255	182	316	490
1,600	146	335	164	91	294	414
	c†	a	b	c	a	a

Linear regression equations, by soil, of log₁₀Pi on means of adjusted yield (Y):

Cecil sandy clay: $Y = 329.6 - 59.0 \log Pi$; $r^2 = 0.99$ ($P = 0.01$)

Cecil clay loam: $Y = 590.0 - 73.3 \log Pi$; $r^2 = 0.85$ ($P = 0.08$)

Fuquay: $Y = 532.0 - 105.4 \log Pi$; $r^2 = 0.94$ ($P = 0.03$)

Muck: $Y = 384.4 - 79.9 \log Pi$; $r^2 = 0.89$ ($P = 0.06$)

Norfolk: $Y = 649.0 - 110.7 \log Pi$; $r^2 = 0.93$ ($P = 0.04$)

Portsmouth: $Y = 567.4 - 45.7 \log Pi$; $r^2 = 0.77$ ($P = 0.12$)

† Different letters indicate significantly different means ($P = 0.05$) across soil types according to the Waller-Duncan K-ratio t-test.

35% in the aldicarb treated plots at the highest Pi. Without nematodes, soybean yields were 11% higher in nontreated than in aldicarb treated plots.

Model development for management purposes: A management decision algorithm was developed for the data from Figs. 2C and 5A. The damage function represented by a negative linear relationship between crop value (v) and $\log_{10}(Pi + 1)$ ($v = 1.881 - 0.284 \log_{10}(Pi + 1)$ for $Pi > 1,250$, otherwise $y = 1.0$) was compared to the response with aldicarb (Fig. 7). Pi is the population density at harvest of the previous season.

The optimal dosage rate is that dosage at which the difference between control

cost and crop value is at a maximum. The optimal treatment level is determined graphically (Fig. 7) or algebraically by finding the point at which the slope of the difference equation is zero (9). The optimal return will be at that Pi where

$$\frac{dReturn}{dPi} = 0.$$

Since the control cost function expresses yield in nematode-infested soil in relation to aldicarb dosage, the function was re-defined to reflect nematode pressure on the crop as a function of aldicarb dosage. The relationship between relative yield and nematode density is

$$y = c + mx, \tag{1}$$

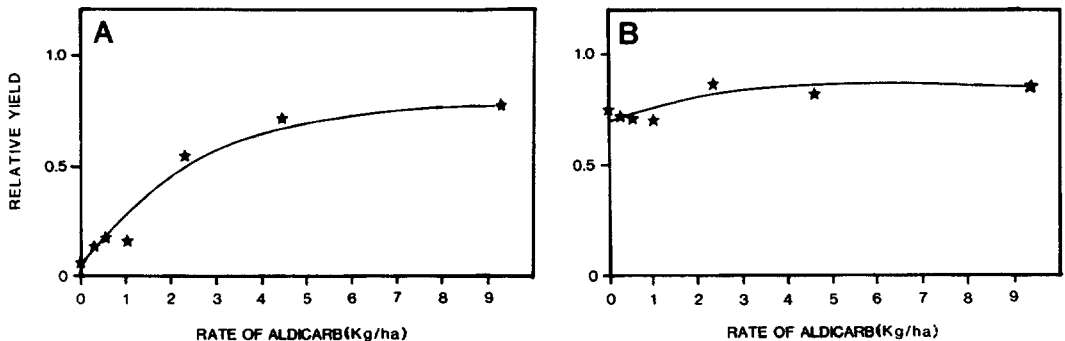


FIG. 5. Responses of Ransom soybeans grown in *Heterodera glycines* infested soil to aldicarb dosage in 1982. A) Norfolk loamy sand: $y = 0.067 + 0.721(1 - e^{-0.57984x})$, $r^2 = 0.98$, $y_{max} = 0.79$. B) Belhaven muck: $y = 0.708 + 0.165(1 - e^{-0.50444x})$, $r^2 = 0.82$, $y_{max} = 0.87$.

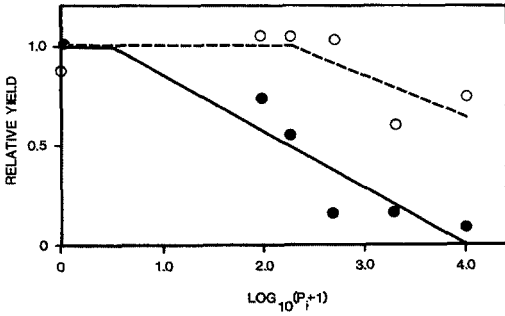


FIG. 6. Response of soybean to aldicarb as affected by initial egg population densities of *Heterodera glycines* in a Lakeland sand in 1982. Without aldicarb (—): $y = 1.213 - 0.305[\log_{10}(x + 1)]$ for $x > 4.0$, $y = 1.0$ for $x \leq 4.0$, $r^2 = 0.89$, $y_{max} = 374.0$. With aldicarb (---): $y = 1.542 - 0.218[\log_{10}(x + 1)]$ for $x > 250$, $y = 1.0$ for $x \leq 250.0$, $r^2 = 0.55$, $y_{max} = 415.0$.

assuming a tolerance limit of zero, where c is the y-axis intercept, m is the slope of the regression line (yield loss per log nematode), and $x = \log_{10}(P_i + 1)$. Crop value was then calculated as:

$$\$_1 = v \cdot y_{max}(c + mx) \quad (2)$$

where $c + mx$ is the relative yield from

equation 1, y_{max} is the maximum yield in the absence of nematodes, and v is the crop value in \$/kg. The control efficacy function is

$$y = y_{min} + a(1 - e^{-bd}) \quad (3)$$

where y_{min} is the minimum yield without nematicide treatment, $(y_{min} + a)$ is the expected yield after nematicide treatment, b is a slope-determining constant, and d is the nematicide dosage. The damage function (equation 1) expresses yield as a function of the nematode population. The control efficacy function (equation 3) expresses yield as a function of nematicide dosage, which is an indirect measure of the nematode population. By setting these two equations equal to each other, the number of nematodes can be expressed as a function of nematicide dosage:

$$c + mx = y_{min} + a(1 - e^{-bd})$$

then,

$$x = [y_{min} + a(1 - e^{-bd}) - c]/m \quad (4)$$

The slope of the linear damage function

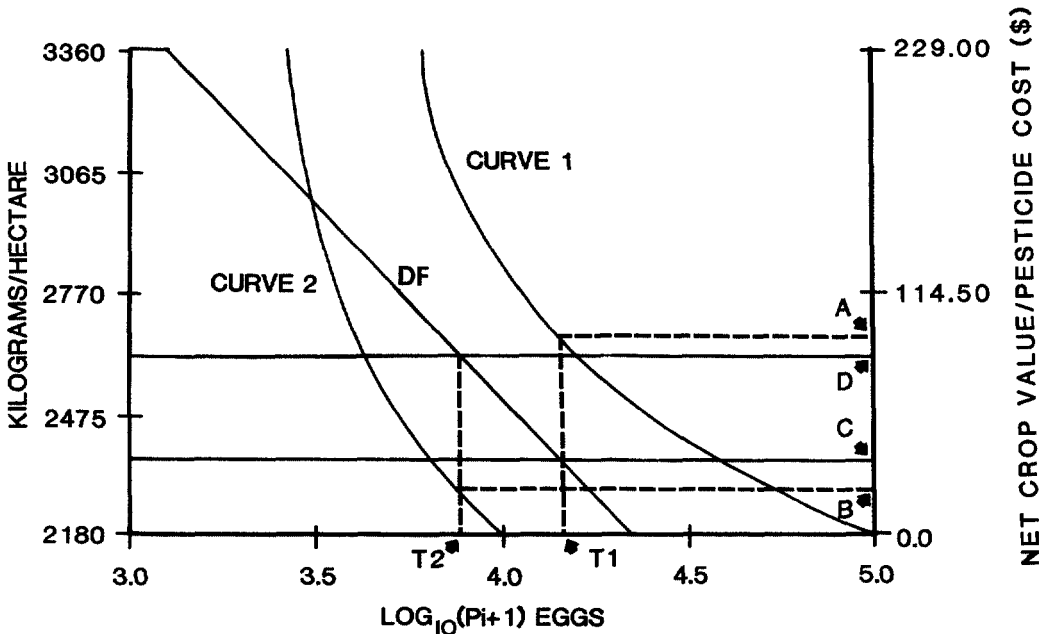


FIG. 7. Determination of an economic threshold using aldicarb as a control tactic. Curve DF is the damage function. Curves 1 and 2 are cost of control function for population densities of 100,000 and 10,000 eggs/500 cm^3 soil, respectively. Points A and B are costs for optimal dosages for curves 1 and 2. Points C and D are crop values at which losses are minimized for curves 2 and 1. T1 and T2 denote points to which populations are effectively reduced.

(equation 1) is $\frac{dy}{dx} = m$, that is, the unit decrease in crop yield per unit increase in \log_{10} nematode density is m . Since m is expressed in terms of relative weight, the rate of decline in crop value is expressed by $\frac{d\$}{dx} = m \cdot y_{max} \cdot v$, where y_{max} is the expected maximum yield from the field and v is the value per unit weight of the crop. The slope of the control efficacy function (equation 4) is its derivative:

$$\frac{dx}{dd} = \frac{-abe^{bd}}{m}$$

With respect to x , this derivative is $\frac{dd}{dx} = \frac{-m}{abe^{bd}}$. If a constant relationship between control cost and treatment level is assumed, the cost of control can be calculated as

$$\$_2 = \frac{dd}{dx} \cdot \text{price} \cdot x \tag{5}$$

where $\frac{dd}{dx}$ is the change in dosage per unit nematode and price is the price per unit of the nematicide. The slope of the control cost function is:

$$\frac{d\$_2}{dx} = \frac{-m \cdot \text{price}}{abe^{bd}}$$

The optimal dosage will be the dosage at the population density at which the difference between crop value ($\$_1$) and control cost ($\$_2$) is greatest. Algebraically this is the point at which the slopes of the two functions are equal, that is,

$$m \cdot y_{max} \cdot v = \frac{-m \cdot \text{price}}{abe^{bd}}$$

then,

$$d = \frac{1}{b} \cdot \ln\left(-\frac{\text{price}}{ab \cdot y_{max} \cdot v}\right) \tag{6}$$

and the cost of this optimal dosage is $d \cdot \text{price}$. The effective P_i at the optimal

dosage is obtained by substituting d into equation 4. The yield (y) associated with the optimum dosage is determined by substituting the x value obtained from equation 4 into equation 1. The crop value at the optimum dosage is $y \cdot y_{max} \cdot v$.

If there is a tolerance limit (T) for the damage function, the optimal solution is no treatment if P_i is less than the tolerance limit. If P_i is greater than the tolerance limit, the optimal dosage obtained from equation 6 may indicate a reduction of the P_i to a level below the tolerance limit when substituted in equation 4. In this case, the optimal dosage is selected as that which would reduce the P_i to the tolerance limit and is provided by substituting T for x in equation 4 and solving for d giving:

$$d = \frac{1}{b} \cdot \ln[(a - c + y_{min} - mT)/a]. \tag{7}$$

The optimal dosage solution is independent of m (equation 6), the slope of the damage function, because the control cost function, as developed in these studies, expresses yield as a function of dosage. However, yield is actually dependent on the sensitivity of the host to the nematode population; as this sensitivity changes (change in m), the yield-dosage relationship changes proportionally. The optimal solution, however, is dependent on the price of the pesticide (price), the maximum yield potential for the field (y_{max}), and the expected unit crop value (v).

DISCUSSION

Edaphic, environmental, and cultural conditions affected the parameters of the damage function relating soybean yields to varying P_i of *Heterodera glycines*. The selected \log_{10} linear damage function with a tolerance limit was an adequate descriptor of the relationship between crop yields and nematode densities in each case. Parameters for the model measured in 1980 are not comparable with those in 1981, as population densities were assessed differently. Population densities in 1980 were measured as the amount of inoculum incorporated into the plot, and in 1981 most

were measured as the population density determined by soil sampling. The viability of the eggs and juveniles in each year probably differed according to the experimental technique.

The ability of *H. glycines* to survive the winter is an important biological measurement for establishing thresholds. Crop damage to annual crops is generally related to Pi (2), as was demonstrated by our research. If samples are collected several months before planting, then a survival factor needs to be computed and may introduce some error in prediction.

Nematicide rates may be analytically determined by recognizing the economics of management and of crop loss (9). For example, assume a maximum yield of 3,363 kg/ha at a unit value of \$0.193/kg, a fixed cost of aldicarb at \$33.00/kg a.i. and a fixed production cost for soybeans at \$419.90/ha. Production costs are subtracted from gross income to determine net profits. Consequently, the maximum profit potential per hectare is $3,363 \times \$0.193 - \$419.90 = \$229.16$.

Using parameter values for the control-efficacy function derived from the Norfolk loamy sand site (Fig. 5A), $b = -0.3793$, and assuming a previous fall count of 100,000 eggs/500 cm³ soil, $y_{\min} = 0.46$ and $a = 0.389$. At this fall population density, the use of aldicarb at the given price is never profitable (curve 1, Fig. 7). There is an optimal aldicarb dosage (2.8 kg a.i./ha at a cost of \$92.79, Point A) which reduces the effective population to 14,454 eggs/500 cm³ soil, level T1 ($\log_{10}(\text{Pi}80 + 1) = 4.16$), producing a crop value denoted by Point C to minimize the loss. If the fall population was 10,000 eggs/500 cm³ soil (curve 2, Fig. 7), $y_{\min} = 0.745$ and $a = 0.184$. The optimum dosage solution is achieved by reducing the effective population to level T2 (7,638 eggs/500 cm³ soil $\log_{10}(\text{Pi}80 + 1) = 3.883$) at a cost of \$19.47 (Point B) (0.588 kg a.i. aldicarb/ha), allowing a net crop value of \$84.67 (Point D) and return on the investment of \$65.20/ha. The aldicarb treatment becomes unprofitable in this case if more than 4.8 kg

a.i./ha is applied, reducing the population below 3,020 eggs/500 cm³ soil. In both examples, the control-cost function becomes asymptotic at a population density that would be associated with a 0.721 relative increase in yield over the nontreated situation. A fall population of 1,000 eggs/500 cm³ soil is below the tolerance limit, and treatment is not needed. In any calculations of this nature, the optimal dosages (Fig. 7, point A for 100,000 eggs, point B for 10,000 eggs) must fall within the legal label application rates for the pesticide.

The time at which aldicarb is applied in relation to the time at which the population is measured causes possible confusion in interpretation of these calculations. Since the treatment is applied in the spring and the damage function used in the calculations relates to fall population densities, the population levels calculated at optimum dosages are the fall equivalents of the spring populations. The actual preplant populations resulting from the treatment levels can be determined from the Pi damage function in Figure 2C. Thus, at level T1, the expected relative soybean yield is 0.699, which is associated with a Pi of 636 eggs/500 cm³ soil. The expected relative yield at T2 is 0.778 at Pi of 242 eggs/500 cm³ soil. The calculations could have been performed with the Pi damage function providing the identical optimal dosage results for populations in the spring.

Optimal dosage calculations indicate that using aldicarb is economically questionable at high population densities of *H. glycines*. Alternative control measures such as resistant cultivars and crop rotation should be considered. At lower population densities, the application of aldicarb as a nematicidal treatment may be economically justifiable (Fig. 7).

In the muck soil, parameter values of the dosage-efficacy function are $b = -0.5044$, and, for a Pi of 1,000 eggs/500 cm³ soil, $y_{\min} = 0.825$ and $a = 0.029$, yielding a negative optimal solution for this preplant density, indicating that any application will result in a reduction of profit over no treatment. Although optimal dosage solution is

independent of the slope of the damage function, the slope does impact the economics and position of the control cost function because it dictates the expected crop value at the current population density in the absence of nematicide treatment. Optimal dosage at a lower P_i is less than that at a higher P_i , allowing greater flexibility as considerable costs can occur with aldicarb treatments and still result in positive net returns if soybean prices are above a certain level (e.g., \$6.00/27.2 kg seed).

Although dollar values for the crop and pesticide may differ seasonally and with location, the principles involved in the management decision process prevail. The importance of gathering reliable information on control efficacy and control-cost functions, as well as on nematode-damage functions, in order to formulate a sound basis for management decisions in soybean production cannot be overemphasized.

LITERATURE CITED

1. Abawi, G. S., and B. J. Jacobsen. 1984. Effect of initial inoculum densities of *Heterodera glycines* on growth of soybean and kidney bean and their efficiency as hosts under greenhouse conditions. *Phytopathology* 74:1470-1474.
2. Barker, K. R., and T. H. A. Olthof. 1976. Relationships between nematode population densities and crop responses. *Annual Review of Phytopathology* 14:327-353.
3. Barker, K. R. (chairman). 1978. Determining nematode responses to control agents. Pp. 114-125 in E. Zehr, ed. *Methods for evaluating plant fungicides, nematicides and bacteriocides*. St. Paul, Minnesota: American Phytopathological Society.
4. Barker, K. R., and J. L. Imbriani. 1984. Nematode advisory programs—status and prospects. *Plant Disease* 68:735-741.
5. Barker, K. R., D. P. Schmitt, and J. L. Imbriani. 1985. Nematode population dynamics with emphasis on determining damage potential to crops. Pp. 135-148 in K. R. Barker, C. C. Carter, and J. N. Sasser, eds. *An advanced treatise on Meloidogyne*, vol. 2. *Methodology*. Cooperative Publication of the North Carolina State University Department of Plant Pathology and the United States Agency for International Development, Raleigh, North Carolina.
6. Bonner, M. J., and D. P. Schmitt. 1985. Population dynamics of *Heterodera glycines* life stages on soybean. *Journal of Nematology* 17:153-158.
7. Brodie, B. B. 1983. Control of *Globodera rostochiensis* in relation to method of applying nematicides. *Journal of Nematology* 15:491-495.
8. Brown, R. H. 1984. Ecology and control of cereal cyst nematode (*Heterodera avenae*) in southern Australia. *Journal of Nematology* 16:216-222.
9. Ferris, H. 1978. Nematode economic thresholds: Derivation, requirements and theoretical considerations. *Journal of Nematology* 10:341-350.
10. Hijink, M. J. 1963. A relation between stem infection by *Phoma solanicola* and *Ditylenchus dipsaci* on potato. *Netherlands Journal of Plant Pathology* 69:318-321.
11. Jones, F. G. W. 1956. Soil populations of beet eelworm (*Heterodera schachtii* Schmidt) in relation to cropping: 2. Microplot and field plot results. *Annals of Applied Biology* 44:25-56.
12. Jones, F. G. W., and R. A. Kempton. 1978. Population dynamics, population models and integrated control. Pp. 333-361 in J. F. Southey, ed. *Plant nematology*. Ministry of Agriculture, Fish and Food Technology Bulletin 7. London: Her Majesty's Stationery Office.
13. Jorgenson, E. C. 1984. Nematicides and non-conventional soil amendments in the management of root-knot nematode on cotton. *Journal of Nematology* 16:154-158.
14. Lownsbey, B. F., and B. G. Peters. 1955. The relation of the tobacco cyst nematode to tobacco growth. *Phytopathology* 45:163-167.
15. Noel, G. R. 1982. Relating numbers of soybean cyst nematode to crop damage. Pp. 17-19 in D. P. Schmitt, ed. *Proceedings of the Fifth Cyst Nematode Workshop*. Raleigh: North Carolina State University.
16. Oostenbrink, M. 1966. Major characteristics of the relation between nematodes and plants. *Mededelingen Landbouwhogeschool Wageningen* 66:1-44.
17. Rodriguez-Kabana, R., P. G. Mawhinney, and P. S. King. 1980. Efficacy of planting time injections to soil of liquid formulations of three systemic nematicides against root-knot nematodes in peanuts. *Nematropica* 10:45-49.
18. Rodriguez-Kabana, R., P. S. King, and M. H. Pope. 1981. Comparison of in-furrow applications and banded treatments for control of *Meloidogyne armaria* in peanuts and soybeans. *Nematropica* 11:53-67.
19. Schmitt, D. P., F. T. Corbin, and L. A. Nelson. 1983. Population dynamics of *Heterodera glycines* and soybean response in soils treated with selected nematicides and herbicides. *Journal of Nematology* 15:432-437.
20. Schmitt, D. P., and G. R. Noel. 1984. Nematode parasites of soybeans. Pp. 13-59 in W. R. Nickle, ed. *Plant and insect parasitic nematodes*. New York: Marcel Dekker.
21. Seinhorst, J. W. 1965. The relation between nematode density and damage to plants. *Nematologica* 11:137-154.
22. Seinhorst, J. W. 1973. Principles and possibilities of determining degrees of nematode control leading to maximum returns. *Mediterranean Journal of Nematology* 1:93-105.
23. Wallace, H. R. 1971. The influence of the density of nematode populations on plants. *Nematologica* 17:154-166.