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Relationship Between Crop Losses and Initial Population Densities of *Meloidogyne arenaria* in Winter-Grown Oriental Melon in Korea

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Abstract: To determine the economic threshold level, oriental melon (*Cucumis melo* L. cv. Geumssaragi-euncheon) grafted on Shintozoa (*Cucurbita maxima* × *Cu. moschata*) was planted in plots (2 × 3 m) under a plastic film in February with a range of initial population densities (Pi) of *Meloidogyne arenaria.* The relationships of early, late, and total yield to Pi measured in September and January were adequately described by both linear regression and the Seinhorst damage model. Initial nematode densities in September in excess of 14 second-stage juveniles (J2)/100 cm^3 soil caused losses in total yields that exceeded the economic threshold and indicate the need for fosthiazate nematicide treatment at current costs. Differences in yield-loss relationships to Pi between early- and late-season harvests enhance the resolution of the management decision and suggest approaches for optimizing returns. Determination of population levels for advisory purposes can be based on assay samples taken several months before planting, which allows time for implementation of management procedures. We introduce (i) an amendment of the economic threshold definition to reflect efficacy of the nematode management procedure under consideration, and (ii) the concept of profit limit as the nematode population at which net returns from the system will become negative.

Key words: Cucumis melo, economic threshold, management efficacy, *Meloidogyne arenaria,* oriental melon, population density, profit limit, root-knot nematode.

Oriental melon (*Cucumis melo* L.), a high-value cash crop in Korea, is transplanted under plastic film in January and grown until October. It has been produced extensively for the last 20 years in Seongju, Korea, and root-knot nematodes, *Meloidogyne* spp., are recognized as serious pests (Kwon et al., 1998; Park et al., 1995). Oriental melon grown in infested soil produces fewer fruits and dies early in July unless the soil is treated with nematicides or rotated to nonhost crops during the previous year. Use of nematicides is increasing in the production area. Economic and environmental considerations, however, demand development of integrated pest management (IPM) programs.

Fundamental to the IPM approach is the development of information regarding nematode population levels below which a particular control method can be considered unnecessary (Ferris, 1978). Studies to determine damaging levels have been conducted for several nematode and crop species (Arens and Rich, 1981; Ferris, 1974; Griffin, 1981; Olthof and Potter, 1972; Seinhorst, 1965), but there is no information for oriental melon as produced in Korea.

Most studies of the effects of nematodes on crops have determined the responses of plants to population levels at the time of seeding or transplanting. However, to have practical value to growers, the host response equation should be derived from nematode population densities several months before seeding or transplanting. This accommodates the time necessary for shipping and processing soil samples, informing growers, and purchasing and delivering required control materials.

The objectives of this study were to: (i) determine the relationships of the yield of oriental melon to population densities of *M. arenaria* at planting and several months before planting, and (ii) estimate the tolerance levels and damage function parameters necessary to optimize control costs.

Materials and Methods

The investigation was conducted at Seongju Fruit Vegetable Experiment Station, Korea. Oriental melon (*Cucumis melo* L. cv. Geumssaragi-euncheon) grafted on Shintozoa (*Cucurbita maxima* × *Cu. moschata*) was used in the experiment. Grafting is a common practice in oriental melon production in Korea because it increases cold tolerance and provides resistance to a wilt disease caused by *Fusarium oxysporum* f. sp. *melonis.*

The site for these studies has a sandy loam soil with relatively high phosphorus (679 mg/kg) and calcium (8.06 mg/kg) content. The soil had 2.5 g/kg organic matter, 0.12 g/kg total nitrogen, electrical conductivity of 2.47 ds/m, and pH 7.4. Standard oriental melon cultural practices were employed during the experiment. Fertilizer (187 kg/ha nitrogen, 63 kg/ha phosphate, and 109 kg/ha potassium) and 30 Mton/ha manure were broadcast and disk-incorporated in October. Rows were ridged into beds 20 cm high and 200 cm wide. The ridges were mulched with black plastic film (0.02-mm thickness), and herbicides were never applied. The beds were framed with wire and covered with clear plastic film (0.02-mm thickness) (Fig. 1). During the night, from planting until mid-April, the plastic film was covered with a blanket (density = 400 g/m^2) to preserve heat. The beds were drip-irrigated (dripper flow = 1.49 liter/hour; Netafim, Fresno, CA) (Fig. 1). After oriental melons were transplanted into the beds, standard cultural practices were followed (Anonymous, 1999) and supplementary nutrients were provided as needed. Insects and diseases were controlled with non-

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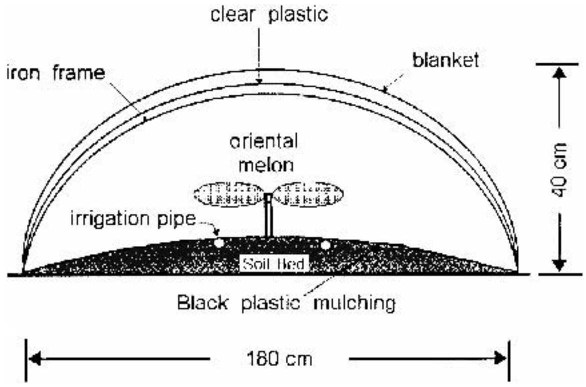

FIG. 1. Schematic of the cultivation of oriental melon on plastic-covered beds during the winter season.

systemic pesticides, i.e., pyrazophos, dichlofluanid, and carbosulfan.

Two types of experiments were conducted. The first involved field plots with varying initial densities of *M. arenaria.* The second was a pot test with four different initial population densities of the nematode.

Field plot experiment: To study the relationship between fruit yield and initial population densities of *M. arenaria,* 48 plots were prepared in soil with a history of root-knot nematode infestation. Plots with a 3-m bed length were divided by plastic barriers extending 20 cm below and 30 cm above the soil surface.

A range of initial population densities (Pi) of *M. arenaria* in plots was established by either no cultivation or continuous cultivation of oriental melon during the summer and by addition of noninfested soil in fall 1999. Preplant Pi levels were determined in September 1999 (4 months before planting) and January 2000 (1 month before planting). Postplant population densities were measured in April (2 months after planting) and June 2000 (4 months after planting). Composite samples of 14 soil cores (2.5-cm diam. × 20-cm deep) were thoroughly mixed. Second-stage juveniles (J2) of *M. arenaria* were extracted from 300 cm^3 of each sample by sugar-flotation-sieving (Southey, 1986). Egg densities prior to planting were considered low and were not assessed.

Seven 42-day-old Geumssaragi-euncheon oriental melon seedlings were transplanted 40 cm apart in each plot on 4 February 2000. Oriental melon fruits were hand-harvested from each plot and weighed at weekly intervals between 20 April and 4 July 2000.

Pot experiment: Pot experiments were prepared with nematode-infested soil from the Seongju Fruit Vegetable Experiment Station. Varying amounts of infested and noninfested soil were mixed to provide the desired range of initial densities (0, 10, 100, and 1,000 J2/100 cm^3) and placed in 26-cm-diam. × 23-cm-height plastic pots (dry soil weight = ca. 2,755 grams). Treatments were replicated eight times in randomized complete blocks. Pots were embedded in soil at 40-cm intervals. The row was mulched with black plastic film, framed, and covered with clear plastic film and a blanket, as in the plot experiment. A 42-day-old Geumssaragi-euncheon oriental melon seedling was transplanted into each pot on 12 February 2000. Oriental melons from each pot were hand-harvested and weighed at weekly intervals between 8 May and 31 July 2000.

Analyses: Regression analyses related total yields (dependent variable) to initial numbers of nematodes (independent variable) in each experiment. To stabilize variances, numbers of nematodes were transformed to $\log_{10}(x+1)$ or $\ln(x+1)$ values, where x is the population level on a given date (Ferris, 1974). Linear models were fitted to the relationship between yield and log-transformed nematode population data (SAS Institute, Inc., Cary, NC). Additionally, the Seinhorst damage function (1965) was fitted to the relationship between yield and the initial nematode population levels.

RESULTS

Nematodes found in the Seongju Experiment Station greenhouse soil were *M. arenaria, Helicotylenchus* sp., *Mesocriconema* sp., and *Rhabditis* spp. Of these, *M. arenaria* is a major pest species. The other plant-parasitic nematodes were present only in low numbers and thus considered to have negligible impact in this study. The root-knot nematode species was identified as *M. arenaria* (Neal) Chitwood Race 2 from perineal patterns and a differential host test (Hartman and Sasser, 1985).

There was a negative linear relationship between yield of oriental melon and log-transformed *M. arenaria* Pi levels. Early, late, and total yields in *M. arenaria*-infested plots were highly correlated with September ($R^2 = 0.24, 0.33, 0.42, P < 0.001$) and January ($R^2 = 0.22, 0.36, 0.44, P < 0.001$) nematode counts (Fig. 2, Table 1). The slopes of the regression lines relating late yields of oriental melon to September and January population levels were much steeper (−0.39 and −0.57, respectively) than the same relationships for early yields (−0.23 and −0.31, respectively). The linear models provided a better fit for the late-yield data than for the early-yield data (Table 1).

Similar analyses were performed with the Seinhorst (1965) damage function as the model to relate yields to nematode densities. September or January nematode population densities predicted late-season (R^2 = 0.33 and 0.25, respectively) and total (R^2 = 0.45 and 0.35, respectively) yields better than early-season yields (R^2 = 0.22 and 0.24, respectively). Relative minimum yield levels were lower for late-season than for early-season harvests (Fig. 3) (Table 2).

The relationship between seasonal multiplication rate (Pf/Pi) and Ln(Pi) for Pi levels measured in September exhibited a typical negative exponential decay pattern reflecting resource limitation of nematode mul-

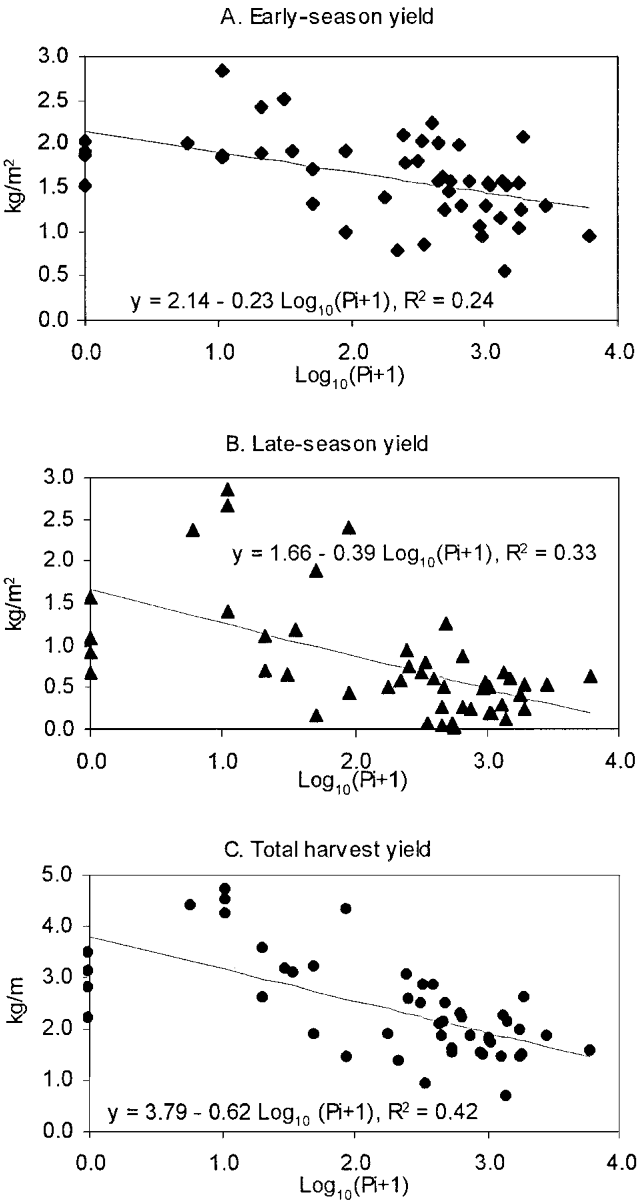

FIG. 2. Linear models: Relationship between oriental melon yield and preplant population densities (Pi) of *Meloidogyne arenaria* in September in a plot experiment. Pi were transformed to $\log_{10}(Pi + 1)$ values for analysis. A) Early yield (April–May). B) Late yield (June–July). C) Total yield.

tiplication in plants damaged by high population levels (Fig. 4) (Ferris, 1985). The maximum multiplication rate in the field plot study was estimated as 325 at Pi below 5/100 cm^3 soil. In the pot study, multiplication rates at Pi of 10 and 100/100 cm^3 soil were less than half those at similar densities in the field study.

Total yields were negatively correlated with initial nematode densities in the pot experiment ($y = 4.73 - 0.45 \log_{10}(Pi + 1)$; $R^2 = 0.22$, $P < 0.05$) (Table 1). The correlation coefficient for the relationship between fruit yield and initial nematode densities was lower in the pot test than in the field plots, possibly because root development was limited in the pot experiment.

TABLE 1. Regression of yields from plots of oriental melon on population densities (Pi) of *Meloidogyne arenaria* at two preplant dates, and yield on Pi in a pot test.

Parameters	Preplant sampling date	Regression of growth vs. nematode density [$\log_{10}(Pi + 1)$ per 100 cm^3 soil]		
		Intercept	Slope	*r*
Plot experiment (kg/m^2)				
Early yield[a]	September	2.13	−0.23	−0.49***
	January	2.23	−0.31	−0.47***
Late yield[b]	September	1.66	−0.39	−0.57***
	January	2.06	−0.57	−0.60***
Total yield	September	3.79	−0.62	−0.65***
	January	4.37	−0.89	−0.66***
Pot experiment (kg/pot)				
Early yield[a]	January	—	—	ns
Late yield[b]	January	3.05	−0.34	−0.36*
Total yield	January	4.73	−0.45	−0.47***

[a] Early yield = April to May.
[b] Late yield = June to July.
***, * slopes significantly different from zero at $P < 0.001$ and $P < 0.05$ (based on analysis of nematode counts transformed to $\log_{10}(Pi + 1)$ values).
ns = relationship not significant.

DISCUSSION

Meloidogyne arenaria causes significant yield losses to oriental melon at population densities commonly found in fields in the Seongju area in Korea. Both linear and Seinhorst damage functions adequately describe results of a field plot experiment (Figs. 2,3). Average production in noninfested soil in the Seongju area is 29.9 Mton/ha (Ministry of Agriculture and Forestry, 1999), with a market value of \$1.30/kg (average of 3 years). There are 4,653 ha of melons grown under plastic in the area, and 53.5% of the soil area is infested with root-knot nematodes at an average population density of 585 J2/100 cm^3 soil (Cho et al., 2000). Based on the damage potential regressions in this study, 585 J2/100 cm^3 soil cause 45% yield reduction of oriental melons valued at \$43.5 million.

We define the economic threshold (ET) as the Pi at which the value of the crop loss is equal to the cost of the management option (Ferris, 1978). There are several interesting components of the calculation for this cropping system. First, not all the fruit harvested from the plants in noninfested soil would have been marketable. Growers usually experience 15–20% losses of fruit, in fields where root-knot nematodes cannot be detected, due to blemish, size constraints, and a number of other factors (Anonymous, 1999). That allows estimation of marketable potential yield of 29.9 Mton/ha (Ministry of Agriculture and Forestry, 1999), which we will partition between early and late harvest in proportion to harvest data from this study. Second, the value of early-harvested oriental melon fruit (\$2.17/kg) is greater than that of fruit harvested later (\$0.98/kg) due to supply-and-demand factors. Third, the cost of management varies depending on the alternatives employed. For these analyses, we consider application of

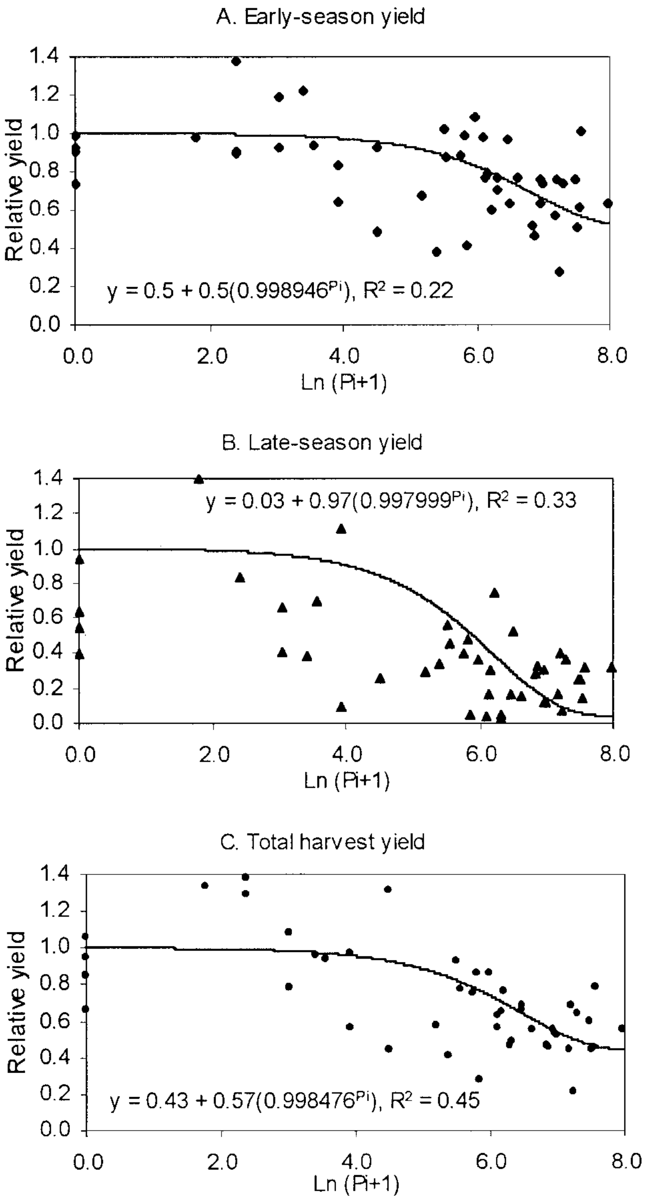

FIG. 3. Seinhorst damage function model: Relationship between oriental melon yield and preplant population densities (Pi) of *Meloidogyne arenaria* in September in a plot experiment. Pi were transformed to $\log_{10}(Pi + 1)$ values for analysis. A) Early yield (April–May). B) Late yield (June–July). C) Total yield.

the nematicide fosthiazate at 3 kg a.i./ha/year at a current cost of \$552.80. Finally, production costs of 33.6% (Ministry of Agriculture and Forestry, 1999) must be subtracted from the realized gross returns to determine the net profit or loss from the crop after nematode damage.

We can describe the relationship between total yield and Pi as a single damage function (Fig. 3C). However, because there are distinct differences in damage levels and crop values between early- and late-season harvests, we developed a double damage function method, using both early- (Fig. 3A) and late-season (Fig. 3B) models to determine the ET. Using the Seinhorst damage functions (Table 2) as an example:

TABLE 2. Seinhorst damage function analysis on the relationship of relative yield of oriental melon and population densities of *Meloidogyne arenaria* (Pi) in September and January.

Parameters	Preplant sampling date	Seinhorst model[a]			
		T	m	z	R^2
Early yield[b]	September	0	0.50	0.998946	0.22
Early yield	January	0	0.51	0.998105	0.24
Late yield[b]	September	0	0.03	0.997999	0.33
Late yield	January	0	0.30	0.996132	0.25
Total yield	September	0	0.43	0.998476	0.45
Total yield	January	0	0.40	0.996347	0.35

[a] $y = m + (1 - m)z^{(P-T)}$ for $y > T$, $y = 1$ for $P \leq T$; y is the yield expressed as a proportion of expected yield in the absence of nematodes, m (minimum yield) is the yield attained at high nematode population levels, T (tolerance level) is the population level below which there is no reduction in yield, z is a regression coefficient <1.0, and P is the preplant population level (Pi).
[b] Early yield = April to May.
[c] Late yield = June to July.

$$L = V_e(HY_e)(1 - (m_e + (1 - m_e)z_e^{(Pi-Te)})) + V_1(HY_1)(1 - (m_1 + (1 - m_1)z_1^{(Pi-T1)})),$$

which can be expanded to:

$$L = V_e(HY_e)(m_e + (1 - m_e)z_e^0 - m_e - (1 - m_e)z_e^{(Pi-Te)}) + V_1(HY_1)(m_1 + (1 - m_1)z_1^0 - m_1 - (1 - m_1)z_1^{(Pi-T1)}),$$

which is simplified to:

$$L = V_e(HY_e)(1 - m_e)(1 - z_e^{(Pi-Te)}) + V_1(HY_1)(1 - m_1)(1 - z_1^{(Pi-T1)}), \quad (1)$$

where L is the loss due to nematode damage, V_e and V_1 are early- and late-season crop values, Y_e and Y_1 are early- and late-season potential yields, H is the harvest coefficient (80% of potential yield, see above), Pi is the initial population level, and the other coefficients are parameters of the Seinhorst damage function for early- and late-season harvests. When $Pi < T_e$, $z_e^{(Pi-Te)}$ becomes z_e^0 in eqn. 1, then $Pi < T_1$, $z_e^{(Pi-T_1)}$ becomes z_1^0. By our stated definition, the ET is that Pi at which the sum of the economic losses at the early and late harvests

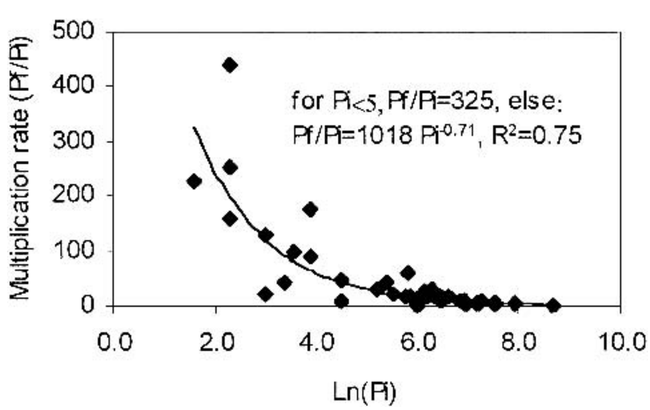

FIG. 4. Relationship between seasonal multiplication rates (Pf/Pi) and preplant population densities (Pi) of *Meloidogyne arenaria* in September.

(eqn. 1) is equal to the proposed management cost. Since an analytical solution of eqn. 1 for ET is complex, we used a spreadsheet to calculate losses for a range of Pi values and selected the ET on the basis of the corresponding array of losses (Fig. 5A). For the current crop values and economics of the oriental melon production system, the double damage function approach allows calculation of the economic threshold at a Pi level of 14 J2/100 cm^3 soil for nematode management by application of fosthiazate.

Interestingly, the ET calculated by the total harvest damage function (Fig. 3C) is quite similar to that based on average crop values (17 J2/100 cm^3 soil). The importance of the double damage function becomes apparent in determining the effect of changes in seasonal crop values on the economics of nematode management and in evaluating strategies to maximize returns. If, for example, average seasonal crop value remains the same but the values of late-season and early-season melons are reversed, the ET is reduced to 11 J2/100 cm^3 soil when calculated from the double damage function (Fig. 5B) but is unchanged based on the total-season model. Further, considerably more of the loss is realized at the late-season harvest. Under current crop values, any production strategy that partitions more of the crop yield into the early harvest will reduce total crop losses and increase the Pi level at which nematicide treatment is justified. Economic threshold values for any management cost with current production economics can be determined from the linear projections of Figure 5A.

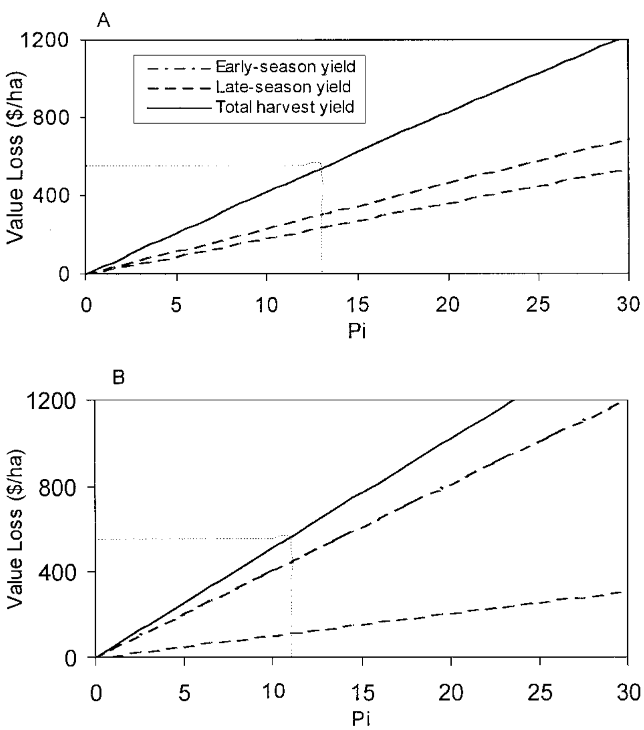

FIG. 5. Relationship of loss in crop value at a range of preplant population densities of *Meloidogyne arenaria* in September to the price of oriental melons early and late in the growing season. A) Early yield price \$2.19/kg, late yield price \$0.98/kg. B) Early yield price \$0.98/kg, late yield price \$2.19/kg. Economic threshold values for any management cost under current production economics can be determined graphically from panel A. The horizontal line represents the cost of a fosthiazate application—currently \$553/ha.

Two further refinements of the ET concept are suggested by our analyses of oriental melon production economics. First, the threshold concept as stated assumes that the nematode population is reduced to zero or at least to the tolerance limit (T) below, which damage is not measurable. However, the efficacy of fosthiazate and other management practices vary significantly (Wong et al., 1970), and a few surviving nematodes may increase sufficiently to cause substantial damage during the late-season harvest. Then, the increase in net returns from the management at the ET level will be less than the cost of the management. Therefore, we amend the definition of the ET to *that Pi at which the difference in crop value with and without management is equal to the cost of the management.* The double damage function in eqn. 1 then becomes:

$$L = V_e(HY_e)(m_e + (1 - m_e)z_e^{(\beta\, Pi - Te)} - m_e - (1 - m_e)z_e^{(Pi - Te)}) + V_1(HY_1)(m_1 + (1 - m_1)z_1^{(\beta\, Pi - T^1)} - m_1 - (1 - m_1)z_1^{(Pi - T^1)}),$$

which simplifies to:

$$L = V_e(HY_e)(1 - m_e)z_e^{(-Te)}(z_e^{(\beta\, Pi)} - z_e^{Pi}) + V_1(HY_1)(1 - m_1)z_1^{(-T^1)}(z_1^{(\beta\, Pi)} - z_1^{Pi}), \quad (2)$$

where β is the proportional residual population after management, i.e., $\beta = 1 - E$ where E is efficacy of the management. When $Pi < T_e$, $z_e^{(\beta\, Pi)}$ and z_e^{Pi} both become z_e^0 in eqn. 2, then $Pi < T_1$, $z_1^{(\beta\, Pi)}$ and z_1^{Pi} both become z_1^0. The ET is the value of Pi in eqn. 2 at which L is equal to the cost of management and varies with management efficacy (Fig. 6).

The second refinement of the ET concept is to introduce a profit limit constraint (N) as *that Pi level at which net returns become zero.* This stems from consider-

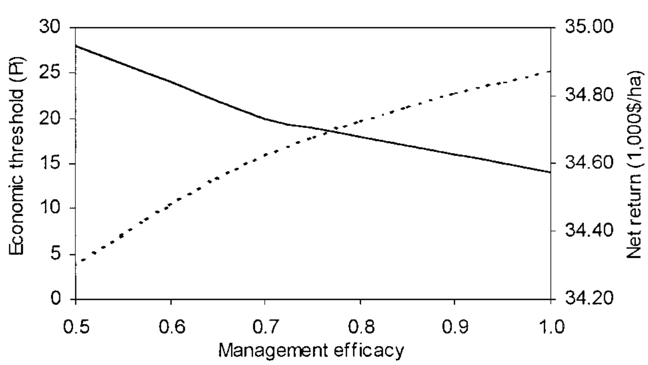

FIG. 6. Effect of efficacy of the management application on the ET as amended herein (solid line, the Pi value at which the returns from management are equal to the management cost) and on net returns under current production economics for oriental melon (dashed line).

ation that the fixed production costs of this and many cropping systems are substantial. In this case, they include costs of bed preparation, mulching, the drip-irrigation system, and plastic cover construction. Since potential net returns (R) are (1 − 0.336) (V_eHY_e + V_lHY_l) for this cropping system (see above), N is determined by spreadsheet solution of eqn. 2 to determine the Pi level at which L = R. Where there is no nematode management, $\beta = 0$ so that eqn. 2 becomes identical to eqn. 1. In the oriental melon production system, without nematode management, the profit limit is not reached because the greatest crop yields are at the early harvest when residual relative minimum yield is 0.5 even at high population levels. Here the resolution provided by the double damage function becomes apparent. Returns from the late-season component of the yield can become negative at moderate Pi in September (PL1 in Fig. 7). Even when the nematicide is applied, returns may become negative at some Pi (PL2 in Fig. 7) if efficacy of the treatment is less than 100%. A strong argument could be made for terminating the crop after the early-season harvest to avoid net losses in the late season when the Pi is high.

Because there are strong linear and Seinhorst relationships between yield of oriental melon and *M. arenaria* J2 counts in both September and January (Figs. 2,3; Tables 1,2), either model or sampling date could be used for yield prediction and advisory purposes. However, in January, when temperatures are below freezing, the soil is covered with mulch, and plastic covers have already been built, it is difficult to apply any nematode control measures. Therefore, we strongly recommend that soil sampling for advisory purposes be performed during the fall when growers still have time to apply the necessary treatments.

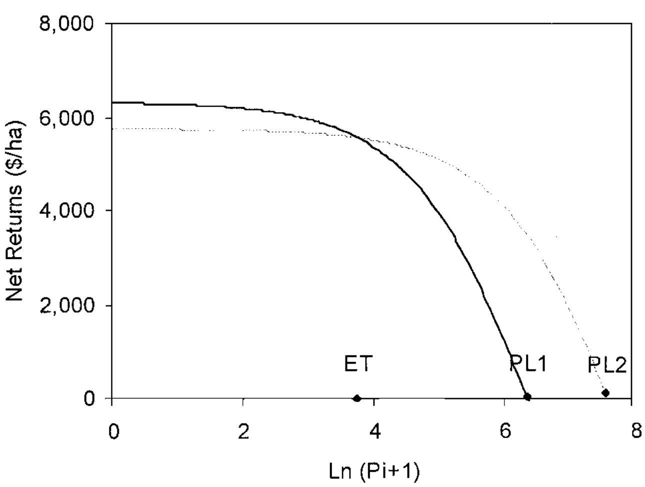

FIG. 7. Net returns ($/ha) from late-season harvest of an oriental melon crop in relation to preplant population densities (Pi) of *Meloidogyne arenaria* in September. The dashed line indicates expected returns from the late harvest after an application of fosthiazate where the efficacy of nematode control was 75%. The Pi at which returns for the management during the late harvest were equal to the cost of management (ET) was 43 J2/100 cm^3 soil. PL1 is the Pi at which net returns for the late harvest become negative without management, and PL2 is the point at which returns become negative with management at 75% efficacy.

Damage functions describing the loss of yield as a function of nematode density can vary with geographic, edaphic, and climatic conditions with cultivars (Cooke and Thomason, 1979; Ferris, 1978; Griffin, 1981; Roberts et al., 1981). Soil temperatures for the crop season influence nematode development and multiplication rates and, consequently, degree of crop damage (Griffin, 1981; Roberts et al., 1981). For example, the tolerance limit of sugarbeets to *Heterodera schachtii* is 430 eggs/100 cm^3 soil when the temperature is 19 °C, but 63 eggs/100 cm^3 soil when the temperature is 23–27 °C (Cooke and Thomason, 1979). In our field plots, the average soil temperature at the 10-cm depth under the plastic film was <10 °C at planting. It increased to 22 °C by the start of the early harvest period in mid April. By the end of the second harvest period in July, the average soil temperature was 29 °C. The warm soil temperatures under plastic film undoubtedly influence the low ET levels of *M. arenaria* on oriental melon.

Although soil moisture is another source of variation (Barker, 1982; Mein et al., 1978), oriental melon usually is grown in drip-irrigated beds mulched with black plastic film (Fig. 1). Consequently, soil moisture in oriental melon greenhouses is relatively constant throughout the growing season. The effects of soil texture and other important edaphic factors (Barker et al., 1985) require further investigation so that the models developed in this study can be made more robust.

The data and concepts provided herein should be useful in nematode assay programs as well as in efforts to determine yield losses to *M. arenaria* in oriental melon production areas. We reiterate that, for practical purposes, assay samples should be taken preferably in September and that soil containing more than 14 juveniles/100 cm^3 should be recommended for nematode treatment at current costs of fosthiazate. The effectiveness of the nematicide treatment, however, has been highly variable (Wong et al., 1970), and development of consistently effective, low-cost control methods is necessary.

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