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# ECONOMIC INJURY LEVELS IN THEORY AND PRACTICE

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## PERSPECTIVES AND OVERVIEW

The topic of economic decision levels probably is the most often-discussed issue in economic entomology and insect-pest management today. The fundamental questions addressed are: How many insects cause how much damage, and is the damage significant? Most entomologists agree that a common decision rule or threshold should answer such questions and that such decision rules are the backbone of progressive pest control (3, 46, 64, 79). At issue is the form such rules should take and how they should be developed.

To date, the most widely accepted form is that of the economic threshold as presented by Stern et al (80). These authors developed their decision rule from basic principles of economic damage and the economic injury level (EIL), and it is from their EIL concept that much of our present theory is derived.

The major advantage of this concept is its simplicity and practicality in most situations. The EIL, defined as "the lowest population density that will cause economic damage," has been used most often to support management decisions with short-range objectives, i.e. a one-season or less planning horizon at the farm level. Additionally, the concept has been applied primarily where management tactics are responsive rather than preventative. Consequently, EILs have been most developed for occasional and perennial pests [sensu Stern et al (80)] where scouting, evaluation, and subsequent therapy are possible.

EILs have application for all pests, however, when used as criteria of management success. In this regard, they are as applicable to severe pests as to occasional pests and as applicable to preventative tactics as to curative ones. This is because most IPM strategies call for the reduction of pest populations to a level below that which is "economic;" i.e. the familiar principle of tolerating pest presence, albeit at noneconomic levels.



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Some authors have criticized the original EIL concept because it is too simple and overlooks the influence of other production factors that can affect the crop/pest system (64, 75). It has also been pointed out that other important externalities are left out by the decision makers who use the original EIL concept. Such externalities include interseasonal dynamics, biological relationships with other pests and predators, environmental contamination by pesticide residues, resistance to pesticides, effects of control in neighboring fields, and health problems relating to pesticides (65). Although criticisms of oversimplification may have merit, it is ironic that simplicity is one reason that the EIL concept has persisted for more than 25 years (75).

The relative importance of economics and decision levels to entomologists and pest managers is indicated by the number of reviews published on these topics in the *Annual Review of Entomology* (31, 50, 52, 78). In addition, a detailed interpretive review by McCarl (47) and an annotated bibliography covering the years 1960–1980 (58) also allow an insight into the widespread interest in these topics. Although each of these publications emphasizes different aspects of the topic, all deal with costs and benefits of management activities and almost all address the original EIL concept.

In much of the literature on pest-management decision making, the topic of economic optimization has been a major focal point. Here, many authors have employed or suggested the use of conventional economic programming techniques, pest/crop systems simulations, and combinations of these (e.g. 2, 9, 14, 24, 25, 40, 51, 65, 66, 70–72, 86). However, to date, economic optimization models have seen only limited development for few crops (primarily alfalfa and cotton), perhaps because of the substantial data requirements. Furthermore, some economists (50, 51) believe that these data requirements are unlikely to be met in most situations. As an alternative, Mumford & Norton (50) suggest the conventional ET "as an operational, if not an ideal, decision rule."

In this review, we make no attempt to resolve the difficult question of propriety of approach to decision making in pest management. Rather, we begin with the premise that the EIL concept of Stern et al (80), although not without drawbacks, is the most widely accepted and practical tool for its purpose, but one that can be refined. We emphasize insect/host damage relationships because of their direct usefulness to producers for making decisions, and because they are the prime ingredient of any decision-making approach. Consequently, we attempt to summarize the historical development of the EIL concept, synthesize basic principles of the idea, explore the array of insect-injury/host-damage relationships, and consider possible directions for refinement of the concept.

## DEVELOPMENT OF THE CONCEPT

Although the EIL was initially defined by Stern et al (80), some of the ideas expressed in their paper had been discussed years earlier. In 1934 a particularly

farsighted paper by Pierce (63) raised questions that became one incentive for developing EILs. Pierce asked: "Is all insect attack to be computed as assessable damage? If not, at what point does it become assessable? Is control work warranted when damage is below that point?"

Although fundamental to the concept, such questions may not have been the initial impetus for developing EILs. Stern et al emphasized the concerns of many perceptive scientists regarding excessive and inappropriate uses of insecticides. In fact, in their 1959 paper Stern et al discussed at some length insecticide resistance, replacement, resurgence, residues, and nontarget effects. Thus, the EIL concept was developed largely as a means for more rational use of insecticides. This perspective is vital in understanding the EIL. The EIL was designed to be most applicable in situations with a discrete, curative control measure (usually this means insecticides). Thus, where the use of such control measures is limited the use of EILs is also limited.

Irrespective of the precise motivation behind its inception, the EIL provided the practical basis necessary for a theory of pest management. Stern et al's integrated control, defined as "applied pest control which combines and integrates biological and chemical control" and subsequent modifications of this idea (integrated pest management) rely on the availability of decision levels for making management decisions. Thus, EILs were and are fundamental for any holistic approach to pest management. However, without discrediting their contributions, we must recognize certain deficiencies in some of Stern et al's approaches.

For example, the EIL name itself is somewhat misleading because the economic injury level is defined as a population density, not an injury level. In fact, some workers suggested that the name be changed to "critical population density" (21). However, implicit in the EIL definition is the notion that a given number of pests produces a given amount of injury (both past and future); numbers are used as a direct index of injury. Because we use insect numbers as an index of the total injury from a pest, it can be more useful to express the EIL in standard units of injury. This approach was first advanced by Harcourt (30) and was subsequently used by Shelton et al (69) to place injury by cabbage defoliators on a common basis. These standard units of injury are the **injury equivalent,** the amount of injury that could be produced by one pest through its complete life cycle; and **equivalency,** the total injury equivalents (for a population) at a point in time. Some advantages of defining EILs in injury equivalents include the possibility of using standard units of injury to describe the same type of injury for many pest species and the ability to incorporate age-specific mortality into a measure of a population's injuriousness.

A more significant deficiency in the Stern et al paper was the lack of a rigorous definition of economic damage. Their definition was, "the amount of injury that will justify the cost of control." Because economic damage was not described mathematically in terms of its components, it could not be assessed

solely on Stern et al's definition. Because the EIL had to be calculated from economic damage, EILs also could not be established. Undoubtedly, the inadequate definition of economic damage delayed the acceptance and precise calculation of EILs. In fact, the first publication of calculated EILs did not occur until over a decade after the original Stern et al paper.

Stern et al's failure to treat economic damage in sufficient depth underlies a weakness in their description. Although they were able to develop a theory for pest management based on ecological principles, the authors placed their emphasis on the pest, not on the damaged host. The principle of economic damage provided a basis for incorporating information on a host's response to injury into the decision-making process, but it remained for later workers to explore this area.



These subsequent explorations have provided a more comprehensive basis for combining information on pests with information on the host in calculating EILs and for distinguishing between injury and damage (5, 43, 87). We define **injury** as the effect of pest (insect) activities on host physiology that is usually deleterious; and **damage** as the measurable loss of host utility, most often including yield quantity or quality or aesthetics. Thus, a certain level of injury may not produce damage or yield loss.

The distinction between injury and damage leads to a second important concept: **damage boundary,** the level of injury (or insect numbers used as an injury index) at which damage occurs. This point was first recognized explicitly by Tammes (87), who called it the "threshold level." Other workers have referred to this point as the "damage threshold" (20, 52), but we believe "damage boundary" is preferable inasmuch as it avoids use of the frequently overworked term "threshold." Although Stern et al did not describe the damage boundary, it is the necessary complement to the EIL. Together, the principles of the EIL and damage boundary answer Pierce's question regarding when insect attack should be considered damage. No injury level below the damage boundary merits control; economic damage, which does merit control, occurs at the EIL which is at or above the damage boundary.

Given this background, the final question remaining is when to initiate control. Stern et al addressed this question by devising the economic threshold (ET) defined as the population density at which control measures should be determined (= initiated) to prevent an increasing pest population from reaching the EIL. The damage boundary, ET, and EIL are all intimately related. The EIL always occurs at or beyond the damage boundary. Usually the ET occurs between the damage boundary and the EIL but in some instances the ET may be below the damage boundary. If the EIL is expressed in injury equivalents, the ET will always be below the EIL; but if the EIL is expressed in insect numbers and pest mortality is very significant, the ET may occur above the EIL.

Unfortunately, no aspect of Stern et al's paper has been as misunderstood and

confused as the ET. Much of the confusion arose from a misuse of Stern et al's terminology by subsequent authors. Numerous workers persisted in calling ETs what were clearly EILs (e.g. 32, 50, 54). Other authors invented new expressions such as "action threshold," "action level," "action threshold level," "dynamic action threshold level," "inaction threshold," "control threshold," "insect injury threshold," "critical injury threshold," and "critical population threshold" for the ET and EIL or their analogues (8, 10, 21, 76, 84, 91). Sometimes these terms were defined to differentiate them from the ET and EIL (e.g. 8, 91), but the persistent use of the buzzwords "threshold" and "level" has robbed these new expressions of significant impact and has seriously weakened the original terms "ET" and "EIL." Other terms represent little more than semantic wheel-spinning, although some expressions arose to correct deficiencies in the original definitions of ET and EIL. For example, the terms "control threshold" and "action threshold" more explicitly convey the idea of time to initiate control than does "economic threshold"; unfortunately, both "control threshold" and "action threshold" have been used to indicate entirely subjective levels for control that do not relate to an EIL. We are convinced that the only hope for sensible and consistent nomenclature is to use the terminology of Stern et al, with a clarification of their definitions as necessary.

The more substantive problems with the ET can be attributed to how it was originally defined. Although Stern et al described the ET in terms of a population density, it actually represents the time for control, i.e. when it is probable that future pest injury will cause economic damage (26, 52, 53); pest numbers are used merely as an index of that time. The use of numbers as a temporal index requires a substantial knowledge about how a pest population is changing in time. Because we can rarely be certain about the population-time relationship, the ET always has been estimated and never calculated. Furthermore, because the ET is set (often arbitrarily) at a level other than the EIL, it is predictive; therefore some degree of uncertainty (usually a great deal) is involved in its use.

## GENERAL EIL MODEL

Although the general EIL concept received considerable acceptance in the 1960s (21, 77), few attempts were made to actually define and quantify the parameters involved. It was not until the 1970s that economic aspects of decision making and pest management were addressed in a mathematical framework (23).

Stone & Pedigo (82) made an early attempt to define and quantify components of the EIL for *Plathypena scabra,* a defoliator of indeterminate soybean. In their study, values of larval leaf consumption were used with agronomists' defoliation data to arrive at expressions of insect numbers and yield

losses. These expressions were combined with actual insecticide application costs and average soybean market values to estimate EILs for five soybean growth stages.

In quantifying the EIL, it was necessary to interpret the meaning of Stern et al's (80) "economic damage." From Stern et al's description, Southwood & Norton (74) described economic damage (ED) as occurring when:

$$C(a) \leq Y[s(a)] \cdot P[s(a)] - Y(s) \cdot P(s), \qquad 1.$$

where $Y$ = yield, $P$ = price per unit of yield, $s$ = level of pest injury, $a$ = control action [$s(a)$ is level of injury as modified by the control action], and $C$ = cost of the control action.

Rather than express ED as a monetary value, Stone & Pedigo (82) found it useful to describe the term as loss of marketable produce, calling it the gain threshold (GT). Using symbols from Equation 1 and assuming that $P(a)=P[s(a)]$ or that quality loss is absorbed as yield, this term can be shown as:

$$\text{GT} = C(a)/P[s(a)] \quad \text{e.g. kg/ha} = (\$/\text{ha})/(\$/\text{kg}) \qquad 2.$$

Stone & Pedigo (82) employed the GT primarily in a step towards calculating EILs, as others have for insect pests in such diverse crops as guar (67), grapes (18), beans (17), sorghum (27), and rice (6). However, the GT, by itself, also is a useful decision criterion (36).

Although entomologists were developing practical procedures for calculating EILs in the early 1970s, it was economists who first proposed models of economic decision rules for pest management. Headley (32) was one of the earliest to present a mathematical expression of the EIL, although he called it the ET and used a marginal-analysis approach. In a subsequent paper, Headley (33) recognized that he was not using the ET term as defined by Stern et al (80). Other economists (26, 40, 52, 85) followed Headley's lead in developing various forms of optimization models; each emphasized different aspects of the variables involved.

Norton (54), however, presented a general model of the EIL as used by entomologists. This model was expressed by using actual data for the potato cyst eelworm on potato as:

$$\theta = C/PDK \qquad 3.$$

where $\theta$ = level of pest attack [ET according to Norton but equal to the EIL of Stern et al (80)], $C$ = the cost per hectare of applying pesticide, $P$ = price of produce per ton, $D$ = loss in yield (tons per hectare) associated with one nematode egg per gram of soil (could be any measure of density), and $K$ =

reduction in pest attack (percentage converted to proportion). In discussing the model, Norton emphasized that θ is variable, depending on changes in the four components, and mentioned that this is the operational or working decision rule of entomologists and plant pathologists.

However, in some, if not many, instances the variables shown in the Norton model are defined somewhat differently by entomologists. Specifically, the variables $D$ and $K$ may be treated in other ways. The $D$ variable, as used, is conveniently obtained from regression analyses where yield reduction is measured as a result of injury from known insect populations or from simulated insect injury. The resulting β coefficients from such analyses are the losses per insect (e.g. 55). This approach is still most practical in dealing with certain insects, e.g. species that remove plant assimilates. However, in other instances (e.g. 90) plant damage is measured as a result of injury units (e.g. percentage defoliation), and injury per insect is measured as tissue destroyed. Therefore, it may be more appropriate to express the $D$ variable as the product of two variables: loss per injury unit (e.g. kilogram loss per percentage leaf area consumed by an insect) and injury units per insect density (e.g. percent defoliation by one insect per meter of row). To express $D$ as the product of these two variables, a linear relationship between injury and damage must be accepted as a reasonable approximation. The other variable, $K$, is not always considered a variable by entomologists because of the exceptionally high expectations of management activities by growers. Because most growers are averse to risk (16, 52), entomologists' control recommendations are aimed at reducing the pest population to a level below the damage boundary and at a time before economic damage occurs; i.e. action is taken before significant damage is done, and the insects remaining after the activity cause no appreciable loss. Management strategies that do not achieve this objective usually are considered ineffective and, unless technology is lacking, are not often recommended.

With the foregoing in mind and in keeping with the notion of the EIL as a potential value, we suggest slight modifications in the Norton model for use in practical insect management:

$$\text{EIL} = C/VID, \qquad 4.$$

where EIL = number of injury equivalents per production unit (e.g. insects/ha, all of which live to attain their full injury potential), $C$ = cost of the management activity per unit of production (e.g. $/ha), $V$ = market value (utility) per unit of the produce (e.g. $/kg), $I$ = injury units per insect per production unit [e.g. proportion defoliated/(insect/ha)], and $D$ = damage per unit injury [e.g. (kg reduction/ha)/proportion defoliated]. If technology does not allow retention of the population below the damage boundary or if an optimal reduction (e.g.

profit maximization) is desired and the residual insect population results in a linear damage function, then $K$ becomes a critical component of the model:

$$\text{EIL} = C/VIDK, \qquad 5.$$

where $K$ = proportionate reduction of the insect population.

## COMPONENTS OF THE EIL MODEL

As shown in the basic model (Equation 4), there are four primary components affecting the EIL: (a) market value, (b) management cost, (c) injury per insect density, and (d) host damage per unit of injury. Although the mathematical relationship of these components is quite simple and straightforward, complexity arises when the variables that comprise the components are considered (Figure 1). The primary components $C$, $V$, $I$, and $D$ are affected by complex secondary variables such as the host-damage/injury and injury/insect-density relationships. Not shown in Figure 1 are tertiary variables such as weather, soil factors, biotic factors, and the human social environment that cause changes in



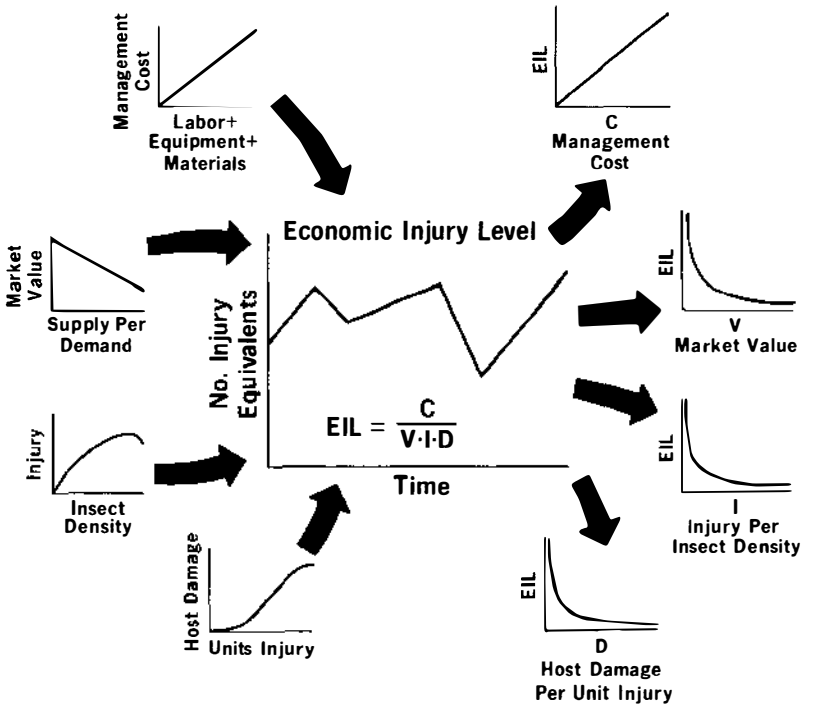


*Figure 1* Relationships of economic injury level components and their variables.

the function of the secondary variables. Consequently, the primary components are difficult to estimate and predict because they are not simple constraints but, rather, complex processes that operate through time (64). In developing EILs, entomologists have tended to simply account for the economic aspects and to conduct research on the biological components.

## *Market Value* (V)

Some estimate about the expected returns from a commodity must be made so that gain thresholds (break-even analyses) can be calculated as a first step for EIL determination. The market value component of the EIL model represents a partial measure of expected returns and thus provides a portion of the economic justification necessary for general acceptance of the concept. Programmable calculators (93) and extension publications that parameterize decision levels based on expected prices (81) represent a good attempt to underscore the dynamic nature of this economic variable. The estimation of an expected crop value, however, must ultimately be determined by producers and must be based on current criteria unique to their operations.

The impetus for producers to forecast their future income was established separately from the development of bioeconomics. The competitive nature of agriculture necessitates the formulation of a marketing strategy by each producer to meet cash flow objectives. Factors that determine the specific marketing plan include (*a*) personal feelings (speculation) about future trends, (*b*) financial conditions unique to each situation, (*c*) seasonal patterns in market prices (estimated with statistical techniques such as time-series analysis), and (*d*) price outlook over several seasons (estimated with econometric modeling and based on supply and demand relationships). Of these four factors, the first two must be determined by the farm manager. Factors *c* and *d,* however, frequently are calculated by public and private sources and are made available to the growers upon request. A successful accounting of these four factors will help determine the optimal time, based on forecasted prices, to market the output.

The quality of a commodity may be important in determining its market price. In situations where several specific grades (and prices) for a commodity exist, the value of the desired grade of production should be used in EIL calculations. Similarly, when quality is associated with appearance (cosmetic quality), the level of control should reflect the desired appearance. A target price, based on the expected quality of production, should be used whenever feasible.

When no clear system of marketing exists for a product, some estimate about the utility of the output to the producer must be made. Forage and pasture crops, for example, often have no established markets but are frequently deemed necessary as inputs for various forms of animal production. Because most

forage and pasture crops are produced for on-farm use, their value is dependent upon the relative contribution that they make to the growth and production of the animal. One way to estimate this value is to determine the substitution price for other, more marketable, feeds (15). To be valid, however, the substitution feeds must be equal in nutritional quality to the on-farm feeds.

## *Management Costs* (C)

The cost of controlling a pest population must be estimated before the profitability of an action can be assessed. As the cost of management increases, the net benefit of control decreases. Therefore, consideration must be given to the type (cost) of control available before EILs can be determined.

The total expense of a control tactic can be divided into several smaller costs. These may include cost of the controlling agent, cost of the application machinery, and labor costs of application. The expense of an insecticide or other control agent is generally predictable; however, the expense of the application method may be less predictable.

Because the expenses associated with equipment and labor may equal or exceed the cost of the control material, care should be taken to formulate the best estimate for these application expenses. If, for example, aerial application (at $8.50/ha) must be substituted for the usual ground application (at $5.50/ha), then the additional cost should be reflected with a higher EIL. Most of the uncertainty with this variable of the model is caused by differences in price between control options rather than between control periods. For this reason, the estimation of management costs probably is the easiest of the four primary EIL components to determine.

## *Injury Per Insect* (I)

The process of injury is a dual-sided phenomenon, governed both by insect and host populations. The insect aspect concerns a particular act or behavior of individuals that, as a rule, causes impairment of a host's ability to survive, grow, and reproduce. The host, as the recipient of the behavior, plays a major role in determining the kind and degree of the injury.

Metcalf et al (48) give one of the most detailed and comprehensive descriptions of injury caused by insects. Bardner & Fletcher (5) and Evans (19) also present useful summaries of the topic as it relates to plants. By far, most instances of injury are caused by insects feeding on host tissues or fluids, although other major causes include injecting toxins and vectoring pathogens. Insect chewing and sucking are the most common feeding behaviors, producing injuries such as leaf skeletonizing, leaf mining, stem boring, and fruit scarring.

Boote (7) classifies pest injury to plants (which he calls "damage") into eight different categories. Insect injury belongs in at least five of these categories: stand reducers, leaf-mass consumers, assimilate sappers, turgor reducers, and

fruit feeders. These categories include injuries that kill plants or impair physiological processes.

Boote addresses pest-caused injuries in the context of physiologically based crop-growth and development models. Insects that reduce stand (e.g. cutworms) are said to produce an immediate loss in plant biomass and decreased photosynthesis in the crop. Effects of stand reduction are governed by number, timing, and dispersion of plants lost. Leaf consumption by most insects is believed to directly affect absolute photosynthesis of the plant canopy, but it probably has little or no effect on photosynthesis per unit of the remaining leaf tissue. Effect of the injury on plant physiology can be accounted for by measuring leaf mass consumed per unit land area, timing of leaf consumption, and vertical distribution (or location) of the defoliation. Assimilate sappers, comprising piercing-sucking and rasping insects, remove plant carbohydrate and nutrients after the carbon is taken up and before the plant can convert it to tissue. As we pointed out, quantifying the details of carbon removal per pest poses a problem, as does measuring the effect of injection of toxic substances during the feeding process (e.g. *Lygus lineolaris* on peaches). Turgor reducers, represented by soil insects and stem feeders, act at root and stem sites to influence plant water and nutrient balance. Insects such as *Diabrotica virgifera* prune maize roots, reducing rooting depth and density, and others such as *Spissistilus festinus* girdle soybean stems, thus destroying conductive tissues. Severe reductions in water uptake (as shown primarily with nematodes) produce decreased plant turgor, followed by reduced expansion of leaves, stems, and fruits, as well as reduced photosynthesis. Finally, insects can injure fruit, which usually means direct destruction of the harvestable produce. Such injury can affect quality (appearance and/or makeup) or yield, or both, depending on use of the produce. Although injury to the harvestable produce may seem simple and straightforward, it is not because yield losses usually are not proportional to percentage loss of reproductive sites. In particular, plant compensatory mechanisms need to be identified to quantify relationships of losses to this type of injury.

A category of insects not mentioned by Boote (7) could be termed architecture modifiers. Injury by these insects causes changes in morphology of the plant such that yield is reduced. For example *S. festinus,* in addition to destroying conductive tissues, also causes plants to lodge. Lodged plants may die outright or may continue to live and grow in a gooseneck fashion. This change in plant architecture can reduce physiological yield of the plant as well as harvestable yield (42). Other examples of architecture modifiers include *Delia platura,* which consumes the plumule of seedling soybean, causing a "Y" plant; and *Papaipema nebris,* which bores in young maize plants, destroying the growing tip and causing tillering and low-yielding or barren plants. In these instances, not only the quantity of tissue is destroyed but also the quality. Such

injury results in potentially drastic changes in subsequent pattern and, perhaps, rate of plant growth. Because of complexity added by morphological changes in plant structure, this type of injury is difficult to understand and to quantify on an injury-per-insect basis. However, for most insects, when the kind of injury is known and can be measured the determination of injury per insect for a given crop variety at a given injury site is straightforward and can be used in calculating the EIL.

For the purpose of calculation, the injury per insect usually has been assumed to have a linear relationship with insect density. However, crowding at high densities has been shown to reduce injury per insect in some insect species because of interference between individuals and/or cumulative reduction in available food (5, 38, 41, 62). Such observations show a density/injury relationship such as that illustrated in Figure 1. Although this phenomenon is of concern, at least for some species the density/injury relationship is linear (i.e. crowding does not occur) at densities up to and including those at the estimated EIL. Thus injury from these species can be treated as additive (62). If the density/injury relationship is not known, evidence suggests that the relationship be considered linear until it is proven otherwise. Such an approach yields conservative (less risky) estimates in establishing operational EILs.



## *Crop Response To Pest Injury* (D)

The relationship between injury and crop yield (or utility) is the most fundamental component of the EIL. This relationship provides the biological foundation upon which consideration of economic and practical constraints can be superimposed. Virtually all theoretical and practical attention to the injury/crop-response interaction has been limited to plants. Indeed, our frequent inability to describe these interactions with veterinary and medical pests is one reason EILs are often unavailable or inappropriate for such species. Therefore, our discussion is limited to the relationship between injury and plant response. Unfortunately, this area of research has been neglected, particularly by entomologists (5, 20, 57).

A generalized description of crop response to pest injury was provided by Tammes in 1961. Subsequently, many workers have expanded on Tammes's model and have further characterized the association between yield and injury. An excellent review of damage from insect injury was provided by Bardner & Fletcher (5), and more recent considerations can be found in Poston et al (64) and Fenemore (20).

Many authors have pointed out the complexity of the interaction between crop response and injury (5, 20, 34, 64, 87). Fenemore (20) identified five major factors that are involved in this relationship: (a) time of injury with respect to plant growth, (b) part of the plant injured, (c) type of injury, (d) intensity of the injury, and (e) environmental effects on the plant's ability to withstand injury.

TIME OF INJURY The time in a plant's growth cycle when injury occurs has an obvious influence on the plant's response to the injury. Generally, seedling plants are most susceptible to injury, whereas young, but not seedling, plants are better able to tolerate or compensate injury. Similarly, plants are very susceptible to injury while yield-producing organs are forming, but when plants are mature injury usually has much less effect (unless the yield-producing structures are injured directly) (5, 20). The timing of pest injury is most often accommodated in EILs by calculation of a separate yield-loss/injury function (and therefore, separate EIL) for each stage of crop development (e.g. 13, 82, 90).

PLANT PART INJURED The part of the plant injured also influences a plant's response. Usually a distinction is made between injury to yield-forming organs (direct injury) and injury to non–yield-forming organs (indirect injury) (20). Most EILs are calculated for only one type of injury because most pests do not produce both direct and indirect injury simultaneously.

Few researchers have considered how plants respond to indirect injury at different locations on the plant (5). But when studies have been conducted, significant differences in yield response have been noted for injuries at different plant sites. For example, Chiang (11) noted different yield responses from maize infested with *Ostrinia nubilalis* at different internodes, and Higgins et al (36) and Ostlie (59) both noted different soybean yield responses to defoliation in different canopy strata.

INJURY TYPES The possible types of injury were discussed previously. It is important to emphasize that the nature of the injury is fundamental to a plant's response to different intensities of that injury.

INTENSITY OF INJURY Unquestionably, the relationship between the intensity (amount) of injury and plant yield is the most important factor in the crop-response/injury interaction. Tammes (87) first recognized the generalized response curve, or damage curve, which was subsequently modified by Fenemore (20). The damage curve describes the theoretical relationship between yield and injury (Figure 2*a*). Not all plants will manifest an injury response that includes every portion of the damage curve, but all potential responses can be described by some part of the damage curve. Tammes did not specifically name or describe the various regions of the damage curve, although later authors labelled some parts (5, 20, 64, 76). To precisely define a plant's response to injury, it is important to have a specific terminology that directly relates to the damage curve. Because no comprehensive terminology has been developed, we have devised the following terms for plant responses in specific areas of the generalized curve (each area is described by a different $x$; see Figure 2*a*):

$x_1$: **Tolerance**—no damage per unit injury; yield with injury = yield without injury; $f(x_1)$ = a constant (zero slope);

$x_{2a}$: **Overcompensation** (stimulation)—negative damage (yield increase) per unit injury; $f(x_{2a})$ = curvilinear relationship, positive (decreasing) slope;

$x_2$: **Compensation**—increasing damage per unit injury; $f(x_2)$ = curvilinear relationship, negative (decreasing) slope;

$x_3$: **Linearity**—maximum (constant) damage per unit injury; $f(x_3)$ = linear relationship, negative (constant) slope;

$x_4$: **Desensitization**—decreasing damage per unit injury; $f(x_4)$ = curvilinear relationship, negative (increasing) slope;

$x_5$: **Inherent Impunity**—no damage per unit injury; yield with injury < yield with no injury, $f(x_5)$ = constant (zero slope).



These responses apply to individual plants and to plant stands; however, the responses displayed by a plant and its plant stand are likely to differ. Generally, individual plants display less of the early portions of the damage curve, but plant stands have a greater ability for tolerance, compensation, and overcompensation (22, 36). Therefore, these three responses are more frequently observed with plant stands than with individual plants. Because EILs usually are developed for plant stands (e.g. numbers per row-meter) and not single plants, the stand response to injury is of primary importance in calculating EILs.

The last two responses in the tail of the curve, desensitization and inherent impunity, frequently do not occur in individual plants or plant stands. When they do exist, economic injury usually occurs at injury levels much lower than those associated with desensitization and inherent impunity. Therefore, these two responses are usually unimportant with respect to EILs and, consequently, are often unrecognized or neglected. However, aphid damage usually is described solely by the desensitization portion of the damage curve (Figure 2*b*) (83, 92). An important distinction must be emphasized between desensitization and what has been called competition or interference between pests (5, 20). Desensitization is a diminishing yield response to additional increments of injury; competition between pests occurs when increasing numbers of pests produce a diminishing effect on yield. In this latter instance, large numbers of pests produce less injury per pest; therefore, the reduced yield response simply follows reduced injury.

Although inherent impunity is not often observed, it may be important in determining how to define yield. For example, the citrus rust mite, *Phyllocoptruta oleivora,* on citrus may produce only a slight yield reduction (fresh weight) followed by little further reduction regardless of mite density (49). The damage curve for such a relationship would correspond to the solid line in Figure 2*c*, representing a minor yield reduction followed by inherent impunity

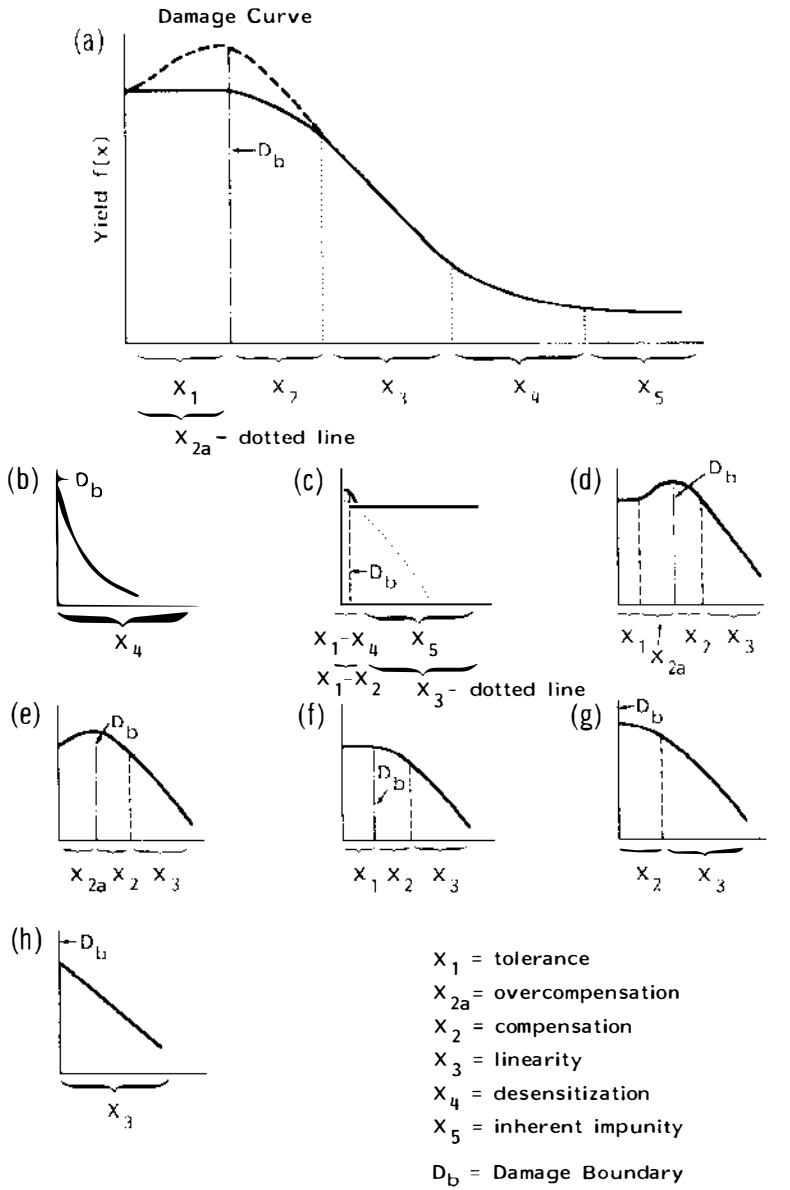


*Figure 2* General (*a*) and specific (*b-h*) forms of the damage curve.

(in this case to mite injury). But if yield is redefined to include appearance, the damage curve is so radically altered that inherent impunity may not appear at all (dotted line, Figure 2*c*). Thus, the precise definition of yield is an important determinant of the shape of the damage curve.

Tolerance and overcompensation (stimulation) probably occur more frequently than desensitization or inherent impunity, but these responses may not be particularly large and may be masked by environmental effects. Additionally, tolerance and overcompensation (Figure 2*d*) often occur at low injury levels relative to economic injury and consequently are overlooked. Probably all plants display some degree of tolerance to any indirect injury, but overcompensation is not as widespread. Nevertheless, many examples of overcompensation have been documented (e.g. 4, 22, 39, 44, 45, 73, 89).

When overcompensation occurs, it produces a response curve like Figure 2*d* or 2*e*. More commonly, responses like those in Figures 2*f*, 2*g*, and 2*h*, combinations of tolerance, compensation, and linearity, are obtained for calculating EILs. Most plants will respond to some level of indirect injury with compensation. Compensation implies that the plant or plant stand is able to prevent the injury from having its maximum effect on yield. In contrast, linearity represents a direct relationship between injury and yield loss. Overcompensation and compensation are primarily limited to indirect injury. An entirely linear response, on the other hand, is characteristic of direct injury, although linearity is also frequently reported for indirect injury (36, 55, 59, 68).

Our ability to distinguish the various responses comprising the damage curve depends largely on the resolution of our experimental techniques (35, 37, 60). As Poston et al (64) have pointed out, some responses to injury may be unrecognized because injury/yield relationships are tested for only a portion of the damage curve. However, by ignoring the total spectrum of injury to which a plant is exposed, we increase the danger of making false assumptions regarding a plant's response to injury. Therefore, extrapolations and conclusions based on data only from regions of the damage curve with economic injury must be constrained.

ENVIRONMENTAL EFFECTS As Tansky emphasizes (88), the environment can be a primary determinant in how plants respond to injury. Within a given season, environmental factors may influence how long a plant remains susceptible to a specific type of injury (1). Similarly, between seasons, a plant's response to the same level of injury may be drastically altered. For example, Higgins et al (36) found a twofold reduction in soybean yield loss per *Plathypena scabra* insect equivalent compared with findings of Hammond & Pedigo (28) at the same location with the same experimental techniques but under different environmental conditions. Such extreme variability emphasizes the need to calculate EILs over a range of environmental conditions. A better

approach probably would be to relate the EIL to various environmental or weather conditions (e.g. 61).

## IMPLEMENTATION OF THE EIL THROUGH THE ET

Although the EIL represents the critical level of damage relative to current biological and economic circumstances, the operable decision criterion is the ET. The ET is a direct function of the EIL and, as such, is subject to changes in EIL variables. In addition, the ET varies with logistical considerations associated with time delays that may vary from one situation to another. Therefore, implementation of the concepts of the EIL through the ET has been a difficult and rather inexact process. A clear understanding of the theoretical significance and practical relationship of the ET and the EIL is necessary before these decision indices can be implemented successfully.

For the purpose of standardization, we will accept the original ET definition as proposed by Stern et al (80) with minor modifications. To more accurately describe the time element, we refine the ET as "the injury equivalency of a pest population corresponding to the latest possible date for which a given control tactic could be implemented to prevent increasing injury from causing economic damage." Because the ET inherently considers the proper timing of a control, an implicit risk (known probability of occurrence) or uncertainty (no known probability of occurrence) is involved with assuming that pest-induced injury will reach or exceed the EIL. If that assumption proves erroneous, the cost of applying the control will not be totally offset and a net loss for the activity will be realized. Furthermore, we emphasize that our ET definition does not necessarily describe the optimal time of control. For instance, when the ET lies above the damage boundary, a monetary loss will accrue before the ET is reached that will not conform to the original break-even point (gain threshold).

If the ET and EIL are expressed in injury equivalents, both the population density and age structure of a population can be considered in describing a population's injuriousness. As an example of an injury-equivalency calculation, consider foliage consumption by *Plathypena scabra* larvae. Experiments by Hammond et al (29) established the mean consumption for each larval stage. These data, presented in Table 1, form the basis for determining injury equivalents. The equivalence coefficient per stage, when multiplied by the number of larvae in that stage, yields the number of injury equivalents for that stage. The sum of the equivalents per stage for all stages is the total number of injury equivalents (IE), or equivalency, at a given time and can be compared to the EIL expressed in injury equivalents. The formula for calculating injury equivalents for a sample is:

$$IE = \sum_{i=1}^{n} e_i \cdot x_i, \qquad 6.$$

where $e$ = the equivalency coefficient at stage $i$; $x$ = the number of insects (damaging stages only) per sample in stage $i$; $n$ = the total number of damaging stages for a pest ($n = 6$ for *P. scabra*). The total level of injury equivalents at a point in time is a function of both the population density and the population age structure. For example, a sample containing 12 second-stage, 6 fourth-stage, and 2 sixth-stage *P. scabra* larvae would have a current injury equivalency of 2.86 [IE = 12(0.0221) + 6(0.1000) + 2(1.0000)]. The fact that most species do not cause injury uniformly over their life period necessitates the use of an equivalency system to characterize pest populations.

The population dynamics of the pest must be estimated before accurate ETs can be calculated. Consider, for example, a pest species such as *P. scabra*, which has discrete generations and a known equivalency relationship on soybean. Once the oviposition period has passed, the resulting generation has a finite number of individuals capable of injuring the crop. As the larvae develop, their equivalence coefficients increase with increasing consumption rate. This produces two contrasting responses. First, the increase in larval size has the same effect on the soybean plant as increasing larval density; thus progress is made toward reaching the EIL. Second, natural mortality from biotic elements (such as predators, parasitoids, and pathogens) and abiotic elements (such as humidity and temperature) act on this finite population to reduce its overall rate of consumption (injury). Figure 3 illustrates a typical *P. scabra*-soybean relationship in Iowa. The EIL for this insect on soybean at different growth stages has been calculated (82) and recently refined (36, 61). As expected, the

**Table 1** *Plathypena scabra* leaf consumption ($cm^2$) and equivalence coefficients on soybean leaves for each larval stage

| Larval Stage[a] | Consumption[b] ($cm^2$) | Fraction of total consumption per stage | Equivalence coefficients per stage |
|---|---|---|---|
| 1 | 0.466 | 0.0086 | 0.0086 |
| 2 | 0.728 | 0.0135 | 0.0221 |
| 3 | 1.411 | 0.0262 | 0.0483 |
| 4 | 2.784 | 0.0517 | 0.1000 |
| 5 | 7.943 | 0.1474 | 0.2474 |
| 6 | 40.563 | 0.7526 | 1.0000 |
| Total = | 53.895 | 1.0000 | |

[a]A 7th stage has been reported to occur 24.2% of the time (93). Therefore, 6th stage includes any 7th-stage larvae that were found.

[b]Consumption of field grown leaves.

EIL changes throughout the season relative to the susceptibility of the host. When we superimpose a typical *P. scabra* growth curve, the ET can be estimated in relation to the EIL. The equivalency function represented by line *a* is representative of a population that will develop enough equivalents to surpass the EIL at point *A*. Inasmuch as it may not be possible to determine the injury curve a priori, the seasonal progress can be estimated and projected by sampling throughout the season (points *B, C,* and *D*). On each date the potential equivalency should be determined for a sample by calculating the equivalency with all equivalence coefficients set equal to one. If this potential equivalency is less than the EIL, sampling is continued. If the potential equivalency of the sample equals or exceeds the EIL, then the change in the equivalency through time, the equivalency rate, should be considered. If the equivalency rate is assumed (at least in the short run) to be linear from the last sample date to the EIL, then a projected date of EIL attainment can be estimated. The formula for estimating the equivalency rate between two sample dates is:

$$\text{IE/day} = \Delta \text{ IE} / \Delta \text{ days} \qquad 7.$$

where, IE/day = the estimated equivalency rate per day (represented by line *DE* in Figure 3); Δ IE = the difference in the observed (sampled) number of insect equivalents from the two sample dates (represented by line *DI*); Δ days = the difference in the actual number of days between the two sample dates (represented by line *CI*).

The number of days (line *DG*) remaining before reaching the EIL ($\text{DAYS}_{\text{EIL}}$) can be calculated using the estimated rate function equation 7:

$$\text{DAYS}_{\text{EIL}} = \text{IE}_r \cdot (\text{IE/day})^{-1} \qquad 8.$$

where $\text{IE}_r$ = the number of injury equivalents remaining between the EIL and the last sample date (represented by line *EG*). The difference in days between points *A* and *E* represents the error attributable to estimating a curvilinear growth function with a linear function based on two points.

The equivalency rate (IE/day), when multiplied by the number of days required to suppress a population, indicates the minimum number of injury equivalents between the EIL and the ET. For example, if the total delay associated with a particular control is represented by line *HF* (measured in days) and the rate of growth is determined by the slope of line *DE* as before, then the ET is represented by the number of injury equivalents at point E minus the number of equivalents between points *E* and *F*.

Several postulates are evident from this geometric analysis. Producers who are averse to risk should sample frequently until they are certain that the date of reaching the EIL is later than the final date of crop susceptibility (in which case no action is necessary). Hence, the chance of making an incorrect ET calcula-

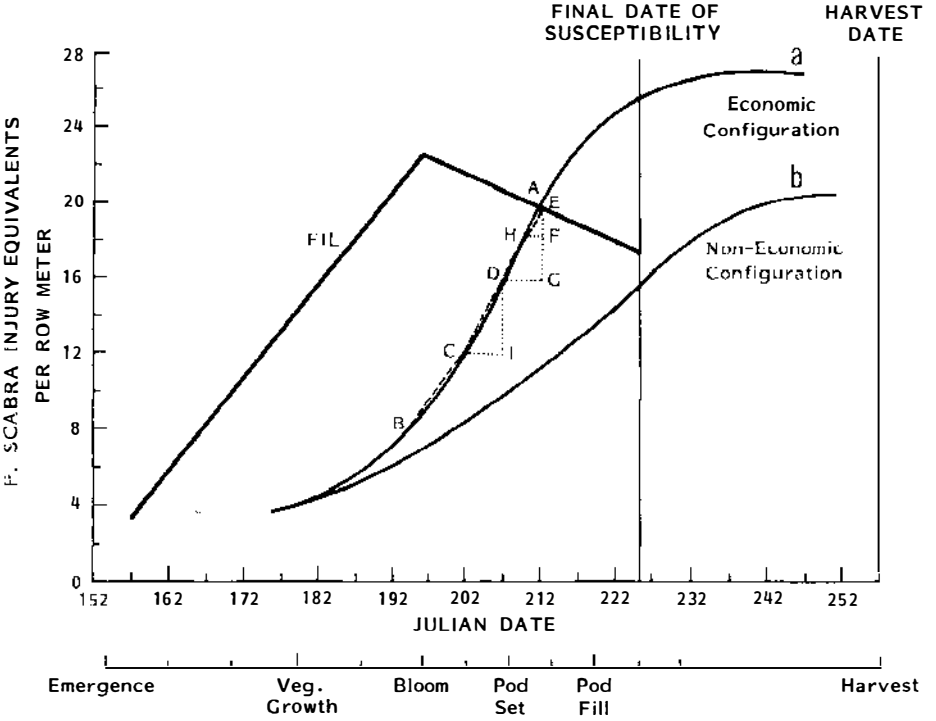


*Figure 3* Example of estimation of the economic threshold for *Plathypena scabra* on soybean.

tion decreases with time. An important characteristic of our model is that as the rate of injury equivalency increases, the interval between the EIL and ET also increases, reflecting the relative need for immediate action. Furthermore, any a priori knowledge of the growth function can be utilized to refine the method of calculating IE/day. By using curvilinear forms of growth functions with equivalency data for three or more sample dates, it may be possible to project equivalency rates with greater accuracy.

As mentioned, natural mortality impacts directly on the growth rate of the injury curve. Stern et al (80) referred explicitly to the concept of preserving or even augmenting beneficial populations as a means of reducing pest levels and perhaps avoiding or delaying pesticide use. They failed, however, to provide a practical method of quantitatively adjusting pest growth with natural mortality. Chiang (12) presented one of the earliest conceptual and quantitative descriptions for the role of natural mortality in ET estimation. More recently, Ostlie (59) introduced a methodology that accounts for the natural mortality of a pest species by using insect life tables. Rather than assuming 100% survivorship, Ostlie calculated the future injury from an individual at stage *i* as the summed product of survivorship in future stages and its associated injury

potential during those stages. This approach, when combined with flexible survivorship confidence limits to account for differences in acceptable risk levels, is very useful for estimating the actual level of injury and represents an advance in the ET concept.

Regardless of the methodology associated with determining the current and future levels of injury equivalents, the actual "threshold" level of equivalents at which a control tactic should be employed depends upon the nature of the tactic itself. Ideally, several ETs would exist, one for each type of control tactic. Each control tactic should be characterized by a series of time delays: (*a*) decision delay, (*b*) implementation delay, and (*c*) suppression delay. To accurately establish ETs relative to EILs, some calculation (estimation) must be made to determine an overall time delay based on the sum of individual delays. As the delay period increases, the distance between the EIL and ET also increases, resulting in a greater probability that the accelerating pest injury will not reach the EIL as anticipated. Therefore, the control tactic that has the shortest time delay (usually insecticides) probably will be the least risky.

As pest management becomes more complex through consideration of multiple generations and/or multiple pests, the concepts of the EIL and ET also become more complex. Although the paradigm presented in Figure 3 reasonably describes the decision parameters involved in ET development for a single-generation pest, it may fail to convey the problems associated with multivoltine pests. Because resurgence or recolonization of a pest population may occur immediately after a control action, the early use of a control for a sub-ET population may result in an additional population peak and subsequent need for suppression at the end of the season. If, however, resurgence is not probable, then early control could prevent injury that would have been sustained beyond the damage boundary but before the ET, and a net profit could be achieved.

## LIMITATIONS OF THE EIL

A number of authors have recognized the limitations of the EIL (e.g. 64, 75). In particular, these limitations relate to the types of pests or injury that can be addressed, the control tactics used, the research requirements, and the use of multiple criteria (e.g. many pest species and variable environments).

Decision levels for the control of many pests cannot be determined with EILs. Many vectors, medical pests, veterinary pests, and pathogens do not evidence a quantitative relationship between damage and injury and, therefore, are not amenable to calculation of EILs. Additionally, because the "market value" of human health and life is priceless, it is virtually impossible to put an economic limit on the control of most medical pests.

Aesthetic considerations also limit our ability to use EILs for some pests. It is often difficult or impossible to place a monetary value on the reduction in aesthetic value associated with a given type of pest injury. Moreover, any assigned values are necessarily subjective, which greatly hinders their usefulness for calculating EILs. Urban pests, which often produce aesthetic injury, comprise one group for which estimation of economic criteria in the EIL is frequently constrained. Additionally, EILs for urban pests often are further complicated by the lack of any injury/crop-response relationships. Instead, the problem may be one of mere presence of the pest. EILs do not seem to offer a means of reducing the large amounts of insecticides used for urban pests because the requirements for calculating traditional EILs cannot be met for most of them. Some authors have suggested the use of an "aesthetic injury level" for certain urban pests (56, 94), but the aesthetic injury level has not been defined in any quantitative sense and essentially consists of only a name.

A similar dilemma exists with forest pests. Pests of fruit, Christmas trees, and similar short-term forest commodities may be amenable to EILs, but other forest pests are not easily described by them. Almost all the components of EILs are difficult or impossible to estimate for forest pests. Accurate market values are often inestimable because of the difficulty in forecasting prices many years in advance; control costs may be very large and frequently must include more environmental and social costs than in other pest management systems; and the injury/crop-response relationship may be abstruse because the growth of the crop spans many years.

Some pests that do have a quantitative relationship to yield still cannot be described with EILs. For example, the yield reduction produced by many pathogens often is related quantitatively to the number of pathogens. Unfortunately, sampling and quantifying of the amount of these pathogens is frequently impractical. Thus, the practical question of whether pests can be easily sampled may determine the feasibility of using EILs. Furthermore, controls for many pathogens are preventative, not curative; therefore, determining whether or not a pathogen population is at the EIL after infection may not be of significant value if the only control options available must be used before infection.

This last example highlights an important limitation of EILs. As previously discussed, the EIL concept was originally developed with the objective of reducing insecticide use. Consequently, both the EIL and ET can be used most appropriately when a single, curative control action can be made. This is not to say that EILs and ETs cannot be, or are not, used to determine when to initiate preventative control measures, but their usefulness in such situations is restricted. Thus EILs and ETs have always found most application with insecticidal control measures.

The usefulness of an EIL and ET for determining when to initiate control is

based on the relationship of the pest population to the EIL. Management decisions for severe pests may not be significantly improved with EILs. However, EILs are useful in evaluating the performance of a control program.

Yet another drawback to the use of EILs is the substantial background research required. The calculation of the injury-per-insect and of the injury/plant-response relationships can be involved and lengthy. Moreover, these relationships may be quite variable, particularly under different environmental regimes. On the other hand, this research requirement, which we have listed as a limitation to the EIL, is also one of its strengths. Unlike many other management criteria, the EIL is firmly based on the biological relations between a pest and its host.

A final problem with EILs is their relative unsuitability for multiple pests. Use of an EIL and ET for management decisions involving many pests is considerably removed from the original use for which they were developed. However, the capacity for making appropriate management decisions with many pests or a pest complex is one important goal of integrated pest management. Possibly, the EIL and ET will lose their usefulness at this level of refinement. But if injuries from different pests produce the same host response and all injuries can be placed on a common basis, or if effects of different injuries are additive and not interactive, the EIL and ET may find application for multiple pests.



## FUTURE OUTLOOK

Many approaches have been suggested for decision making in insect pest management, but none has been as pervasive as the EIL concept of Stern et al (80). Although the EIL concept is not without limitations, most would agree that it continues to offer a practical approach to pest-related decision making in a broad sense. Crucial to the question of practicality is the type of pest involved and the availability of information on both the pest and production system. In organizing available information for development and implementation of the EIL, Poston et al (64) recognized four categories under which most existing and anticipated programs fall (Figure 4). From the original Stern et al (80) theory, research has progressed to definition of the primary EIL components and has produced calculated levels for single species on which many present ETs (simple thresholds) are based. Such developments represent the state-of-the-science for this concept. However, many questions remain unanswered in the attempt to develop truly comprehensive thresholds.

Perhaps the best method for approaching comprehensive thresholds through the EIL is by examining the host response to injury. Theoretically, this examination must emphasize the host physiology and physiological responses to injury. Practically, an improved understanding of physiological responses to

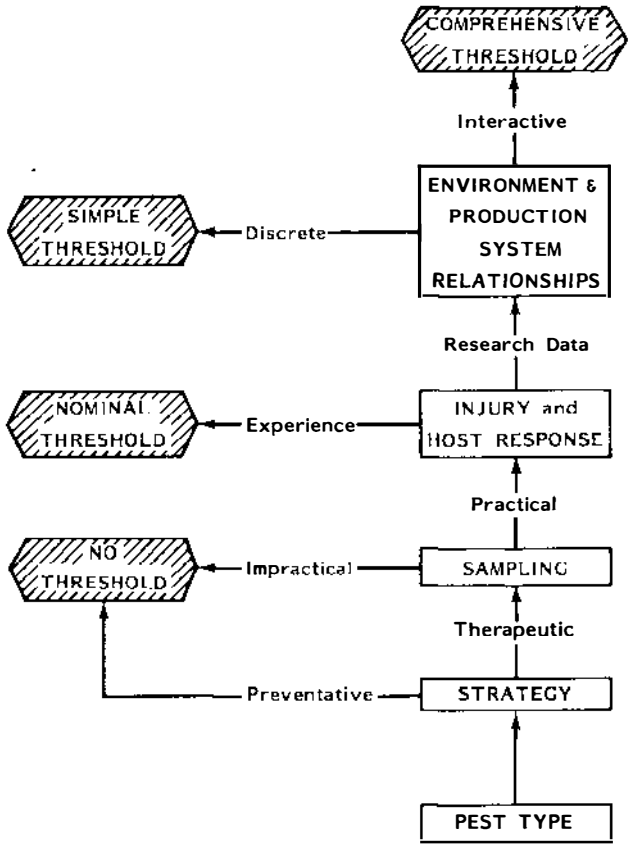


*Figure 4* Implementation categories of the economic threshold, after Poston et al (64).

injury may be incorporated into EILs by developing standard equivalents for guilds of species with similar injuries. Thus, a single EIL in standard equivalents could serve for a complex of pests having the same type of injury. Such an approach would permit the use of EILs for many multiple pest situations. However, multiple pests causing different types of injury probably could not be described with standard equivalents. At this level of sophistication, the EIL concept becomes "conceptually fatigued" (64) and must be either significantly refined or replaced. The challenge is to develop management indices that not only consider how multiple pests impinge on and interact with a host's physiology but that also are simple to use.

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