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ECONOMICS AND MARKETING

Plant-Based Economic Injury Level for Assessing Economic Thresholds in Early-Season Cotton

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INTERPRETIVE SUMMARY

Two basic components of decision making in pest management are the *economic injury level* and *economic threshold*. The economic injury level has been defined as the lowest pest population density that will cause economic damage. The economic injury level is a theoretical value that, upon attainment by a pest population, can cause the amount of injury which will justify the cost of treatment (i.e. economic damage). The economic threshold is defined as the pest population density at which control should be initiated to prevent an increasing pest population from exceeding the economic injury level.

Decision-makers choose an economic threshold, that is they make a decision to take control action, based on any of several factors, including insect populations, farmer and applicator schedules, weather, equipment, farm size, intuition, and others. While theoretically there are economic injury level values for decision-makers to consider in evaluating an economic threshold, they are largely, if not completely, ignored. That is partly due to the fact that most economic injury levels are insect-specific and are not practical when one must consider the multi-pest, multi-stress, dynamically-changing conditions that are present in cotton production.

In this paper, we have proposed and developed a plant-based economic injury level for decision-makers to verify the effectiveness of economic thresholds in pest control decisions in early-season cotton production. In the period between first square and first flower, square sheds are evidence of injury to the cotton plant from any variety of insects. It has long been observed that the cotton plant has the potential for tolerance and/or compensation for early fruit insect damage without affecting yield. We have included the compensation capacity of the plant in our economic injury level model. We also use plant-monitoring data on square sheds and nodal development in the model to capture some of the dynamics of changing square shed rates and project near-future injury potential. In addition to the above components, the economic injury level model evaluates the value of production potential and costs associated with treatment and no treatment. Included in costs are the cost associated with maturity delay due to square sheds and cost of yield loss. A break-even shed rate at first flower is calculated to serve as an economic injury level that is an estimate of the point when plant injury becomes economic damage. The break-even shed rate is then transformed into a shed rate limit for the number of squaring nodes in the field on the latest plant monitoring date to allow comparison with the actual shed percentage.

Numerous options for insect control will be available to cotton producers in the near future, as demonstrated by the activity of transgenic and novel foliar control strategies. As a result, we anticipate better control, but an increased need for constant reassurance that some unexpected pest is not causing damage that may be difficult to detect. The egg counts that are often used to anticipate threatened damage from Heliothine pests clearly are not useful in the transgenic cotton that is expected to kill the newly hatched larvae. In transgenic

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Abbreviations: BOLLMAN, boll management portion of COTMAN computer software; COTMAN, cotton management computer software; SQUAREMAN: square management portion of COTMAN computer software; SquareMap: COTMAN plant monitoring data collected during squaring period.

cotton the decision-maker needs plant data to confirm that no damage is occurring. Even more potentially stressing for the decision-maker are the novel chemicals that kill well, but slowly. The mere presence of live pests in a field that has been treated, even when the insects are sick and non-feeding, is enough to require some kind of reassurance that no damage is being done. In these situations a plant-based economic injury level is clearly needed.

By comparing the observed square shed percentage with the shed limit derived from the break-even shed rate (the plant-based economic injury level), one can assess the effectiveness of a previous economic threshold. When the economic threshold triggered action that failed to prevent injury from exceeding the break-even, that is, the observed square shed percentage is above the shed limit, the crop is on a course that may lead to damage if an adjustment in the economic threshold for a given tactic(s) is not or has not been corrected. When the economic threshold does not trigger action, the grower can be reassured, and the economic threshold decision can be confirmed by showing that plant injury remains below the economic injury level.

To effectively utilize the plant-based economic injury level, it is necessary to collect timely field monitoring data during the squaring period and to be able to quickly use that data to calculate the economic injury level. The economic injury level calculations have been incorporated into the COTMAN computer program to provide that functionality.

ABSTRACT

The conventional *economic injury level* is defined as the lowest insect population density that will cause economic damage, while the *economic threshold* is the population level where insect control should be initiated to avoid exceeding the economic injury level. Cotton (*Gossypium hirsutum* L.) production faces multiple insect pests, multiple stresses and new developments such as transgenic cotton that make an economic injury level based on insect populations less practical. The application of an economic threshold in cotton pest control decisions suffers from the lack of an economic injury level to confirm those decisions. This paper proposes an economic injury level model based on plant injury (square shed frequency). The model uses control costs, crop value, dynamic plant-monitoring results and cotton's compensation capacity for early-season loss to calculate a break-even injury level for first flower. The break-even level is transformed into a shed rate limit for stage of plant development, against which producers can compare the actual shed rate at any time prior to first flower. A shed rate below the limit indicates that initiated control prevented pests from causing economic injury while a shed rate above the limit indicates that the economic threshold was inadequate to prevent an increasing infestation from causing economic damage. The plant-based economic injury level is intended to not only verify insect management decisions but also help recognize more efficient and comprehensive economic thresholds. The economic injury level model has been incorporated into the COTMAN computer program to facilitate implementation by producers.

Two basic components of decision making in pest management are the *economic injury level* and *economic threshold*. The economic injury level was defined by Stern et al. (1959) as the lowest population density that will cause economic damage. The economic injury level is a theoretical value that, upon attainment by a pest population, can cause the amount of injury which will justify the cost of treatment, i.e. economic damage. The economic threshold is defined as the pest population density at which control should be initiated to prevent an increasing pest population from exceeding the economic injury level (Stern et al., 1959; Pedigo et al., 1986). The basic philosophy of economic threshold is to permit sufficient time for the initiation of control measures and for these measures to take effect before the population exceeds the economic injury level. Although the two components are to reflect different infestation levels with different emphases, a close relationship between the economic threshold and the economic injury level is expected. The economic injury level defines an upper bound on break-even conditions and the economic threshold includes a margin to insure that the economic injury level is not exceeded.

In reality, most decision-makers either set up the economic threshold arbitrarily without considering the economic injury level, or make no distinction between the economic injury level and the economic threshold. In the former case, the arbitrary economic threshold usually reflects schedules of the farmer and applicator, weather, equipment, farm size, the farmer's intuition and any number of such factors that are difficult to model. In the latter case, the assumption of near instantaneous control becomes necessary to superimpose the two population levels, which, in cotton production, is an increasingly risky assumption because of insecticide resistance, slow-acting control tactics, and the brief life stages wherein insects are susceptible to control. Pedigo et al. (1986) suggest that the best method for developing comprehensive economic thresholds through an economic injury level is by examining the host physiology and physiological response to injury. They conclude that without such adjustments, the economic injury level concept is "conceptually fatigued." The challenge is to incorporate more host and pest dynamics into the economic injury level, which can help to verify pest management decisions and to recognize more efficient economic thresholds. In this paper, we propose a dynamic plant-based economic injury level using early-season plant injury as measured by square sheds.

The development of a dynamic plant-based economic injury level facilitates the use of an economic injury level to judge the success of an economic threshold. For example, occasionally one finds a decision-maker in cotton production who is willing to withhold an application of insecticide because beneficial insects can be seen in the field. Such creative thresholds are consistent with the best integrated pest management precepts, but current economic injury level rules fail to provide that decision-maker with validation of the decision, i.e., that the delay in use of insecticide did not cause damage. This is because most pest-based economic injury levels can only be utilized in a single-pest situation and do not reflect dynamics in pest population. The perennial growth habit and indeterminate nature of the cotton crop also complicate the decision-making process. It has long been observed that the cotton plant has the potential for tolerance and/or compensation for early fruit insect damage (Eaton, 1931; Hamner, 1941; Dunman et al., 1943; Mistric and Covington, 1968; Kincade et al., 1970; Gutierrez et al., 1981; Kennedy et al., 1986; Brook et al., 1992a,b; Sadras, 1994). However, most cotton growers seem to recognize compensation only as a bailout solution after plant injury inadvertently occurs. Few seem willing to sit patiently by, watch plant injury increase, and deliberately integrate plant compensation into the management scheme. Although potential economic benefits exist, such tactics will likely not be integrated without validation. Perhaps decision-makers would be willing to consider natural enemies and to use plant compensation as part of their management tactics if plant-based rules could convey continuous assurances that crop injury remains within acceptable bounds.

The economic injury level model proposed in this paper uses real-time plant monitoring data on nodal development and plant injury. The model includes defined responses of cotton to pest injury, current price, control costs, costs associated with yield loss and crop delays resulting from early-season pest injury, and other components that are used to estimate the point when plant injury becomes economic damage.

Producers can utilize the new plant-based economic injury level only if data collection and the economic injury level calculations can quickly and easily be incorporated into the production system. To facilitate utilization by producers, the economic injury level calculations have been included in the COTMAN computer program (Bourland et al., 1994; Zhang et al., 1994) which will be widely available in 1998. An overview of the implementation of the economic injury level model in COTMAN is presented later in this paper.

The Conventional Economic Injury Level Model

Formal models utilizing the economic injury level concept in a mathematical framework were developed to address the economic aspects of decision-making in pest management. One commonly cited model was presented by Norton (1976). The model was developed to solve the decision problem concerning the control of potato cyst eelworm (*Globodera* spp.) by a nematicide and was expressed as the following:

$$\underset{\text{(benefit of control)}}{PDK\theta} = \underset{\text{(cost of control)}}{C} \qquad [1]$$

Where: P is price of potatoes (*Solanum tuberosum* L.) per tonne; D is loss in potato yield (t/ha) associated with one egg per gram of soil; K is reduction in pest attack achieved by the nematicide; θ is level of pest attack (eggs per gram of soil); and C is cost of applying nematicide per hectare.

The economic injury level (θ*), which is also the break-even pest density, is then calculated as:

$$\theta^{*} = \frac{C}{PDK} \qquad [2]$$

Mumford and Norton (1984) further explained the basic economics of this model graphically (see Figure 1). In this graph, the economic injury level, represented by pest attack or pest density, is located at the break-even point where net revenues under the two alternative courses of action, treatment and no treatment, are equivalent. Pest population densities lower than this point lead to the economic decision of no treatment as higher net revenues are realized than with treatment. Conversely, it will be economical to treat at pest densities greater than the economic injury level level.

The mathematics involved in the model illustrate the break-even concept of the economic injury level. The following equations are two net revenue functions that calculate net revenues under conditions of treatment and no treatment, respectively:

$$\textit{Net revenue(treatment)} = \textit{Gross revenue - C - PD}\theta\textit{(1-K)} \qquad [3]$$

and

$$\textit{Net revenue(no treatment)} = \textit{Gross revenue - PD}\theta \qquad [4]$$

Equation (3) shows that the decision of treatment will incur the cost of insecticide C. As treatment can only reduce pest density θ by K percent, at the end of the season there will be a pest density of θ *(1-K)* surviving in the fields which will then result in $D\theta$ *(1-K)* as the yield loss. Net revenue in this case is equal to gross revenue minus costs associated with the control treatment and yield loss. The net revenue function under the decision to treat is represented by the dashed line in Figure 1. In equation (4) the decision of no treatment will result in all pests surviving and causing $D\theta$ as the yield loss. The net revenue function under the decision of no treatment is represented by the solid line in Figure 1. Since at θ* (the break-even pest density), the two net revenue functions cross each other, by equating (3) and (4), we have:

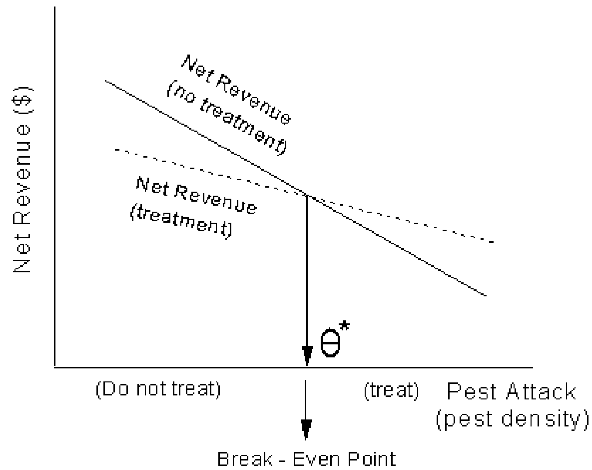

Fig. 1. Basic economics of The Economic Injury Level Model

$$\textit{Gross revenue - C - PD}\theta\textit{(1-K)} = \textit{Gross revenue - PD}\theta \qquad [5]$$

Independent of the insect control decisions, gross revenue always refers to the same value of potential yield, where no production costs or value of yield loss are subtracted. Therefore, equations (3) and (4) have identical gross revenues. It is only the costs (control costs plus value of yield loss) that cause the two net revenues to differ. We follow the same logic in presentation of the plant-based economic injury level. Equation (5) can be transformed to equation (1) and the break-even pest density θ* can be calculated.

Optimization models have been developed by others for specific reasons: multiple-species infestations (Hutchins et al., 1988), environmental costs (Higley and Wintersteen, 1992; Pedigo and Higley, 1992), and natural enemies (Brown, 1997). Each of these models emphasizes different aspects of the topic, but the economics of the Norton (1976) model remain the basis for most of the economic injury level models (Pedigo et al., 1986). The difficulty in predicting dynamics of the change in the pest population density and realizing instantaneous control complicates the use of these models as operational tools. The insect-based economic injury level also becomes conceptually cumbersome when utilized in multiple-species and multiple-stress situations (Pedigo et al., 1986).

As one of the most complicated crops in the world, cotton requires systematic management where the timing of input applications such as insecticides is critical. In the following sections, we propose a new economic injury level model which incorporates more dynamics and serves as a validation tool for the pest population-based economic threshold in early-season cotton pest management.

MATERIALS AND METHODS

The Plant-Based Economic Injury Level

The plant-based economic injury level model we propose utilizes the same economic principles as the Norton (1976) model, but incorporates new variables. Net revenues under options of insect control and no control are calculated. A break-even plant injury level is then calculated where the two net revenues are equal.

Plant-based rules up to first flower emphasize the importance of early-season square sheds. Studies have shown that square abscission between first square and first flower can be attributed largely to insect damage rather than physiological causes (Guinn, 1982; Mauney and Henneberry, 1978). The cause of square shedding can be verified by inspecting squares in the process of abscission (Williams et al., 1987), but we assume that most early-season square loss is due to damage caused by one or more insect pest species that feed on developing squares. The model considers the cotton plant's ability to compensate for early season square loss. In addition to the observed shed rate, we use recent changes in square shed to anticipate future losses in order to capture the insect dynamics. The economic value of potential production, as well as the costs for insect control, are considered in calculating the plant-based economic injury level.

Variables in the Plant-Based Economic Injury Level Model

Variables in the model include cost of control, costs associated with plant injury and maturity delay, value of potential production, plant compensation capacity and plant monitoring information on square sheds and nodal development. Many of the variables have a research base that assists in assigning reasonable values. Following is a list of definitions for the variables in the model, along with a discussion of applicable research.

***C* Represents Cost of Control**. The cost of control is provided by the producer ($/ha)*0.405 (i.e. $/acre). Normally this includes cost of the insecticide plus application, although others could be added, such as environmental cost (Higley and Wintersteen, 1992; Pedigo and Higley, 1992).

***Y* Represents Yield**. The producer provides the yield potential of the field (kg of lint/ha)*1.12 (i.e. lb of lint/acre). The field production history as well as current observations are invaluable in setting this value.

***V* Represents Value**. The producer provides the price expected to be received for cotton ($/kg of lint)*0.454 (i.e. $/lb of lint).

***T* Represents Total Sympodia**. The producer projects the total number of sympodia (plant structures) expected at first flower in each field. If the field is producing vigorous vegetative growth, as defined by the COTMAN Target Development Curve (Bourland et al., 1992; Bourland et al., 1997), *T* would be equal to 10.25. The field production history as well as current observations should be used to provide a realistic value.

***R* Represents Recovery**. Compensation or recovery capacity is expressed as the percentage of first-position square shed at first flower above which yield is reduced. Holman (1996) conducted a field study in 1992 and 1994 in Arkansas, investigating the effect of early-season cotton floral bud (square) loss due to insect damage on yield and maturity delay. His results indicated that up to 19% first-position square shed at first flower did not result in yield loss. However, above 19%, square loss resulted in significant yield decrease. Other information is also available in defining *R*. Sadras (1994) used data from Brook et al. (1992b) to show that the yield level may influence compensation, with the compensatory capacity declining at high yield levels. Yield of Holman's control plots was 1233 kg/ha (1100 lb/acre), which is good but not within the high range where compensation estimates would be suspect. Of course, the length of growing season, and the frequency and severity of late-season problems also may influence one's choice of *R*. Gutierrez et al. (1981) in working with bollworm (*Helicoverpa zea* Boddie) and boll weevil (*Anthonomus grandis* Boheman) in Nicaragua found losses accrued only if more than 30% of squares and fruits were attacked. In Arkansas, a generalized recommendation for plant bugs in cotton by Johnson and Jones (1996) indicates an economic threshold of 25% square shed. This reflects a long held consensus among entomologists in the region. We conclude that plant compensation for 19 to 30% square loss seems realistic.

***D* Represents Yield Loss Damage**. Shed rate above *R*, the crop compensation capacity, can result in yield loss, while we assume that a shed rate below *R* results in no yield loss. Here damage is defined as the percent yield loss caused by a unit increase in shed rate above *R*. Holman (1996) found that for each 1% shed rate above 19% there was a yield decrease of 7.56 kg/ha. Recognizing that absolute amount of yield loss is related to the total yield potential, we converted Holman's yield loss estimate to a percentage loss, i.e. percent of the lint yield potential, *Y*. The percentage was estimated by using Holman's data from plots with greater than 19% shed to solve a nonlinear regression equation. The estimated coefficient from the regression indicates that a one unit increase in the shed rate above 19% will cause the yield potential, *Y*, to decrease by 0.97%. This percent decrease is used instead of the 7.56 kg/ha for calculation of the lint yield loss when the shed rate exceeds the crop compensation capacity.

***M* Represents Maturity Delay**. Maturity delay is measured in days of crop delay caused by 1% first-position square shed measured at first flower. Holman (1996) calculated maturity delay associated with 1% square loss as 0.1818 days. The delay in maturity was measured by collecting nodes above white flower data and calculating days from planting to physiological cutout (Oosterhuis et al., 1997).

***P* Represents Protection Cost**. Cost of an extended period of crop protection associated with crop delay is expressed in dollars per hectare per day. The price one pays for protecting a late crop depends upon the infestation level, stage of crop susceptibility and control costs. King et al. (1996) conducted a study in Arkansas, which has a history of strong late-season infestations, to determine costs associated with late-season insect control. Actual crop and cost data were collected from 267 individual fields in three geographic regions, the Northeast, the Eastern/Central, and the Southeast regions of Arkansas. Results indicate that the average daily insecticide costs were $1.56/(ha/d) [$0.63/(acre/d)] in the Northeast region, $2.84/(ha/d) [$1.15/(acre/d)] in the East/Central region, and $4.94/(ha/d) [$2.00/(acre/d)] in the Southeast region of Arkansas. South Arkansas typically has higher late-season infestations of bollworms, tobacco budworms [*Heliothis virescens* (F.)], and boll weevil than other regions of the state that makes protection more costly. The value of $4.94/(ha/d) [$2.00/(acre/d)] is a reasonable estimate when high infestations are expected. However, producers may substitute other values that are appropriate for their specific situations.

***X1* and *X2* Represent Number of Squaring Nodes at Time One and Time Two**. Actual number of first position squaring nodes are collected at two consecutive time points from individual fields. The SquareMap procedure that is part of the COTMAN program (Bourland et al., 1994) or other plant monitoring methods can be used to obtain the data. Typically data are collected once or twice a week from 40 plants in 16-20 ha (40-50 acre) fields.

***Y1* and *Y2* Represent Square Shed Rate at Time One and Time Two**. At the same time that information is obtained for *X1* and *X2*, the number of first position square sheds is recorded for the same plants. The number of sheds at each time is then divided by the number of squaring nodes at that time and multiplied by 100 to obtain the square shed rate.

***A* Represents Activity**. The aggregate feeding activity, by all square-feeding insects present, is a measure of the increase in the number of square sheds per new node added since the previous sampling date. It is calculated using information for *X1*, *X2*, *Y1*, and *Y2*. The variable *A* is used to apply a numerical expression to what Stern et al. (1959) referred to as "an increasing pest population," when one or more insect populations are causing square injury. The calculation of A will be discussed in a later section.

The Plant-Based Economic Injury Level Model Formulation

The new plant-based economic injury level model is composed of two major formulas. The first formula calculates the break-even shed rate at first flower, and the second formula converts the break-even shed rate at first flower to a shed rate limit for the current number of squaring nodes. The second formula allows use of the model results at decision points before first flower. The actual shed rate in the field can be compared to the shed rate limit to validate pest management decisions.

Formula for the Break-Even Shed Rate at First Flower. The break-even shed rate at first flower is calculated by the following formula:

$$\theta^{*} = \frac{C}{V * Y * D} + R - \frac{100 * A * (T - X2) * M * P}{T * V * Y * D} - \frac{100 * A * (T - X2)}{T} \quad [6]$$

where: θ^{*} is the break-even shed rate at first flower; C is cost of insect control (\$/ha)*0.405, that is \$/acre; V is price of cotton (\$/kg of lint)*0.454, that is \$/lb of lint; Y is expected yield (kg of lint/ha)*1.12, that is lb of lint/acre; D is percent yield loss caused by 1% increase in shed rate above R; R is recovery or compensation capacity, the percent first-position square shed at first flower above which yield is reduced; A is square shed change per new squaring node growth since last sampling date; T is expected number of squaring nodes at first flower; $X2$ is the current number of squaring nodes; M is maturity delay in days caused by 1% square shed at first flower; and P is average delay cost per day (\$/ha)*0.405/d, that is \$/(acre/d).

Formula for the Shed Rate Limit at Current Squaring Node Number. Once the break-even shed rate at first flower is found, the shed rate limit is derived for the currently observed number of squaring nodes, $X2$, as the following:

$$\theta_{X2} = \frac{\theta^{*} * T}{X2} \quad [7]$$

By comparing $Y2$, the currently observed shed rate, with the shed rate limit, θ_{X2}, decisions on insect control can be validated. If $Y2$ is lower than θ_{X2}, it indicates that the actual shed rate is under the shed rate limit. This implies that the damage level will be lower than the economic injury level at first flower with no control as the result of the effectiveness of the previous economic threshold and/or the previous insect management tactics. However, if $Y2$ is higher than θ_{X2}, the actual shed rate is above the shed rate limit. This implies that the previous economic threshold or tactics have failed to prevent an increasing insect infestation from causing economic damage, and adjustments in the economic threshold or tactics may be warranted. Hence, the plant-based economic injury level can validate the pest population-based economic threshold.

Introduction of A, the Per Node Shed Change Variable. One variable worth extra attention in the model is the variable A, which represents the aggregate feeding activity. This is a measure of the change in square shed number per every new square added since the previous sampling date. A reflects numerically the dynamics of one or several dynamic pest populations that cause square injury. It is used to project the trend of pest activity and future crop injury. As long as square sheds and total squaring nodes are available for two sampling dates, A can be calculated and incorporated to derive the break-even shed rate at first flower. The formula for the calculation of the variable A is the following:

$$A = \frac{X2 * Y2 - X1 * Y1}{X2 - X1} \quad [8]$$

where: $X2$ is actual squaring node number on sampling date two; $Y2$ is actual square shed rate on date two; $X1$ is actual squaring node number on date one; and $Y1$ is actual square shed rate on date one.

A plays an important role in the model because it helps us project near-future pest activity. One assumption in the model is that immediate control action will be effective enough to prevent future square loss up to the point when the cotton crop reaches first flower. Another assumption we make by using information on *A* is that the no control decision will result in continuation of the pest activity, causing future square loss at the same rate as the current one, i.e., the current per node shed change, *A*. These assumptions are made because of limited data to project injury dynamics. In evaluating these assumptions, one should recognize that the plant-based economic injury level model is to be used in real time with frequent data collection. In practical terms, the assumptions are that the injury rate will only remain the same during the short time-span from the current date until the next data collection date. It is also recognized that subjective assessments about changes in insect infestations are made frequently, and this trend provides a quantifiable basis for such an assessment. The two assumptions derive two possible shed rates at first flower under options of control and no control. With control action, no further square loss occurs after the current date, and the shed rate at first flower is calculated as:

$$\begin{aligned} &\textit{Shed rate at first flower (control)} \\ &= \frac{X2 * Y2}{T} * 100 \\ &= \theta \end{aligned} \quad [9]$$

With no control action, future square loss occurs at the same rate as the current one, *A*, and the shed rate at first flower is calculated as:

$$\begin{aligned} &\textit{Shed rate at first flower (no control)} \\ &= \frac{A * (T-X2) + (X2*Y2)}{T} * 100 \\ &= \frac{A * (T - X2) * 100}{T} + \theta \\ &= \theta' \end{aligned} \quad [10]$$

Depending on the value the shed rate at first flower takes, different costs and net revenues are calculated under both the control and no control options. The following section addresses in detail the possible values each shed rate can take and the effect they have on the net revenue calculation.

Economics of the Plant-Based Economic Injury Level Model

A closer examination of the plant-based economic injury level model shows that it is derived by the same economics as the Norton model. The advantage of the plant-based model is that it uses plant injury data directly to incorporate dynamics of pest activity and it is more complicated because of the integration of cotton's compensation capacity. As discussed earlier, one distinguishing characteristic of the cotton crop is its capability to compensate for early-season fruit loss. However, any square loss could cause maturity delay, exposing the growers to a higher probability of adverse weather occurring before harvest completion and a higher cost for managing late-season insect infestations (Eaton, 1931; Munro, 1971; Bagwell and Tugwell, 1992; Cochran et al., 1994; Sadras, 1994). Therefore the plant-based economic injury level also takes into consideration this indirect cost associated with square loss. The variable *R* is the shed rate at first flower that delimits the compensation capability - shed rate at first flower below *R* may not cause loss of yield while shed rate exceeding *R* may result in yield loss. Therefore, shed rates estimated in equations (9) and (10) are associated with different costs depending on whether they are located in the range above or below *R*. As a result, net revenue functions under decisions of control and no control take different shapes as shed rate at first flower goes from one range to another.

To calculate the two net revenue functions, one must consider each possible cost under the decisions of treatment and no treatment. Possible costs associated with each decision are now presented individually.

Since a complete effectiveness of insecticide is assumed, the decision of treatment will prevent future sheds from occurring and hence stop shed rate at first flower at θ (see Equation 9). If θ is lower than *R*, there is only maturity delay cost associated with θ. However, if θ is higher than *R*, there are both maturity delay and yield loss costs associated with it. As a result, there are at least two ranges for θ: (1) $\theta > R$ or (2) $\theta \leq R$. Within each range, there is a different net revenue function for the decision of treatment. If $\theta \leq R$, the net revenue function is: gross revenue minus cost of control and maturity delay cost caused by θ. If $\theta > R$, the net revenue function becomes: gross revenue minus cost of control, maturity delay cost and yield loss caused by θ. That is: when $\theta \leq R$, *Net revenue = Gross revenue - C -* $\theta * M * P$; and when $\theta > R$, *Net revenue = Gross revenue - C -* $\theta * M * P - (\theta - R) * V * D * Y$.

The decision of no treatment has two possibilities: (i) additional square loss occurs as the consequence of no control over insects or; (ii) there is no more square loss even without insect control. The variable *A* in the model reflects both possibilities. A positive *A* indicates increase in sheds while an *A* equaling to zero indicates no increase in sheds. It is theoretically impossible for *A* to take a negative value since the number of squaring nodes and the number of square sheds can only remain the same or increase. However, in reality, sampling errors can cause a negative *A*. Those errors are ignored in this presentation of the model. Under the decision of no control, the shed rate at first flower is calculated as θ' (see Equation 10). Like θ, this shed rate at first flower can take different ranges that are associated with different costs and produce different net revenue functions. Therefore, under the decision of no control, depending on which range θ' takes, we have: when $\theta' \leq R$, *Net revenue = Gross revenue -* $(\theta') * M * P$; and when $\theta' > R$, *Net revenue = Gross revenue -* $(\theta') * M * P - (\theta' - R) * V * D * Y$.

When we consider the possible ranges of θ and θ' together, there are three possible combinations: (1) $\theta \leq R, \theta' \leq R$, (2) $\theta \leq R, \theta' > R$ and (3) $\theta > R, \theta' > R$. Each of the possible combinations is now considered. If (1) $\theta \leq R, \theta' \leq R$, by using equation (10) we find the lower range for θ as:

$$\theta \leq R - \frac{A * (T - X2) * 100}{T} \qquad [11]$$

If (2) $\theta \leq R, \theta' > R$, by using Equation (10) we find the second range for θ as:

$$R - \frac{A * (T - X2) * 100}{T} < \theta \leq R \qquad [12]$$

If (3) $\theta > R, \theta' > R$, again, by comparing θ and θ' we find the upper range for θ as:

$$\theta > R \qquad [13]$$

Therefore, θ can take three ranges(see Equations 11, 12 and 13). Within each range, θ, as well as θ', are associated with different costs and, consequently, produce different net revenue functions under both decisions of treatment and no treatment.

In range one (see Equation 11), the net revenue function under treatment is: *Net revenue = Gross revenue - C -* $\theta * M * P$. The net revenue function under no treatment is: *Net revenue = Gross revenue -* $\theta' * M * P$. To locate the break-even point, θ^*, in this range, the two net revenues are equated to each other: *Gross revenue - C -* $\theta * M * P$ = *Gross revenue -* $\theta' * M * P$. Substituting Equation (10) into this formula gives us:

$$\begin{aligned} &Gross\ revenue - C - \theta * M * P \\ &\quad = Gross\ revenue \\ &\quad - \left(\frac{A * (T - X2) * 100}{T} + \theta\right) * M * P \end{aligned} \qquad [14]$$

Mathematically the two θs cancel each other out from this equation, which indicates that in this range there is no break-even point at all. In practical terms, this means that within this range, net revenues under each yes or no control option will never be equal to each other. Generally, this indicates that one of the options always results in a higher net revenue than the other. Although there is no break-even point, the two net revenues can be compared. The model as implemented in COTMAN displays the two net revenues when this condition occurs.

In range two (see Equation 12), net revenue function under treatment is: *Net revenue = Gross revenue - C -* $\theta * M * P$. The net revenue function under no treatment is: *Net revenue = Gross revenue -* $\theta' * M * P - (\theta' - R) * V * D * Y$. By equating the two net revenue functions, we find:

$$\begin{aligned} &Gross\ revenue - C - \theta * M * P \\ &\quad = Gross\ revenue \\ &\quad - \left(\frac{A * (T - X2) * 100}{T} + \theta\right) * M * P \\ &\quad - \left(\frac{A * (T - X2) * 100}{T} + \theta - R\right) * V * D * Y \end{aligned} \qquad [15]$$

Solving for the break-even point, θ^*, gives us Equation (6), the break-even shed rate at first flower formula.

In range three (see Equation 13), net revenue function under treatment is: *Net revenue = Gross revenue* - *C* -θ * *M* * *P* - (θ - *R*) * *V* **D***Y*. The net revenue function under no treatment is: *Net revenue = Gross revenue* -θ' * *M* * *P* - (θ'- *R*) * *V* * *D* * *Y*. In this case, the equation cannot be solved for the break-even point, which indicates that the two net revenues will never cross each other in this range.

Therefore, the only range in which it is possible to solve for the break-even point, θ^*, is the second range (see Equation 12). The two net revenues under the yes and no treatment options are equal to each other at the break-even point.

Assumptions of the Plant-Based Economic Injury Level Model

Several assumptions have been made in the plant-based economic injury level model. One assumption is that the objective of farmers is to maximize profits or net revenues. This is a conventional assumption that economists often make. Of course, in agriculture, there are cases where the growers are so risk-averse that their main objective may be to reduce the variance of production outcomes instead of to maximize profits. Taking into consideration the nature of the cotton industry, we regard the profit-maximizing assumption a reasonable approximation of cotton farmers' objectives.

We also make the utilitarian assumption that timely control actions, once triggered by the economic threshold, will prevent future square loss from occurring. This may sound as if an assumption that 100% effectiveness is required of a tactic, but in fact we do not assume perfect control power. Rather we assume that the cotton squares are not equally susceptible to shedding as the season progresses. Generally speaking, the squares are less vulnerable to shedding because of the proliferation of feeding sites which are of little or no value to production, and because of the reduced susceptibility of squares as they increase in size. Furthermore we assume that most risk-averse growers hold exceptionally high expectations of management activities, so once control is initiated, high levels of control will be achieved.

Another assumption is made in the calculation of net revenue under the decision of no treatment. We assume that without insect control, square loss will increase by the same per node shed change rate as the previous one, *A*, and this will result in shed rate at first flower as θ' (see Equation 10). As shown in the previous section, *A* is calculated from two real consecutive data points and used as a projection of the rate of future square loss. This is done because there is limited data to more accurately forecast future injury. However, with frequent data collection, the assumption, in practical terms, is applied only from the current date to the next data collection date when the model is re-evaluated.

Implementation of the Plant-Based Economic Injury Level in the COTMAN Computer Program

For the economic injury level calculations to be useful to producers for validating an economic threshold, they must be immediately available once data are collected. The economic injury level calculations are complicated and one practical solution for making the results easily available is to include the computations in a computer program. While it is possible to include the calculations in other programs, we have implemented the economic injury level model in the COTMAN expert system computer software. The COTMAN software had over 170 registered users in nine states in 1997, and will be more widely available in 1998. Cost estimates to collect data and run COTMAN weekly for a season are less than $4.94/ha ($2.00/acre) (Robertson et al., 1997), and the data required to calculate the economic injury level are already included.

The COTMAN system uses plant monitoring to adjust crop management based upon plant response to pests and environment. In the computer program, data from individual fields are collected once or twice a week and summarized in tables and graphs for decision-makers to quickly assess crop status. Plant-based rules are recommended and utilized in the system. One important foundation of the COTMAN rule base is that instead of estimating and using insect population densities to predict plant damage, plant injury as represented by square sheds is observed directly. Specific targets of plant growth and fruit retention are used as guides.

The COTMAN system is divided into two components, the SQUAREMAN component for use from first square to first flower and the BOLLMAN component for use after first flower. The plant-based economic injury level model has been included in the SQUAREMAN component. Data collection involves mapping plants in each field once or twice a week. Typically 10 plants are selected at each of four different sites in a 16-20 ha (40-50 acre) field. Each square is recorded as retained or shed. Once those data are recorded in COTMAN, they are used to calculate the number of squaring nodes, *X1* and *X2*, and the square shed rates, *Y1* and *Y2*, that are used in the model to capture dynamics of pest activity, *A*. Within COTMAN, producers can also access information for a field and change default values for most of the other variables in the model. Only *D*, yield loss damage, and *M*, maturity delay, are not user-supplied. As producers gain more experience with the model, they can begin to fine-tune the values to best reflect their production situations.

The plant-based economic injury level is calculated in COTMAN and the results are presented in tables and graphs. A bar graph compares the actual shed rate for a field to the shed rate limit calculated from the model so that a producer can quickly assess the effectiveness of a previous economic threshold and/or control action.

RESULTS

Model Sensitivity Test

One important advantage of the new plant-based technique is that it incorporates great dynamics into the economic injury level calculation. A computer program such as COTMAN provides the facility to change the values of most variables and to recalculate the economic injury level. It is quite common that as cotton develops from first square to first flower, growers may detect a different tendency in pest activity as well as crop response, which then leads to a different expectation on compensation capacity. They may also change their expectation of several items involved in the cost and benefit analysis, such as the cost of control, price of cotton, total squaring node number at first flower, and cost of protecting late crops. All can be dynamic and can result in different break-even shed rates (the economic injury levels) and thus different shed rate limits. The following sections present seven examples to illustrate this point.

Default values used for each of the variables are displayed in the tables. All examples use the same value of *A*, per node shed change, which is calculated using: *X1* (squaring node number for date 1) equal to 3.6; *Y1* (actual shed rate for date 1) equal to 2.8%; *X2* (squaring node number for date 2) equal to 6.8; and *Y2* (actual shed rate for date 2) equal to 16.5%. *A* is therefore calculated as $A = (X2*Y2 - X1*Y1) / (X2 - X1) = 0.32$.

Example 1. Change the Value for *R*, Compensation Capacity. Assume the user first input 19% as the compensation capacity. Later a decision is made to depend more on the crop's compensation or recovery capacity and the value is raised to 25%. Values of the other variables remain unchanged. This seemingly small change in *R* has a dramatic influence on the economic injury level calculation and leads to a totally different conclusion (Table 1). Because of the change of the economic injury level, the shed rate limit for the current number of squaring nodes changes as well. Notice that the actual shed rate for date 2, *Y2*, is above the limit with the compensation capacity at 19%. This implies that the previous economic threshold was not effective. However, as the compensation capacity goes up to 25%, *Y2* is well below the shed rate limit, representing a damage level below the economic injury level. Intuitively, it means that if we can rely on crop compensation, we do not have to control pest activity at an early stage. A higher economic injury level indicates that

Table 1. Change the value of compensation capacity, *R*.

	V	*C*	*T*	*P*	*Y*	*R*	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.54	37	10.25	2.84	1121	19	10.13	15.3	Yes
After	1.54	37	10.25	2.84	1121	25	16.13	24.3	No

Table 2. Change the value of cost of control, *C*.

	V	*C*	*T*	*P*	*Y*	*R*	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.54	37	10.25	2.84	1121	19	10.13	15.3	Yes
After	1.54	86	10.25	2.84	1121	19	13.07	19.7	No

Table 3. Change the value of price of cotton, *V*.

	V	*C*	*T*	*P*	*Y*	*R*	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.11	37	10.25	2.84	1121	19	11.16	16.8	No
After	1.98	37	10.25	2.84	1121	19	9.89	14.9	Yes

Table 4. Change the value of expected number of squaring nodes at first flower, *T*.

	V	*C*	*T*	*P*	*Y*	*R*	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.54	37	11.00	2.84	1121	19	8.64	14.0	Yes
After	1.54	37	8.25	2.84	1121	19	15.42	18.7	No

Table 5. Change the value of expected yield, *Y*.

	V	*C*	*T*	P	Y	R	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.54	37	10.25	2.84	1121	19	10.13	15.3	Yes
After	1.54	37	10.25	2.84	673	19	11.37	17.1	No

more pests can be tolerated and prompts the decision that pesticides should be used less frequently.

Example 2. Change the Value for *C*, Insect Control Cost. In this example, assume that keeping other variables the same, the user finds there are two types of insecticide available but with different costs. Calculation of the economic injury levels by using different values for the cost of control gives different economic injury levels (Table 2). When the cost of control is $37/ha ($15/acre), the economic injury level is rather low and the actual shed rate, *Y2*, is above the shed rate limit, which indicates that the previous economic threshold was not effective and economic damage can be incurred if no additional control is implemented. However, with the cost of control going up to $86/ha ($35/acre), the economic injury level goes up as well and the actual shed rate is below the shed rate limit. This indicates that if the cost of an insecticide treatment is very high, it is economical to tolerate more injury and apply insecticide at a higher level of damage. A higher economic injury level suggests a higher tolerance for pest activity.

Example 3. Change the Value for *V*, Cotton Price. Different values for *V*, expected cotton price, can result in different economic injury levels and hence prompt different conclusions on previous control actions. Table 3 shows that keeping other variables the same, changing the value of *V* from $1.11 to $1.98 /kg ($0.45 - $0.80/lb) results in a decrease of the calculated economic injury level. A higher price for cotton increases the potential loss from a no control decision and indicates a lower tolerance for pest activity.

Example 4. Change the Value for *T*, Expected Nodes at First Flower. The variable *T* represents the total sympodia expected by the producer at first flower in each field. Table 4 shows that a higher value for *T* results in a lower economic injury level. A high value for *T* usually suggests a high expectation on square numbers, which can indicate a high potential yield. With the higher yield potential associated with a higher *T*,

Table 6. Change the value of delay cost, *P*.

	V	*C*	*T*	*P*	*Y*	*R*	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.54	37	10.25	2.84	1121	19	10.13	15.3	Yes
After	1.54	37	10.25	1.56	1121	19	10.28	15.5	Yes

Table 7. Change the value of compensation capacity, *R*, and the value of delay cost, *P*.

	V	*C*	*T*	*P*	*Y*	*R*	Economic injury level	Shed limit	Shed rate above limit?
	$/kg	$/ha	no. of sympodia	$/(ha/d)	kg/ha	%	%	%	
Before	1.54	37	10.25	1.56	1121	19	10.28	15.5	Yes
After	1.54	37	10.25	2.84	1121	25	16.13	24.3	No

the cost of control can be justified at a lower pest level.

Example 5. Change the Value for *Y*, Yield. Changing the value for *Y* results in different economic injury levels as well. Table 5 shows that a higher value of *Y* results in a lower economic injury level. A higher yield potential indicates treatment can be economical at a lower pest level.

Example 6. Change the Value for *P*, Cost of Delay. The cost of protecting delayed cotton, *P*, also has influence on the calculation of the economic injury level. In Table 6, we observe a decrease in *P*. Keeping other variables the same, the economic injury level increases from 10.11 to 10.26. Although the validation on control action is the same - pest control may help avoid economic damage at first flower - we can still detect from the increase of the economic injury level that a lower delay cost prompts more tolerance of pest activity.

Example 7. Change the Value for *R*, Compensation Capacity, and *P*, Cost of Delay. The above examples are cases in which the value of one variable is changed and other variables remain the same. Changes involving more than one variable become more complicated and less predictable because of the high interaction between variables. For example, the grower anticipates a higher compensation capacity and changes it from 19% to 25%. Heavy late-season insect pressure is expected and late season crop protection cost is raised from $1.56 to $2.84 /(ha/d) [$0.63 to $1.15/(acre/d)]. Table 7 lists the values for each variable and the economic injury level under the two scenarios. Although the raise in delay costs should result in a lower economic injury level so as to avoid higher delay cost at the end of the season, the increase in the compensation capacity is too overwhelming and plays the dominant role in this case. It allows a higher tolerance for pest infestation.

Table 8. Numerical calculations of elasticity values.

Variable	Default value	Elasticity value
A, pest activity (per node shed increase)	0.32	e_A = -1.098
R, compensation capacity, %	19	e_R = 1.88
C, cost of insect control, $/ha	37	e_C = 0.22
Y, yield potential, kg/ha	1121	e_Y = - 0.186
V, price of cotton, $/kg	1.54	e_V = - 0.186
D, % yield loss/shed > *R*	0.97	e_D = - 0.186
M, days of maturity delay/shed %	0.1818	e_M = - 0.033
P, late-season protection cost $/(ha/d)	2.84	e_P = - 0.033
T, number of squaring nodes at 1st flower	10.25	e_T = - 2.16

Elasticity Analysis of the Model

Elasticity measures the proportional response of one variable relative to another. As a summary measure of responsiveness, elasticity can help identify the effects of a percent change of one variable on another. The numerical calculations of the elasticity values for variables in the model are presented in Table 8 and the equations for the elasticity calculations are presented in Appendix A. The elasticities indicate the impact a 1% change in the value of a specified variable will have on θ^*, the break-even shed rate at first flower. For example, a 1% increase in *R*, the compensation capacity, would result in a 1.88% increase in θ^*. Hence, an increase in the compensation capacity would lead to an increase in the economic injury level and would suggest that more damage could be tolerated and insecticide would optimally be used less frequently. A negative sign on the elasticity implies an inverse relationship between θ^* and the variable under consideration, that is, an increase in the value of the variable results in a lower economic injury level. Note that elasticity calculations presented in Table 8 were derived using the default value for each variable.

The elasticity measures can also be used to reflect the relative importance of each variable in determining θ^*. The variables T, R, and A have the most influence while M and P have the least. In other words, θ^* is more responsive to the changes in T, R, and A than to changes in the other variables.

SUMMARY AND DISCUSSION

Many approaches have been suggested for decision-making in pest management. Stern et al. (1959) proposed the combined use of the economic injury level and the economic threshold. The economic injury level was designed to define an upper bound on break-even conditions and the economic threshold was to serve as an operational guide that would insure that economic damage would be avoided. In practice, the economic threshold is rarely defined with a prescribed economic injury level to validate its effectiveness.

In this paper we proposed a plant-based economic injury level for assessing the economic threshold in early-season cotton insect management. Although based on the same economic theory, the plant-based economic injury level model is quite different from the conventional economic injury level model. It incorporates cotton's compensation capacity for early-season square loss. It also incorporates the per node shed change variable, A, into the calculation, which makes the model time-specific and field-specific. The plant-based model is dynamic because it uses updated field monitoring data to calculate A and to provide the most current criteria. The growers who have direct access to the crop provide field-specific plant monitoring data to calculate A, and they can provide information on many other variables in the model. Pulling all the information together, this plant-based economic injury level model helps to determine if an economic threshold is effective and how effective it is.

An assessment of an insect-based economic threshold through a plant-based economic injury level for early-season insects can be made in its simplest form by comparing actual square shed percentage with the shed rate limit derived from the break-even point. When the economic threshold-triggered action failed to prevent injury from exceeding the break-even shed rate, the crop is on a course that may lead to damage if an adjustment in the economic threshold for a given tactic(s) is not or has not been corrected. When the economic threshold does not trigger action, the grower can be reassured, and the economic threshold decision is confirmed by showing that plant injury remains below the economic injury level.

One essential requirement of a truly functional economic injury level is that it be simple and easy to use, which is one advantage enjoyed by the plant-based economic injury level. Modern computer technology allows us to perform the complex calculations in a simple, fast and functional manner by incorporating it into the COTMAN expert system. Feasibility studies using this technology suggest that cost for the total COTMAN program will be less than \$4.94/ha (\$2/acre). Execution of the plant-based economic injury level within computer programs such as COTMAN should add no additional cost since required plant monitoring data are already included. We believe, therefore, that this essential requirement can be met and that the plant-based economic injury level can help meet compelling management demands that seem imminent with new developments in cotton production.

Numerous options for insect control will be available to cotton producers in the near future, as demonstrated by the activity of transgenic and novel foliar control strategies (Leonard et al., 1997). As a result, we anticipate better control, but an increased need for constant reassurance that some unexpected pest is not causing damage that may be difficult to detect. The egg counts that are often used to anticipate threatened damage from Heliothine pests clearly are not useful in the transgenic cotton that is expected to kill the newly hatched larvae. In transgenic cotton the decision-maker needs plant data to confirm that no damage is occurring. Even more potentially stressing for the decision-maker are the novel chemicals that kill well, but slowly. The mere presence of live pests in a field that has been treated, even when the insects are sick and non-feeding, is enough to require some kind of reassurance that no damage is being done. In these situations a plant-based economic injury level is clearly needed.

Integration of tactics, including biological control agents, plant compensation, insect growth regulators and others will likely depend upon solid decision rules that dispel fear of the unknown. Ideally, insect-based economic threshold could be supported through a plant-based economic injury level. We believe the plant-based economic injury level provides an opportunity for each decision-maker to learn to take advantage of his/her situation. For example, the elasticity analysis shows that early plant structure (T) can have a large influence on the economic injury level. Growers frequently know what to expect from plant growth. With the plant-based economic injury level, a grower could begin to factor in that kind of information.

Because the plant-based economic injury level reflects crop dynamics, the user must carefully consider the time-frame of control actions and plant sampling. The index of the aggregate feeding activity (A) on squares by one or more species is a useful indicator of the change in two factors: (1) insect feeding, and (2) node growth occurring during the time defined by the last two samples taken. Both dynamic factors represented by A can have a large influence on the economic injury level, as shown in the elasticity. Interpretation of these changes must include consideration of the question of whether A captures the last action triggered by an economic threshold. For example, assume that the economic threshold triggered a control action on one day, and data for the plant-based economic injury level were collected the next day. Results may indicate a large A, suggesting that feeding per new node was high. However, that evaluation might change if one had waited three to four days when control and growth had progressed enough to reflect progress. Viewed from another perspective, sequential measures of A would allow documentation of the time required to gain control of a situation under the growing conditions.

Successful utilization of the plant-based economic injury level requires rapid utilization of timely information. By incorporating the economic injury level calculations into the COTMAN computer program, we feel we can provide that opportunity. We recognize that values of many components in the plant-based economic injury level can best be determined by the user, so we have provided those options. Regardless of the value of the component, we believe that a more comprehensive economic threshold will follow assessment with a defined plant-based economic injury level. Currently, few use the same economic threshold and no economic threshold is well defined. We believe that any economic threshold can be assessed through a defined plant-based economic injury level, in the spirit of the original concept presented by Stern et al. (1959).

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APPENDIX A. FORMULAS FOR ELASTICITY CALCULATIONS

The original formula to calculate θ^* is:

$$\theta^* = \frac{C}{V * Y * D} + R - \frac{100 * A * (T - X2) * M * P}{T * V * Y * D} - \frac{100 * A * (T - X2)}{T} \tag{A.1}$$

To make the calculations of the elasticities easier, we transform the formula for θ^* into:

$$\theta^* = \frac{C*T+R*T*V*Y*D-100*A*(T-X2)*M*P-100*A*(T-X2)*V*Y*D}{T*V*Y*D} \tag{A.2}$$

The elasticity of A for θ^* is then calculated as:

$$\begin{aligned} e_A &= \frac{\frac{\Delta\theta^*}{\theta^*}}{\frac{\Delta A}{A}} = \frac{\Delta\theta^*}{\Delta A} * \frac{A}{\theta^*} = \frac{\partial\theta^*}{\partial A} * \frac{A}{\theta^*} \\ &= \left(- \frac{100*(T-X2)*M*P}{T*V*Y*D} - \frac{100*(T-X2)}{T} \right) * \frac{A}{\theta^*} \\ &= - \left(\frac{100*A*(T-X2)*M*P+100*A*(T-X2)*V*Y*D}{C*T+R*T*V*Y*D-100*A*(T-X2)*M*P-100*A*(T-X2)*V*Y*D} \right) \end{aligned} \tag{A.3}$$

To simplify the presentation of the elasticity, we assign the final denominator in equation A.3 to the variable, β, since it is identical in all the elasticity equations:

$$\beta = C*T+R*T*V*Y*D-100*A*(T-X2)*M*P-100*A*(T-X2)*V*Y*D \tag{A.4}$$

Substitute β into equation A.3 and the elasticity for A is calculated as:

$$e_A = - \left(\frac{(100*A*(T-X2)) * (M*P+V*Y*D)}{\beta} \right) \tag{A.5}$$

Similar to the above calculation, the elasticity of R for θ^* is:

$$e_R = \frac{\partial\theta^*}{\partial R} * \frac{R}{\theta^*} = \frac{R*T*V*Y*D}{\beta} \tag{A.6}$$

The elasticity of C for θ^* is:

$$e_C = \frac{\partial\theta^*}{\partial C} * \frac{C}{\theta^*} = \frac{C*T}{\beta} \tag{A.7}$$

The elasticities of *Y*, *V* and *D* for θ^* are:

$$e_Y = \frac{\partial\theta^*}{\partial Y} * \frac{Y}{\theta^*} = \frac{100*A*(T-X2)*M*P-T*C}{\beta} \quad [A.8]$$

$$e_V = \frac{\partial\theta^*}{\partial V} * \frac{V}{\theta^*} = \frac{100*A*(T-X2)*M*P-T*C}{\beta} \quad [A.9]$$

$$e_D = \frac{\partial\theta^*}{\partial D} * \frac{D}{\theta^*} = \frac{100*A*(T-X2)*M*P-T*C}{\beta} \quad [A.10]$$

The elasticities of *M* and *P* for θ^* are:

$$e_M = \frac{\partial\theta^*}{\partial M} * \frac{M}{\theta^*} = -\left(\frac{100*A*(T-X2)*M*P}{\beta}\right) \quad [A.11]$$

$$e_P = \frac{\partial\theta^*}{\partial P} * \frac{P}{\theta^*} = -\left(\frac{100*A*(T-X2)*M*P}{\beta}\right) \quad [A.12]$$

The elasticity of T for θ^* is:

$$e_T = \frac{\partial\theta^*}{\partial T} * \frac{T}{\theta^*} = -\left(\frac{100*A*X2*(M*P+V*Y*D)}{\beta}\right) \quad [A.13]$$