ECONOMIC THRESHOLDS UNDER UNCERTAINTY WITH APPLICATION TO CORN NEMATODE MANAGEMENT

L. Joe Moffitt, Darwin C. Hall, and Craig D. Osteen

Abstract

An economic threshold of agricultural pest management is derived. Results provide a method for researchers to use in making improved pest control recommendations to farmers without farm level decisionmaking. An empirical illustration for lesion nematode management in irrigated corn is given and directions for further research are indicated.

Key words: economic thresholds, uncertainty, pest management, corn, nematodes.

Two persistent themes in the literature of pest management economics are the presence of uncertainty in pest populations and the use of economic thresholds for managing pests (Carlson, Headley, Feder). This paper integrates these themes by describing an economic threshold management tool under uncertainty. The paper is written from the point of view of applied researchers charged with recommending decision rules to farmers for managing agricultural pests. Accordingly, the objective is not to present complex, optimal decision rules but rather to derive decision rules which are efficient among rules consistent with the existing method of agricultural pest management; i.e., management via a population threshold concept. Although the paper is written from an applied perspective, this does not mean that the analysis is significantly more simple than analyses devoted to optimal pest management strategies. In fact, as will become evident, those to whom this paper should be most valuable—extension personnel and experiment station researchers who develop and recommend pest control methods, government regulators concerned with restrictions on pesticide use, and other pest management economists—must endure some complexity in order to use the method. As it turns out, the complexity borne at this level is necessary in order to provide efficient, simple decision rules for the farm level.

Although discussions of agricultural pest management often bring to mind images of fields teeming with voracious insects, other, less visible, pest problems can also be serious in terms of their effect on crop yields. Pests which reside beneath the surface of the soil have received less attention than other agricultural pests for most crops but are a problem for a number of crops in several regions of the country. In particular, field corn grown throughout the coastal plains of Georgia, Florida, the Carolinas, and other southern states suffer from the presence of the lesion nematode *Pratylenchus* spp., a deleterious parasite of corn root systems. Despite their economic importance as a pest, and with some exceptions (see e.g., Osteen et al., Ferris), nematode management methods based on economic analysis have been largely absent. For purposes of clarity and to avoid unnecessary generality, the threshold concept under uncertainty already alluded to is developed in the context of an empirical model for lesion nematode management in irrigated corn.

CONCEPTUAL FRAMEWORK

The concept of the economic threshold—a pest population level defined to aid pest control decisionmaking—has been developed by both economists and biological scientists. The economic threshold was originally defined by entomologists as *"the population large enough to cause damages valued at the cost of practical control"* (Edwards and Heath). This definition now commonly referred to as the *action threshold,* has been interpreted in empirical studies (see e.g., Gutierrez et al.) as the minimum population level for which it is profitable to apply a pre-specified, fixed amount of pesticide, ordinarily a recommended or label dosage rate. Economists, on the other hand, have typically treated dosage as a continuous decision variable in their models, defining the *economic threshold* as *"the population that produces incremental damage equal to the cost of preventing that damage"* (Headley). In other words, the economic threshold is the pest population level subsequent to application of a computed, profit-maximizing dosage rate.

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This is in contrast to the action threshold which is defined in terms of pest density prior to taking an action. The economic threshold is not in general one population level but rather a variable which depends on many factors including the size of the initial infestation (Hall and Norgaard).

In practice, the economic threshold has offered little advice for farm-level decisionmaking other than the admonition to "maximize profit." The concept has not experienced widespread use in agricultural pest management primarily because it is difficult to use relative to the competing action threshold. It requires, for example, that a model of the pest-crop system and optimization procedures be implemented to compute optimal dosage each time a pest control decision is encountered or else that researchers make computations for various infestation levels, prices, etc. and provide producers with tables showing the dosage that should be applied to maximize profit in each biologic-economic milieu. In contrast, application of the action threshold concept requires only two numbers (population threshold and dosage rate) making it simple to use. An example, from among the many that could be cited, of recommendations based on the action threshold is *"if defoliation exceeds 20 percent, then apply 1 pound of carbaryl"* (Kogan and Luckmann). Derivation and recommendation of decision rules of this type by cooperative extension personnel and experiment station researchers perhaps represent the major impact of integrated pest management research on agriculture.

A serious shortcoming of the action threshold relative to the economic threshold is its efficiency. Since decisionmaking based on the economic threshold is profit maximizing by definition, it is clear that the action threshold and decision rules derived from it, such as the case of the defoliation example above, must fall short of profit maximization. Hence, although decisionmaking based on the action threshold can be valuable (Fohner et al.), there is currently considerable interest among growers, researchers, policymakers, and others in pest management for decision rules which are developed from the standpoint of reality and practicality in application but which also achieve profitability as close as possible to the complex, optimal rules suggested by economic theory (Poston et al.).

In the following, an expression for expected profit as a function of the action threshold under uncertainty is derived. The necessary condition for expected profit maximization in this discrete choice decision framework is combined with the standard optimality condition associated with the continuous choice framework of the economic threshold. The result is a decision rule which farmers can use in exactly the same manner as recommendations derived from the action threshold but which is more profitable. The mixture or M-threshold concept, developed in a later section, is thus a mixture of the optimizations underlying the economic and action thresholds and represents a compromise between efficiency and practicality.

ECONOMIC MODEL AND THRESHOLDS

Lesion nematodes are pests which exist in corn root zones and reduce production by interfering with normal root function. Reduction of nematode populations is possible through soil applications of nematicides. A description of nematode pest management for corn and forms for dosage and kill functions are contained in Osteen et al. An empirical model of similar character to that analysis may be based on the following:

$$(1) \quad \Pi = p_y Y - vP - f$$
$$(2) \quad Y = Y_o - \alpha B$$
$$(3) \quad B = B_o e^{-\beta P}$$

where:

Π = profit (dollars per acre),
p_y = price of corn (dollars per bushel),
Y = yield (bushels per acre),
v = price of nematicide (dollars per lb. of active ingredient (a.i.)),
P = nematicide treatment (lb. a.i. per acre),
f = nematicide application cost (dollars per acre),
B = nematode density (number per 150 cubic centimeters), and
Y_o, α, B_o, β = positive parameters.

Equation (1) expresses profit as a function of dosage and yield. The parameter α in equation (2) is a damage per pest coefficient while equation (3) indicates the relationship between dosage and kill. The analysis that follows does not depend on the particular functional forms chosen in equations (1) through (3).

If the parameters in equations (1) through (3) are known, nematode management may be undertaken according to alternative threshold concepts in a straightforward manner. The economic threshold (Headley) requires that dosage be selected so as to maximize profit. Substituting equations (2) and (3) into equation (1) and recognizing that dosage is restricted to be nonnegative gives the decision problem to be solved:

$$(4) \quad \underset{(P)}{\text{Maximize}}\ \Pi = p_y Y_o - p_y \alpha B_o e^{-\beta P} - vP - f$$

subject to $P \geq 0$.

The necessary condition for an internal solution[1] to equation (4) is:

$$(5)\quad \frac{\partial \Pi}{\partial P} = 0.$$

Simplifying equation (5) permits the optimal dosage to be expressed as a function of the nematode population level:

$$(6)\quad P^h = \frac{\ln(\beta p_y \alpha B_o) - \ln v}{\beta}.$$

The economic threshold is the residual population following treatment with the optimal dosage; viz.,

$$(7)\quad B^h = B_o e^{-\beta P^h} = \frac{v}{\beta p_y \alpha}.$$

Note that the dosage in equation (6) varies continuously with the initial population level and this fact has undoubtedly contributed to the lack of acceptance of the economic threshold as an applied management tool.

The action threshold (Edwards and Heath), denoted B^n, is based on a discrete choice decision problem where the choice set consists of either not treating or applying a fixed (label) dosage, say P^n. The decision problem to be solved is:

$$(8)\quad \underset{(P)}{\text{Maximize}}\ \Pi = p_y Y_o - p_y \alpha B_o e^{-\beta P} - vP - f$$

$$\text{subject to:}\quad P = p^n \text{ or } P = 0.$$

Profit maximization within the constraints imposed by this decision problem involves applying dosage P^n if profit with this dosage exceeds profit with no treatment. From equation (8), profit-maximizing dosage is positive if

$$(9)\quad p_y Y_o - p_y \alpha B_o e^{-\beta P^n} - vP^n - f > p_y Y_o - p_y \alpha B_o$$

and is zero otherwise. Rearranging equation (9) permits optimal dosage to be expressed as a function of the nematode population level as follows:

$$(10)\quad p^a = \begin{cases} p^n \ ; \text{ if } B_o > \dfrac{vP^n + f}{p_y \alpha (1 - e^{-\beta P^n})} \equiv B^n \\ 0 \ ; \text{ otherwise.} \end{cases}$$

Nematode management according to the action threshold is thus, to apply dosage P^n if $B_o > B^n$ and not to treat if $B_o \leq B^n$. Recommendations developed according to equation (10) have become popular in applied pest management due primarily to their simplicity. Again, note that the action threshold requires only that a farmer determine if the population exceeds a specific number and if it does to treat with a specific dosage.

APPLIED NEMATODE MANAGEMENT AND THE MIXTURE THRESHOLD

In practice, nematode management and, in the authors' experience, management of pests on numerous crops as well as livestock, proceed as follows. Armed with a dosage and an action threshold, both of which may have been recommended by cooperative extension personnel or researchers, scouting is undertaken at the farm level to assess whether the population exceeds the action threshold. If it is determined that the population exceeds the threshold, the fixed, contemplated dosage is applied; otherwise, treatment is deferred. The dosage and threshold may, of course, differ with the specific features of the pest problem at different points in time. However, the decision process at the farm level remains essentially the same.

The subsequent analysis subsumes all features common to this decision process, including risk neutral decisionmaking preferences. In the following, an expression for the expected profit which a farmer will receive if pest management is undertaken according to an action threshold concept is derived and this expression is used to derive the threshold which is best in terms of expected profit.

The initial infestation, B_o in the model equations (1) through (3) can assume a different value each time a pest control decision must be made by a farmer. From the point of view of a researcher attempting to recommend an action threshold for farm level use, the initial infestation must be regarded as a random variable. It is assumed that past experience with the pest permits the researcher's uncertainty regarding the size of the infestation to be captured by a probability density function, denoted $g(\bullet)$.

Grower profit, given an action threshold, B^n, and dosage, P^n, can be derived as follows. According to the decision rule associated with the action threshold, dosage P^n is applied if $B_o > B^n$. Profit, given that dosage P^n is applied, is shown on the left side of the inequality in equation (9). Expected profit, given that dosage P^n is applied, is:

$$(11)\quad E[\Pi \mid B_o > B^n] = \int_{-\infty}^{\infty} [p_y Y_o - p_y \alpha B_o e^{-\beta P^n} - vP^n - f] g(B_o \mid B_o > B^n) dB_o$$

where the conditional density, $g(\bullet \mid B_o > B^n)$ is:

$$(12)\quad g(x \mid B_o > B^n) = \frac{g(x)}{\Pr[B_o > B^n]} \ ; \text{ if } x > B^n \quad \text{or } = 0, \quad \text{otherwise.}$$

No treatment is made in this decision framework if $B_o \leq B^n$. Profit, given no treatment, is shown on the right side of the inequality in equation (9). Expected profit, given no treatment, is:

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[1]Internal solutions are assumed to avoid the complications introduced by the positivity constraint and the presence of a positive, fixed application cost. The substance of the subsequent discussion is not altered by this assumption.

(13) $E[\Pi \mid B_o \leq B_n] = \int_{-\infty}^{\infty} [p_y Y_o - p_y \alpha B_o] g(B_o \mid B_o \leq B^n) dB_o$

where the conditional density, $g(\bullet \mid B_o \leq B^n)$, is:

(14) $g(x \mid B_o \leq B^n) = \frac{g(x)}{Pr[B_o \leq B^n]}$; if $x \leq B^n$
or $= 0$, otherwise.

Unconditional expected profit when decisionmaking is based on the action threshold can be written using standard probability formulas (Mood et al.). The expression for expected profit is:

(15) $E[\Pi] = E[\Pi \mid B_o > B^n] \bullet Pr[B_o > B^n] + E[\Pi \mid B_o \leq B^n] \bullet Pr[B_o \leq B^n]$.

Substituting(12) into (11), (14) into (13), and the resulting expressions into (15) gives:

(16) $E[\Pi] = \int_{B^n}^{\infty} [p_y Y_o - p_y \alpha B_o e^{-\beta P^n} - vP^n - f] g(B_o) dB_o + \int_{-\infty}^{B^n} [p_y Y_o - P_y \alpha B_o] g(B_o) dB_o$.

Equation (16) gives expected profit as a function of the action threshold, B^n, and the positive dosage, P^n. However, before deriving the mixture threshold from equation (16), first, consider P^n as given. In this case, maximizing expected profit as a function of B^n only, solves:

(17) $\underset{(B^n)}{\text{Maximize}}\ E[\Pi]$, where $E[\Pi]$ is shown in equation (16). Solving the necessary condition,

(18) $\frac{\partial E[\Pi]}{\partial B^n} = 0$,

for B^n gives the same expression as was obtained earlier for the action threshold in equation (10). This result is not surprising since the action threshold in equation (10) was selected to maximize expected profit subject to a constrained dosage level. Thus, equation (16) merely provides an explicit expression for expected profit when a population threshold is used to make a discrete choice about dosage. Equation (16) can be used to derive both an optimal threshold and dosage as is seen in the following.

If the decisionmaking process at the farm-level is maintained intact, improved pest management with existing technology is possible only through changes in the fixed dosage and/or the action threshold. The mixture, or M-threshold, maximizes expected profit while regarding the current pest control decision framework as fixed. To clarify further the objective and output from computation of the M-threshold, consider the soybean defoliation example described earlier. In this case, the recommendation was "if defoliation exceeds 20 percent, then apply 1 pound of carbaryl." Use of this recommendation, in the manner already described, leads to expected profit given by an expression in the form of equation (16) with $B^n = 20$ and $P^n = 1$. However, there appears to be no guarantee, from the manner in which recommendations based on the action threshold are developed, that an alternative recommendation such as "if defoliation exceeds 25 percent, apply .75 pounds of carbaryl" ($B^n = 25$, $P^n = .75$) might not lead to a larger value of equation (16). The M-threshold concept is the decision rule of this type which maximizes equation (16). Thus, it leads to recommendations of identical character to those recommendations currently being offered by the research community for farm level use. Farmers can use these recommendations in exactly the same manner as recommendations based on the action threshold. Moreover, recommendations based on the M-threshold are guaranteed to be at least as profitable as current recommendations.[2]

The M-threshold may be evaluated as follows. First, the decisionmaking process associated with the action threshold is adopted. Expected profit in this context is given by equation (16). Second, the necessary condition for optimal dosage, equation (5), underlying the economic threshold is combined with the necessary condition for optimal population level, equation (18), underlying the action threshold. Solution of the necessary conditions gives the M-threshold and its associated dosage. The M-threshold is thus the solution to:

(19) $\underset{(P^n, B^n)}{\text{Maximize}}\ E[\Pi]$, where $E[\Pi]$ is shown in equation (16). The necessary conditions for a solution of equation (19) are:

(20) $\frac{\partial E[\Pi]}{\partial P^n} = \int_{B^n}^{\infty} [\beta p_y \alpha B_o e^{-\beta P^n} - v] g(B_o) dB_o = 0$

and by Leibniz's rule:

[2]The fact that it is appropriate to consider dosages of a pesticide other than the label rate in application is supported by several factors. First, the label rate for a pesticide often is not a single number but rather a range of values which sometimes permits considerable flexibility in selection of dosage. Second, use of a pesticide at any dosage below the label rate or range is permissable under federal law and the laws of many states. Finally, researchers should not regard even a specific label rate as an unalterable parameter. The fact that energy researchers did not regard the 65 mph national speed limit as unalterable during the 1970's is ample evidence that legal parameters can change when scientific research demonstrates that more efficient alternatives are available (Jondrow et al.).

$$(21)\quad \frac{\partial E[\Pi]}{\partial B^n} = [p_y Y_o - p_y \alpha B^n] g(B_o) - [p_y Y_o - p_y \alpha B^n e^{-\beta P^n} - vP^n - f] g(\beta_o) = 0.$$

Equation (20) requires that the fixed, contemplated dosage associated with the M-threshold equate the expected value of marginal product *when a treatment is made* with the price of nematicide. Note that this dosage will differ from that associated with simply substituting average population into the expression for optimal dosage under the economic threshold (equation (6)). Equation (21) indicates that the M-threshold functions exactly as an action threshold given expected profit-maximizing dosage.[3] Simultaneous solution of equations (20) and (21) gives the M-threshold, B^*, and its associated dosage, P^*. Recommendation of (B^*, P^*) for farm level use should lead to the largest average profit possible within the confines of present agricultural pest control decisionmaking.

To investigate the evaluation of the M-threshold in an empirical setting, experimental data on lesion nematode control in irrigated corn were used from multi-plot testing undertaken during 1977 at the Coastal Plain Experiment Station in Tifton, Georgia. A sample of eight observations on yield, nematode population, and nematicide treatment were used to estimate equations (2) and (3) by the method of maximum likelihood. Coefficient estimates are shown in Table 1. The nematicide tested was aldicarb (Temik®), presently being considered for registration for use on corn although as yet unregistered for this use in any state. Prices in equation (1) were estimated as follows: $Py = \$3.41$ (USDA) and $v = \$14.40$ (Agsystems Research). Because nematicide treatment can be made during the course of other production procedures, application cost was regarded as negligible ($f = 0$). Finally, data on the uncontrolled nematode population for a 2-year period were used to estimate the density function, $g(\bullet)$, which was assumed to be normal with mean $= \mu = 46.25$ and standard deviation $= \sigma = 41.7$.

In the case of the normal density for $g(\bullet)$, equations (20) and (21) become:

$$(22)\quad \sigma\beta p_y \alpha \frac{1}{\sqrt{2\pi}} e^{\left[-\frac{1}{2\sigma^2}\left(\frac{vP^* + f - \mu p_y \alpha(1 - e^{-\beta P^*})}{p_y \alpha (1 - e^{-\beta P^*})}\right)^2 - \beta P^*\right]} + (\mu\beta p_y \alpha e^{-\beta P^*} - v)\left[1 - \Phi\left(\frac{vP^* + f - \mu p_y \alpha(1 - e^{-\beta P^*})}{\sigma p_y \alpha(1 - e^{-\beta P^*})}\right)\right] = 0$$

and

TABLE 1. ESTIMATED COEFFICIENTS FOR CORN NEMATODE DAMAGE AND NEMATODE DOSAGE-KILL FUNTIONS, TIFTON, GEORGIA, 1977

Coefficient[a]	Estimated value	t-Statistic
Y_o	107.41	7.64
	(14.06)[b]	
α	.4633	.63
	(.7355)	
B_o	25.00	4.28
	(5.84)	
β	1.222	1.46
	(.837)	

[a]Coefficients correspond to equations (2) and (3).
[b]Numbers in parentheses are estimated asymptotic standard errors.

$$(23)\quad B^* = \frac{vP^* + f}{p_y \alpha (1 - e^{-\beta P^*})},$$

respectively, where Φ denotes the standard normal distribution function and (P^*, B^*) denote the optimal values of P^n and B^n. Solution of equations (22) and (23) with the parameter values shown earlier gives $P^* = 1.76$ and $B^* = 18$. The M-threshold nematode management strategy is as follows: If nematode density exceeds 18 per 150 cc of soil, apply 1.76 pounds a.i. of aldicarb per acre; otherwise do not treat with aldicarb. Recommendation to and implementation of this strategy at the farm level will lead to larger expected profit equation (16) than any comparably simple nematode management decision rule.

As mentioned earlier, there is considerable interest in developing pest management decision rules for farmers which are practical and which come close to being as efficient as complex, optimal rules. The extent to which profit under the M-threshold approaches the optimal profit achieved by the economic threshold is an empirical question with the answer depending on the application under consideration. A comparison of expected profit and expected nematicide use sheds some light on the relationship between these alternative management strategies in the present case. Expected profit corresponding to the economic threshold strategy equations (6) and (7) may be evaluated according to:

$$(24)\quad E[\Pi \mid \text{Economic Threshold}] = p_y Y_o \bullet \Phi\left(\frac{B^h - \mu}{\sigma}\right) + p_y \alpha \left[\frac{\sigma}{\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(B^h - \mu)^2} - \mu \Phi\left(\frac{B^h - \mu}{\sigma}\right)\right] + \left\{ p_y Y_o - \frac{v}{\beta} - f - \frac{v}{\beta}[\ln(p_y \alpha \beta) - \ln v] \right\}\left[1 - \Phi\left(\frac{B^h - \mu}{\sigma}\right)\right] -$$

[3]Second-order conditions and their interpretation are available from the authors.

$$\frac{v}{\beta}\int_{B^h}^{\infty} \ln x \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2\sigma^2}(x-\mu)^2} dx ,$$

while expected nematicide use is given by:

$$(25)\quad E[P \mid \text{Economic Threshold}] = \frac{1}{\beta}[\ln (p_y\alpha\beta) - \ln v]\left[1 - \Phi\left(\frac{B^h-\mu}{\sigma}\right)\right] + \frac{1}{\beta}\int_{B^h}^{\infty} \ln x \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2\sigma^2}(x-\mu)^2} dx.$$

Expected profit achieved by nematode management according to the M-threshold equations (22) and (23) is given by:

$$(26)\quad E[\pi \mid \text{M-Threshold}] = p_yY_o\Phi\left(\frac{B^*-\mu}{\sigma}\right) + p_y\alpha\left[\frac{\sigma}{\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(B^*-\mu)^2} - \mu\Phi\left(\frac{B^*-\mu}{\sigma}\right)\right] + (p_yY_o - f - vP^*)\left[1-\Phi\left(\frac{B^*-\mu}{\sigma}\right)\right] - p_y\alpha e^{-\beta P^*} \cdot \left\{\frac{\sigma}{\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(B^*-\mu)^2} + \mu\left[1-\Phi\left(\frac{B^*-\mu}{\sigma}\right)\right]\right\}$$

Expected nematicide treatment under the M-threshold is:

$$(27)\quad E[P \mid \text{M-Threshold}] = P^*\left[1-\Phi\left(\frac{B^*-\mu}{\sigma}\right)\right]$$

Expected profit and nematicide treatment corresponding to application of the economic threshold and the M-threshold alternatives, equations (24) and (27), are shown in Table 2. In the present example, as is evident from Table 2 figures, the M-threshold comes very close to achieving the optimal associated with the economic threshold. Moreover, expected nematicide use is increased by only a small amount when the M-threshold is used rather than the economic threshold. While additional empirical studies are needed to investigate the generality of these empirical results, the present case suggests that the efficiency loss from using the M-threshold rather than the economic threshold alternative is a small price to pay for the practicality associated with the M-threshold concept.

CONCLUDING REMARKS

This paper has described a practical decision rule for managing agricultural pests under uncertainty. The M-threshold concept was developed to maximize expected profit given that the nature of decisionmaking is constrained to current practice. Computation of the M-threshold was demonstrated for the nematicide aldicarb for use in controlling nematodes in corn. Results show the feasibility of the M-threshold in an empirical setting. An empirical comparison of expected profits and expected nematicide use achieved under the economic threshold and the M-threshold alternatives revealed only small differences. However, a number of empirical studies is required to shed light on the generality of this result. Incorporation of risk preferences and identification of the role of the M-threshold and associated dosage in altering profit variability also remain to be investigated.

The M-threshold is derived by solving a marginal decision problem at the research level while recognizing that a discrete choice treatment decision will be made from the point of view of total profit at the farm level. Although the M-threshold was designed for use by researchers in developing pest control recommendations for farmers, there does not appear to be any reason to restrict application of this methodology to pest management. Many production decisions are characterized by rules-of-thumb applied in choosing between a finite number of alternatives. The M-threshold method should be useful in finding the efficient rule-of-thumb in such cases.

TABLE 2 EXPECTED PROFIT AND EXPECTED NEMATICIDE USE UNDER THE ECONOMIC AND MIXTURE THRESHOLDS FOR CORN NEMATODE MANAGEMENT, TIFTON, GEORGIA, 1977

Management strategy	Expected profit[a]	Expected nematicide use
	(dollars/acre)	(lb. a.i./acre)
Economic threshold	342.35	1.28
Mixture threshold	341.11	1.32

[a]Expected profit reported is for comparison of nematode management strategies only. Other production costs common to both management strategies have not been deducted from these profit figures.

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