Journal of Nematology 23(3):353–361. 1991.

Maximizing the Potential of Cropping Systems for Nematode Management[1]

J. P. NOE,[2] J. N. SASSER,[3] AND J. L. IMBRIANI[4]

Abstract: Quantitative techniques were used to analyze and determine optimal potential profitability of 3-year rotations of cotton, *Gossypium hirsutum* cv. Coker 315, and soybean, *Glycine max* cv. Centennial, with increasing population densities of *Hoplolaimus columbus.* Data collected from naturally infested on-farm research plots were combined with economic information to construct a microcomputer spreadsheet analysis of the cropping system. Nonlinear mathematical functions were fitted to field data to represent damage functions and population dynamic curves. Maximum yield losses due to *H. columbus* were estimated to be 20% on cotton and 42% on soybean. Maximum at-harvest population densities were calculated to be 182/100 cm^3 soil for cotton and 149/100 cm^3 soil for soybean. Projected net incomes ranged from a $17.74/ha net loss for the soybean–cotton–soybean sequence to a net profit of $46.80/ha for the cotton–soybean–cotton sequence. The relative profitability of various rotations changed as nematode densities increased, indicating economic thresholds for recommending alternative crop sequences. The utility and power of quantitative optimization was demonstrated for comparisons of rotations under different economic assumptions and with other management alternatives.

Key words: cotton, crop rotation, damage function, economic threshold, *Glycine max, Gossypium hirsutum, Hoplolaimus columbus,* lance nematode, population dynamics, soybean.

Manipulation of cropping systems is one of the oldest and most proven management practices to minimize the impact of plant-parasitic nematodes. Prescribed crop rotations, which limit population increases, have been identified as particularly effective tools against these obligate parasites. By removing the host for an adequate length of time, the population may be reduced below economic thresholds.

In 1911, Bessey (5) recommended the use of crop rotations to control infestations of root-knot nematodes in vegetables. Since then, numerous studies have demonstrated the practical advantages of sequencing crops. A computer literature search resulted in more than 200 citations dealing with "crop rotation." A sampling of these citations showed that most have focused on end-of-rotation population densities as indicators of successful rotations (1,7,9, 10,12,18,19,22–25,27,29–31,33,37,40, 42–44,46,48,49). Typically, limited numbers of sequences were selected from a set of crops, the rotations were implemented in field trials, and final nematode population densities were measured. Variations on this design have included simultaneous considerations of nematicides (7,23,33), fallow (7,12), soil types (8,9), fertilizer amendments (41,42), tillage (19), organic amendments (31), and resistance (37).

Fewer studies have included consideration of crop yields in evaluating rotations (22,24,28,43,44,48), with most reporting the yield of only the most important crop in the rotation. Little information is available on the overall productivity and economic viability of crop rotation systems. Rodríguez-Kábana et al. (44) reported on the profitability of various soybean–peanut rotations, showing net profits for different combinations of crop rotations and nematicide usage to control *Meloidogyne arenaria* (Neal) Chitwood. Kinloch (29) included predictive models for postharvest densities of *M. incognita* (Kofoid & White) Chitwood in an analysis of crop losses in soybean–maize rotations. Jones and Kempton (26) simulated population dynamics of

---

Received for publication 21 March 1990.

[1] Colloquium paper presented at the 27th Annual Meeting of the Society of Nematologists, 12–16 June 1988, Raleigh, NC. This work was supported by the United States Agency for International Development, Crop Nematode Research and Development Project, North Carolina State University, under cooperative agreement No. DAN-4149-A-00-4054-00, Project No. 936-4149, and by state and Hatch funds allocated to the Georgia Agricultural Experiment Stations.

[2] Assistant Professor, Department of Plant Pathology, University of Georgia, Athens, GA 30602.

[3] Professor Emeritus, Department of Plant Pathology, North Carolina State University, Raleigh, NC 27695.

[4] Nematologist, Nematode Advisory Service, North Carolina Department of Agriculture, Blue Ridge Road Center, Raleigh, NC 27607.

Globodera rostochiensis (Woll.) Behrens on potato using models for nematode reproduction, root damage, and nematode survival. Duncan (13) used data from field plots to determine quantitative host–parasite relationships, and simulate the effects of *M. incognita* on a cotton–cowpea cropping system. Ferris and Noling (17) discussed the use of critical-point models in a predictive management recommendation program, using *M. incognita* on cotton–cowpea as an example system.

Thus, the identification of effective crop rotations has been largely a matter of trial and error, through the deployment of research designs which include direct comparisons of specified cropping sequences. These methods, although effective for evaluating planned comparisons, have numerous limitations. Only preplanned crop rotations can be evaluated within a given design, and there is no mechanism to add other comparisons or evaluations of additional management practices to the resulting data. Also, previous crop rotation research has emphasized evaluations based on final output of the system, i.e., total yield or final nematode population densities, which does not add to our understanding of host–parasite dynamics during the individual growing seasons.

With the emergence of improved quantitative approaches to the analysis of nematode host–parasite relationships (3,4,15), more detailed and comprehensive analyses of cropping systems are possible. Using a framework of previously described quantitative methods (34,35), we have demonstrated the potential of cropping systems analyses. The crop–nematode system used for this demonstration consists of *Hoplolaimus columbus* Sher on cotton and soybean, using data collected from on-farm plots in North Carolina.

MATERIALS AND METHODS

Population densities of *H. columbus* were assessed at planting and at harvest, and yield data were collected from naturally infested on-farm plots over two growing seasons. Mathematical models representing damage functions and population changes were fitted to data from the field plots. The models then were used to simulate rotation systems of cotton and soybean in a microcomputer spreadsheet environment. Economic data on crop production costs and market prices were added to the spreadsheet simulation to predict economic performance of selected rotations. The economic performance of these rotations then were plotted against at-plant densities of *H. columbus* to demonstrate the potential utility of this quantitative approach for developing and evaluating nematode management alternatives.

Field data collection: Two grids of 64 plots each were established on a farm in Scotland County North Carolina (Marlboro loamy sand—clayey, kaolinitic, thermic, typic Paleudults). Each plot consisted of four rows, 20 m long and 1 m apart. Grids eight plots wide by eight plots long were arranged over previously assayed clusters of *H. columbus* so that wide ranges of population densities were obtained by utilizing naturally occurring spatial aggregation (36). Plots were arranged along crop rows immediately after planting, and soil samples were collected for nematode assays.

Soil samples for nematode assay were obtained by bulking and mixing 12 individual 2.5-cm-d soil cores collected to a depth of 20 cm in a zig-zag pattern from the rhizosphere of the two center rows of each plot. Plant-parasitic nematodes were extracted from 500-cm^3 subsamples by elutriation and sucrose centrifugation (approximate efficiency = 0.20) (2,11). Nematodes were identified, counted, and reported per 100 cm^3 soil.

Both sites were planted to cotton, *Gossypium hirsutum* L. cv. Coker 315, and at-plant nematode assays were collected 23 May 1985. Plants were defoliated 6 September. Cotton was harvested and final nematode assays were collected 19 September from the two center rows of each plot when the plants were fully senescent. Seed cotton yields were converted to lint weights with a conversion factor of 0.33.

During the second growing season, soybean, *Glycine max* (L.) Merrill cv. Centennial, was planted on both sites and at-plant nematode assays were collected 11 June 1986. Steel marking pins had been established at the end of the previous growing season to allow precise relocation of the grids. Beans were harvested and final nematode assays were collected 7 October from the two center rows of each plot when plants were fully senescent.

The fields containing research plots were managed by a commercial grower using recommended practices for each crop, except that no nematicidal compounds were applied. No disturbance of the normal agricultural ecosystem was imposed by the data collection procedures, so resulting information accurately represented grower conditions.

Mathematical analyses: Our goal in analysis was to obtain mathematical functions that offered the best possible representations of nematode damage functions, relating crop yields to at-plant densities of *H. columbus*, and nematode population changes, relating harvest densities of *H. columbus* to at-plant counts. For this purpose, two nonlinear functions were selected and fitted to the data collected from field plots.

In order to simplify the analysis and presentation of results, crop damage and nematode population increase functions were fitted to frequency class means constructed from nematode counts and yield data from both sites (16). In this procedure a frequency analysis was done on at-plant *H. columbus* densities, and then data were arranged into 16 equal-size categories of eight data points each. Because of the ranking inherent in the frequency analysis, the categories represented increasing nematode densities. After the observations in the dataset were grouped in this manner, means of at-plant and harvest *H. columbus* densities and crop yields were calculated for each group (Table 1) and used for further analyses.

The inverse-logistic function (P. B. Burrows, unpubl.) used to represent nematode damage was

$$Y = m + \frac{(M - m)}{1 + \left(\frac{Pi}{u}\right)^b} \qquad (1)$$

where Y represents crop yield, Pi is at-plant nematode density, M is maximum yield, m is minimum yield, and u and b together determine shape and location of the resulting curve.

Nematode population changes during the growing season were represented by the increasing exponential function

$$Pf = M(1 - e^{-bPi}) \qquad (2)$$

where Pf is the harvest population density, Pi is the at-plant density, M is the maximum population density, and b determines the exponential rate of increase. Both functions (eq. 1, eq. 2) are dependent on Pi, which was selected as a population estimate having potential for application in a nematode management advisory system. The formula relating Pf to Pi was necessary to estimate residual populations at the end of a growing season. The indicated nematode damage and population change functions were fitted to field data using nonlinear least-squares estimation (45).

In an attempt to describe overwinter survival, both linear and decreasing exponential functions were fitted to the relationship between harvest *H. columbus* counts from the first season (Pf1) and at-plant counts from the second season (Pi2). However, no significant density dependence was detected in the Pf1 to Pi2 relationship. The average survival rate of *H. columbus* was 70%, and this constant survival rate was assumed in subsequent analyses.

Cropping system analysis: A discrete stepwise analysis of various rotations of cotton and soybean was constructed in a microcomputer spreadsheet program (Microsoft Excel, Microsoft Corp., Redmond, WA). First, a range of input Pi was generated as representative of the field data (0–350 *H. columbus* per 100 cm^3 soil). This column in the spreadsheet then was used as a data

TABLE 1. Frequency class means,† ranges, and coefficients of variation (CV) for at-plant and harvest counts of *Hoplolaimus columbus* and yield of cotton and soybean used in nonlinear regression analysis.

	H. columbus/100-cm^3 soil						Yield		
	At-plant			Harvest					
Freq. class	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV
				Cotton					
1	7	2–12	51	112	52–230	52	877	741–1,107	15
2	16	14–18	10	127	34–288	77	818	647–920	11
3	22	20–24	8	124	34–230	50	907	733–1,115	13
4	26	24–26	4	144	36–432	92	843	671–1,061	14
5	31	28–34	8	148	90–208	27	852	413–1,084	23
6	37	34–38	4	160	100–248	38	875	780–975	8
7	40	38–42	3	132	26–222	51	829	569–1,022	21
8	46	42–48	5	192	108–310	36	802	592–1,045	17
9	51	48–54	4	152	30–264	52	786	460–1,076	30
10	58	56–62	4	182	52–386	78	855	468–1,123	25
11	67	64–70	3	177	100–364	52	795	741–897	6
12	74	70–78	4	163	76–304	46	752	694–819	6
13	83	80–88	3	182	84–326	45	746	546–905	15
14	97	90–100	3	216	104–400	41	683	382–913	26
15	115	100–128	8	218	60–354	45	735	507–920	17
16	161	132–250	24	166	56–348	58	699	499–889	18
Overall	58	2–250	70	162	26–432	54	803	382–1,123	19
				Soybean					
1	19	4–28	41	42	2–159	135	2,382	1,400–4,025	40
2	30	28–32	6	20	4–36	53	2,292	1,540–3,780	33
3	36	32–38	6	58	4–328	192	1,804	857–3,150	39
4	45	40–52	10	28	6–74	97	2,052	875–3,027	37
5	58	52–66	8	49	12–96	69	1,678	630–3,325	49
6	73	68–80	6	68	22–156	64	2,387	647–4,515	55
7	83	82–84	1	58	6–196	121	1,914	752–3,220	48
8	90	84–96	5	28	0–98	113	1,477	315–2,783	68
9	101	96–112	7	93	10–344	123	2,021	665–3,115	47
10	121	112–124	5	37	6–68	56	2,023	420–3,920	67
11	134	124–144	6	54	18–100	63	1,348	280–2,205	45
12	161	148–168	4	161	16–488	110	1,680	332–3,010	57
13	170	168–172	1	129	20–304	89	1,840	630–2,765	45
14	183	172–192	4	118	10–416	113	1,555	175–2,362	45
15	240	196–284	13	113	8–248	92	1,687	315–2,975	54
16	322	288–376	10	117	26–456	123	1,177	560–2,800	74
Overall	117	4–376	70	73	0–488	131	1,832	175–4,515	51

† Mean of eight observations per frequency class; 8 × 16 classes = 128 total observations per crop.

series of Pi for the next column, which contained the formula for a damage function (eq. 1) as generated from the field data for either cotton or soybean. The damage functions calculated estimated yields per hectare for each Pi. These estimated yields served as input for the next column in the spreadsheet, which calculated net profits based on market prices (5-year average) (39) and fixed and variable costs of production for cotton (20) and soybean (14). Prices used were \$1.27/kg lint cotton, \$0.09/kg cotton seed, and \$0.21/kg seed soybean. Cotton production costs were estimated as \$791.00/ha fixed and \$0.24/kg variable. Soybean production costs were estimated as \$368.00/ha fixed and \$0.003/kg variable.

The next column in the spreadsheet calculated crop-dependent Pf (harvest *H. columbus* densities) from Pi in the first column, again using the nonlinear formula (eq. 2) based on field data. These counts were "overwintered" in the next spreadsheet column, using a survival rate of 0.70 based on the change in *H. columbus* densi-

TABLE 2. Parameter estimates and nonlinear regression statistics for damage functions and *Hoplolaimus columbus* population increases for cotton and soybean.

	Parameter estimate	Asymptotic standard error	Least squares analysis			
			Source	df	Sum of squares	Mean square
			Cotton			
Damage function†						
m	693.0	37.0	Regression	4	10,379,230	2,594,807
M	861.0	16.9	Residual	12	13,024	1,085
u	68.0	11.1	Total	16	10,392,253	
b	4.1	2.3				
Population increase‡						
M	182.00	8.90	Regression	2	427,449	213,750
b	0.06	0.01	Residual	14	7,691	549
			Total	16	435,190	
			Soybean			
Damage function						
m	1,210	550.5	Regression	4	54,502,656	13,625,664
M	2,100	168.7	Residual	12	1,100,295	91,691
u	150	73.0	Total	16	55,602,951	
b	3	3.1				
Population increase						
M	149.000	45.500	Regression	2	101,311	50,656
b	0.007	0.004	Residual	14	11,853	847
			Total	16	113,164	

† m = minimum yield (kg/ha); M = maximum yield (kg/ha); u and b are parameters that determine curve shape.
‡ M—maximum population density (number of nematodes/100 cm^3 soil); b determines exponential rate of increase.

ties from harvest of the first season until planting for the second season. This column of overwintered *H. columbus* densities was used as input in the next crop cycle, and the entire procedure was repeated as necessary to complete the 3-year crop rotation evaluation. Crop damage and nematode increase functions were used as appropriate for the selected rotation.

At the end of a 3-year sequence, the overwinter column of nematode counts was calculated to represent the residual nematode population densities at the end of a rotation. A final column was calculated as the sum of the net profits for each year divided by 3, to represent the average net profit per hectare per year for each beginning Pi for each 3-year rotation. All constants, including parameter estimates for the crop damage and nematode increase functions, and economic variables were kept in a separate area of the spreadsheet and linked to their respective functions. Thus, the function parameters and economic constraints could be changed easily, and the entire spreadsheet could be recalculated. All possible 3-year rotations of cotton and soybean were programmed into the spreadsheet and compared on the basis of average net profits.

RESULTS

The nonlinear functions (eq. 1, eq. 2) adequately described host–parasite relationships in both crops. Sums of squares ratios and standard errors of parameter estimates indicated good fitting to the field data (Table 2). However, estimation of the damage function parameter *b* in the soybean analysis was poor, with a standard error greater than the parameter estimate. This indicates considerable variability in the data with respect to the optimum shape of the damage function. Coefficients of variation within most of the data ranges (Table 1) were high, as expected for field data, and this variation is reflected in the least-squares parameter estimation.

Estimates of maximum (861 kg/ha) and minimum (693 kg/ha) cotton lint yields

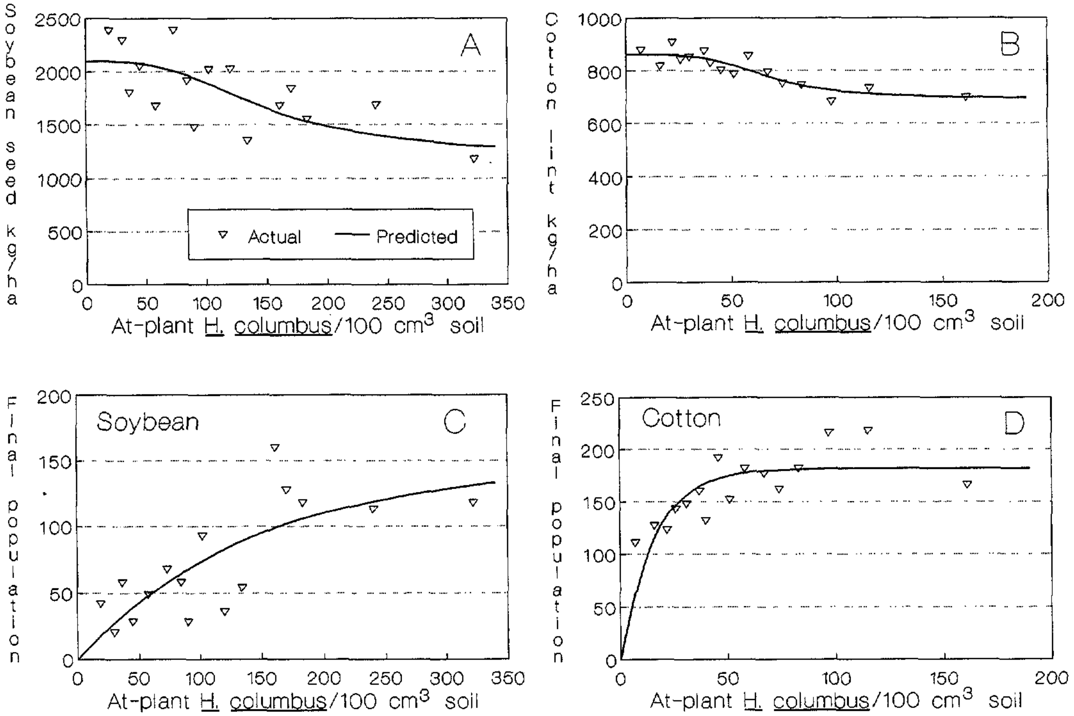

FIG. 1. Damage functions and nematode population increase curves. A, C) Soybean. B, D) Cotton. Parameter estimates and least-squares statistics are in Table 2.

from the damage function (Table 2) reflected a 20% decrease in yield in response to increasing nematode numbers. Parameter estimates for maximum (2,100 kg/ha) and minimum (1,210 kg/ha) soybean seed yields indicated a potential 42% decrease as nematode numbers increased. Estimates of maximum at-harvest nematode densities were 182/100 cm^3 soil in cotton population increase functions, and 149/100 cm^3 soil in soybean.

Fitted curves and data points shown in Figure 1 demonstrated the flexibility of the functions used and the goodness of fit obtained with nonlinear least-squares parameter estimation. Greater yield decrease and increased variability in the data for soybean were demonstrated by comparison of the damage function figures for soybean and cotton (Fig. 1A, B). Also, a greater rate of population increase and higher estimated at-harvest nematode counts for cotton were shown in a comparison of the population curves (Fig. 1C, D). Although variable, expected trends were evident in the scatter plots of frequency-class data.

Microcomputer spreadsheet analyses of all possible 3-year rotations resulted in a wide range of projected 3-year average net incomes. With a beginning *H. columbus* population density of 350/100 cm^3 soil (the highest density analyzed) projected net incomes ranged from a loss of −$17.74/ha for the soybean–cotton–soybean (s-c-s) sequence, to a net profit of $46.80/ha for the cotton–soybean–cotton (c-s-c) sequence (Fig. 2A). Thus, under the worst-case scenario with respect to nematode pressure, appropriate cropping sequence selection reversed a net-loss situation into a profitable enterprise. In the same analysis, rotation to 1 year of soybean (c-s-c) was more than twice as profitable as the monoculture of cotton (c-c-c) (net profit of $20.26/ha) (Fig. 2A).

After the spreadsheet analyses were recalculated with an increase in the projected price of soybean seed to $0.26/kg, the s-c-s rotation was more profitable than c-s-c up to an at-plant *H. columbus* density of 160/100 cm^3 soil (Fig. 2B). At nematode population densities higher than 160/100 cm^3

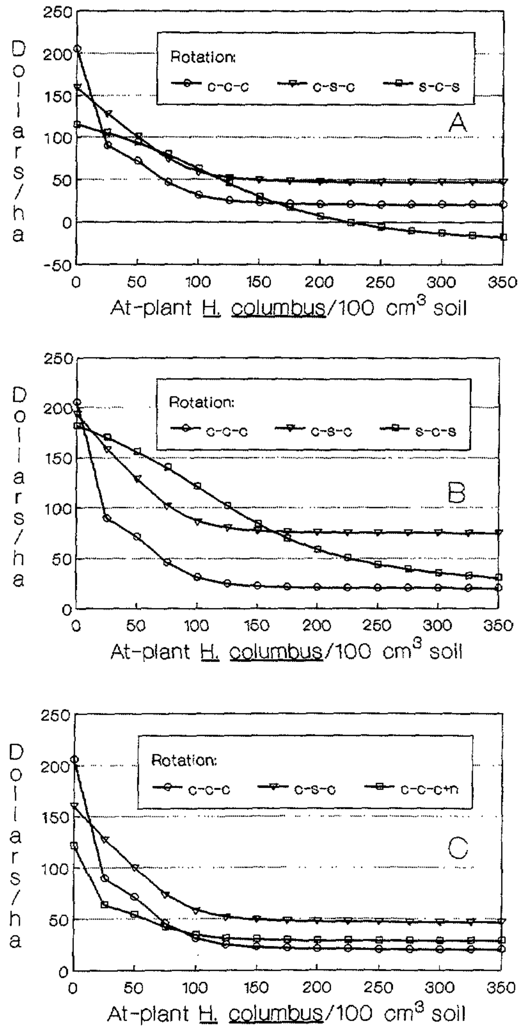

FIG. 2. Projected average net income (profit or loss) for 3-year rotations of cotton and soybean versus increasing nematode numbers. Data were calculated from microcomputer spreadsheet analysis based on damage functions and population increase curves in Figure 1 and economic data. Rotations are cotton–cotton–cotton (c-c-c), cotton–soybean–cotton (c-s-c), and soybean–cotton–soybean (s-c-s). A) Calculated using economic data given in methods. B) Change in relative profitability of rotations after increasing the assumed price of soybean from $0.21 to $0.26/kg seed. C) Evaluation of economic impact on the c-c-c sequence from addition of a nematicide (c-c-c+n) which reduces crop damage by 50% and costs $84.00/ha.

soil, the c-s-c rotation was again more profitable. The monoculture of cotton (c-c-c) was the least profitable sequence in this comparison, as expected with the higher projected price for soybean. This recalculation showed the sensitivity to commodity prices of projected results and demonstrated the utility of the analyses in the calculation of crop-sequence recommendation thresholds.

A third spreadsheet recalculation was based on assumptions related to application of a hypothetical nematicide to cotton which decreased crop damage by 50% and increased fixed costs by $84.00/ha. The 50% decrease in crop damage was implemented by refitting the parameters of the cotton damage function to reflect the new density-dependent levels and including the new damage function parameters in the spreadsheet setup variables. The cost of application was added to the fixed costs for cotton. The recalculated analysis showed that nematicide application increased net profits by $9.00/ha at *H. columbus* population densities higher than 100/100 cm^3 soil in the c-c-c vs. c-c-c+n sequence comparison (Fig. 2C), whereas rotation to 1 year of soybean (c-s-c) with no nematicide was still the most profitable alternative. This analysis showed the utility of the analytical system for evaluating the potential profitability of alternative management tools over a range of nematode densities. As in the preceding analysis, thresholds for selection of cropping sequences or alternative management practices can be determined from examination of the resulting profitability curves.

DISCUSSION

Quantitative optimization is potentially a powerful tool in the analysis of crop rotations and other nematode management practices. Using a limited base of field data and various economic assumptions, we were able to construct a microcomputer spreadsheet analysis that responded logically to increasing nematode population densities and was sensitive to crop sequencing, as well as to the impact of nematicidal treatment.

Our field data were collected by methods specifically designed for analysis of quantitative host–parasite relationships. It is possible that data available in the literature could prove useful in constructing similar systems. Our estimates of potential yield losses were within ranges previously reported for *H. columbus* on cotton (21,32) and soybean (6,38,47), and estimates of reproduction and at-harvest nematode numbers on soybean were similar to those previously reported (6,38,47). We were unable, however, to find published information on damage functions and reproductive curves, or sufficient data to construct these functions.

Although our estimates of total damage and reproductive capacity may be within published ranges, we have not attempted to represent a verified or validated system. The base of data used to construct the quantitative functions reported was not extensive enough to allow generalizations. Variation in the data was typically high, and more information would be required to construct an applied management system.

The impact of different cultivars, growing seasons, and soil types also must be considered. Isolated effects of each of these factors could easily be factored into the formulations used for damage functions and population dynamics. However, our purpose was to demonstrate the potential usefulness of a quantitative optimization approach using natural agroecosystem data and economic information. With slight modification, most crop rotation studies could provide data suitable for similar analytical procedures, thus enhancing the potential impact and applications of resulting information.

LITERATURE CITED

1. Alam, M. M., S. K. Saxena, and A. M. Khan. 1977. Influence of different cropping sequences on soil populations of plant-parasitic nematodes. Nematologica Mediterranea 5:65–72.

2. Barker, K. R. 1985. Nematode extraction and bioassays. Pp. 19–35 *in* K. R. Barker, C. C. Carter, and J. N. Sasser, eds. An advanced treatise on *Meloidogyne,* vol. 2. Methodology. Raleigh: North Carolina State University Graphics.

3. Barker, K. R., and J. P. Noe. 1987. Estimating and using threshold population levels. Pp. 75–81 *in* J. A. Veech and D. W. Dickson, eds. Vistas on nematology. Society of Nematologists.

4. Barker, K. R., and J. P. Noe. 1988. Techniques in quantitative nematology. Pp. 223–236 *in* J. Kranz and J. Rotem, eds. Experimental techniques in plant disease epidemiology. Berlin: Springer-Verlag.

5. Bessey, E. A. 1911. Root-knot and its control. Bulletin 217, USDA Bureau of Plant Industry, Washington, DC.

6. Boerma, H. R., and R. S. Hussey. 1984. Tolerance to *Heterodera glycines* in soybean. Journal of Nematology 16:289–296.

7. Braithwaite, C. W. D. 1974. Effect of crop sequence and fallow on populations of *Rotylenchulus reniformis* in fumigated and untreated soil. Plant Disease Reporter 58:259–261.

8. Brodie, B. B., J. M. Good, and W. E. Adams. 1969. Population dynamics of plant nematodes in cultivated soils: Effect of sod-based rotations in Cecil sandy loam. Journal of Nematology 1:309–312.

9. Brodie, B. B., J. M. Good, and W. H. Marchant. 1970. Population dynamics of plant nematodes in cultivated soils: Effect of sod-based rotations in Tifton sandy loam. Journal of Nematology 2:135–138.

10. Brody, J. K., and C. W. Laughlin. 1977. The effect of vegetable cropping sequences on population development of *Meloidogyne hapla.* Revista de Agriculture 52:13–18.

11. Byrd, D. W., K. R. Barker, H. Ferris, C. J. Nusbaum, W. E. Griffin, R. H. Small, and C. A. Stone. 1976. Two semi-automatic elutriators for extracting nematodes and certain fungi from soil. Journal of Nematology 8:206–212.

12. Carter, W. W., and S. Nieto, Jr. 1975. Population development of *Meloidogyne incognita* as influenced by crop rotation and fallow. Plant Disease Reporter 59:402–403.

13. Duncan, L. W. 1983. Predicting effects of plant-parasitic nematode communities on crop growth. Ph.D. dissertation, University of California, Riverside.

14. Dunphy, E. J., and D. F. Neuman. 1989. North Carolina soybean budget, coastal plain. Bulletin 73-1, North Carolina Cooperative Extension Service, Raleigh.

15. Ferris, H. 1981. Mathematical approaches to the assessment of crop damage. Pp. 405–420 *in* B. M. Zuckerman and R. A. Rohde, eds. Plant parasitic nematodes. New York: Academic Press.

16. Ferris, H. 1984. Nematode damage functions: The problem of experimental and sampling error. Journal of Nematology 16:1–9.

17. Ferris, H., and J. W. Noling. 1987. Analysis and prediction as a basis for management decisions. Pp. 49–85 *in* R. H. Brown and B. R. Kerry, eds. Principles and practice of nematode control in crops. New York: Academic Press.

18. Ferris, V. R., and R. L. Bernard. 1971. Crop rotation effects on population densities of ectoparasitic nematodes. Journal of Nematology 3:119–122.

19. Gallaher, R. N., D. W. Dickson, J. F. Corella, and T. E. Hewlett. 1988. Tillage and multiple cropping systems and population dynamics of phytoparasitic nematodes. Annals of Applied Nematology 2: 90–94.

20. Guthrie, D. S., and W. D. Eickhoff. 1988.

North Carolina cotton budget, southern coastal plain. Bulletin 76-1, North Carolina Cooperative Extension Service, Raleigh.

21. Hussey, R. S. 1977. Effects of subsoiling and nematicides on *Hoplolaimus columbus* populations and cotton yield. Journal of Nematology 9:83–86.

22. Hutton, D. G., P. L. Coates-Beckford, and S. A. E. Eason-Heath. 1983. Management of *Meloidogyne incognita* populations by crop rotation in a small-scale field trial and nematode pathogenic effects on selected cultivars (Jamaica). Nematropica 13:153–163.

23. Johnson, A. W., and G. M. Campbell. 1980. Managing nematode population densities on tomato transplants using crop rotation and a nematicide (fensulfothion). Journal of Nematology 12:6–19.

24. Johnson, A. W., C. C. Dowler, and E. W. Hauser. 1975. Crop rotation and herbicide effects on population densities of plant-parasitic nematodes. Journal of Nematology 7:158–168.

25. Jones, F. G. W. 1956. Soil populations of beet eelworm (*Heterodera schachtii* Schm.) in relation to cropping. 2. Microplot and field plot results. Annals of Applied Biology 44:25–56.

26. Jones, F. G. W., and R. A. Kempton. 1978. Population dynamics, populations models, and integrated control. Pp. 333–361 *in* J. F. Southey, ed. Plant nematology. London: Her Majesty's Stationery Office.

27. Khan, A. H., S. K. Saxena, and I. Mahmood. 1984. Effect of different cropping sequences on the population of plant parasitic nematodes. Pakistan Journal of Nematology 2:29–36.

28. Kinloch, R. A. 1983. Influence of maize rotations on the yield of soybean grown in *Meloidogyne incognita* infested soil. Journal of Nematology 15:398–405.

29. Kinloch, R. A. 1986. Soybean and maize cropping models for the management of *Meloidogyne incognita* in the coastal plain. Journal of Nematology 18:451–458.

30. Mai, W. F., and G. S. Abawi. 1980. Influence of crop rotation on spread and density of *Heterodera schachtii* on a commercial vegetable farm in New York. Plant Disease 64:302–305.

31. Morgan, G. T., and W. B. Colins. 1964. The effect of organic treatments and crop rotation on soil populations of *Pratylenchus penetrans* in strawberry culture. Canadian Journal of Plant Science 44:272–275.

32. Mueller, J. D., and M. J. Sullivan. 1988. Response of cotton to infection by *Hoplolaimus columbus.* Annals of Applied Nematology 2:86–89.

33. Murphy, W. S., B. B. Brodie, and J. M. Good. 1974. Population dynamics of plant nematodes in cultivated soil: Effects of combinations of cropping systems and nematicides. Journal of Nematology 6:103–107.

34. Noe, J. P. 1986. Cropping systems analysis for limiting losses due to plant-parasitic nematodes: Guide to research methodology. Raleigh: North Carolina State University Graphics.

35. Noe, J. P. 1988. Theory and practice of the cropping systems approach to reducing nematode problems in the tropics. Journal of Nematology 20:204–213.

36. Noe, J. P., and C. L. Campbell. 1985. Spatial pattern analysis of plant-parasitic nematodes. Journal of Nematology 17:86–93.

37. Norse, D. 1972. Nematode populations in a maize–groundnut–tobacco rotation and the resistance of maize varieties to *Meloidogyne javanica.* Tropical Agriculture 49:355–360.

38. Nyczepir, A. P., and S. A. Lewis. 1979. Relative tolerance of selected soybean cultivars to *Hoplolaimus columbus* and possible effects of soil temperature. Journal of Nematology 11:27–31.

39. Olson, J. L. 1986. North Carolina agricultural statistics. Bulletin 159, North Carolina Crop and Livestock Reporting Services, Raleigh.

40. Prasad, J. S., and Y. S. Rao. 1978. Influence of crop rotations on the population densities of the root lesion nematode, *Pratylenchus indicus* in rice and rice soils. Annales de Zoologie Ecologie Animale 10:627–633.

41. Rodríguez-Kábana, R., and R. J. Collins. 1979. Relation of fertilizer treatments and cropping sequence to populations of two plant-parasitic nematode species. Nematropica 9:151–166.

42. Rodríguez-Kábana, R., and R. J. Collins. 1980. Relation of fertilizer treatment and cropping sequence to populations of *Pratylenchus scribneri.* Nematropica 10:121–129.

43. Rodríguez-Kábana, R., H. Ivey, and P. A. Backman. 1987. Peanut–cotton rotations for the management of *Meloidogyne arenaria.* Journal of Nematology 19:484–486.

44. Rodríguez-Kábana, R., D. G. Robertson, P. A. Backman, and H. Ivey. 1988. Soybean–peanut rotations for the management of *Meloidogyne arenaria.* Annals of Applied Nematology 2:81–85.

45. SAS Institute. 1985. SAS user's guide: Statistics, version 5. SAS Institute, Cary, NC.

46. Sasser, J. N., and C. J. Nusbaum. 1955. Seasonal fluctuations and host specificity of root-knot nematode populations in two-year tobacco rotation plots. Phytopathology 45:540–545.

47. Schmitt, D. P., and J. L. Imbriani. 1987. Management of *Hoplolaimus columbus* with tolerant soybean and nematicides. Annals of Applied Nematology (Supplement to Journal of Nematology 19) 1:59–63.

48. Sharma, S. K., I. Singh, and P. K. Sakhuja. 1980. Influence of different cropping sequences on the population of root-knot nematode, *Meloidogyne incognita,* and the performance of the subsequent mungbean crop. Indian Journal of Nematology 10:53–58.

49. Wilson, G. F., and F. E. Caveness. 1980. The effect of rotation crops on the survival of root-knot, root-lesion, and spiral nematodes. Nematropica 10:56–61.