known to be unusually susceptible to pest attack, thereby intensifying the need for control activity. Conversely, crops should be grown in a manner to avoid or reduce difficult pest problems. It is necessary for the plant protectionist working with plant and soil scientists to insist on agroecosystem planning that satisfies the world need for food and at the same time minimizes pest problems and avoids catastrophic events. This concept does not condemn monoculture, nor does it reduce the efficiency of specialized technical agriculture. It does stress the importance of integrating crop production and crop protection systems.

CASE HISTORIES

The soybean, *Glycine max* (L) Merr., is well adapted to the midwestern United States, despite the presence of the destructive potato leafhopper, *Empoasca fabae* (Harris). Pubescent-type 'Harosoy' soybean plants grow waist-high without chemical protection from this pest, whereas glabrous-type 'Harosoy' soybean plants are so severely attacked that they attain a height of only 8–10 in. Typical stunting of glabrous (smooth, nonpubescent) varieties caused by the potato leafhopper is illustrated in Fig. 1.2. Planting pubescent soybean varieties adapted to the area is good agroecosystem planning. Reducing crop susceptibility to insect damage is one of the most effective and environmentally desirable tactics available.

A less obvious method is crop planting to avoid certain pests while anticipating and planning for others. Planting corn in rotation with other crops provides control of the western and northern corn rootworms, but it may aggravate other pest problems (Table 1.1). Petty (1972) shows that only the western corn rootworm, *Diabrotica virgifera virgifera* LeConte, and the northern corn rootworm, *D. barberi* Smith & Lawrence, increase where corn is grown continuously on the same acres, whereas white grubs, *Phyllophaga* spp., and the black cutworm, *Agrotis ipsilon* (Hüfnagel), increase when corn is grown in rotation with soybeans. There are 10 insects that increase when corn is grown in rotation with pasture and hay crops, but the insect pests that may increase in corn–soybean–hay crop rotations are collectively less important than the corn rootworms or they are occasional pests in only some fields in some years. Thus, in the U.S. corn belt corn rotation with a safe crop such as soybean or sorghum is a good corn rootworm-management tactic. However, a grower would anticipate a possible need to treat some fields for other soil pests when using the crop rotation corn rootworm-managment system.

C. Cost/Benefit and Benefit/Risk

Individual producers of food and fiber are faced with decisions concerning pest control. While the importance of these decisions varies with the crops produced, the method of production, and the geographical location of the production unit, almost every producer is required to do something about pests (Headley, 1982). Decision making in pest control involves economic facts and value judgments as to what ought to be done. In practice, decisions are based on considerations that are subjective, and personal bias is often

Figure 1.2 Typical stunting of glabrous varieties of soybean plants caused by the potato leafhopper.

part of decision making no matter how carefully the costs and benefits have been assessed. Further, farmers are becoming more concerned about the risks of their actions and about how society perceives their stewardship of renewable natural resources, soils, and water. Consequently, the economics of decision making in pest management is not concerned only with the dollars and cents of pest damage and control, but also with the goals and behavior of those who make pest-management decisions (Mumford and Norton, 1984).

1. ***Cost/Benefit*** Faced with the possibility of pest damage, the producer is interested in tactics that reduce that uncertainty, as long as the amount of expenditure is commensurate with the amount of the probable damage. By using pesticides the uncertainty of pest problems can be greatly diminished. However, applying a prophylactic insecticide treatment long before needed also involves uncertainty as to whether the pest will appear, how much damage the pest will cause, how well the insecticide will work, and the value of the crop that is threatened. Farmers should be willing to pay for information that reduces uncertainty, such as pest scouting and state Cooperative Extension Pest Alert Bulletins, because this information could reduce pesticide use and cost. Since pesticide use tends to reduce uncertainty, information could be substituted for pesticides, depending on costs and availability, to reach the same level of utility or satisfaction for a farmer (Feder, 1979; Mumford and Norton, 1984). Pest scouting, for example, requires more time in the field but it is very cost effective.

Perhaps the simplest and useful measure of cost relating to economic damage is the gain threshold illustrated and described by Pedigo (1989). He expressed it as follows:

$$\text{Gain threshold} = \frac{\text{Management costs (\$/acre)}}{\text{Market value (\$/unit)}} = \text{units/acre}$$

For example, if management costs (scouting, insecticide) equal \$10 per acre and the market value of a unit (pounds, bushels, bales, crates) is \$2, then the gain threshold is 5 units per acre, that is, the yield needed to equal costs. In agricultural the implication of yield increase, often used to show benefit from treatment, is usually erroneous. The use of pesticides rarely increases yield; rather, use prevents loss of yield.

In many agricultural pest-control activities the benefits are not known, as they are usually not measured, and the costs of prevention become costs of production. Improving capabilities for predicting pest problems and defining economic thresholds will place increased emphasis on costs and benefits. Crop life tables provide a solid foundation for the analysis of pest damage and cost/benefit in pest management.

CASE HISTORY

Crop life tables provide excellent guidelines in the planning of pest-management strategies, particularly when coupled with meaningful cost/benefit analysis. Harcourt (1970) presented a typical life table (Table 1.2) and loss statistics (Table 1.3) for a planting of early-market cabbage. In Table 1.2 the first column gives the sampling period, namely, the stage of growth attained. The *lx* column represents the number alive (or potentially marketable) at the beginning of the period, and the *dx* column the number dying (or "written off") within the period. The *dxF* column shows the agent or factor responsible for *dx*, and 100*rx* is the percentage mortality based on the initial population. It is obvious that the young plants have the highest mortality and that cutworms, cabbage caterpillars, and root maggots were major mortality factors. Insects caused losses of \$317.47, diseases \$34.18, and miscellaneous factors (mechanical damage, rodents, weather, and so on \$26.01. The operating profit at \$436.30 was just over 50% of potential revenues at the time of planting.

*2. **Benefit/Risk*** The social economics of pest control are necessary considerations in developing pest-control strategy, particularly when pesti-

Table 1.2 Life Table for a Planting of Early-Market Cabbage, Ottawa, 1968

Growth Period, *x*	Mean Number Living Per Plot, *lx*	Mortality Factor, *dxF*	Mean Number Dying per Plot, *dx*	Percentage Mortality, 100*rx*
Establishment	319.2 ± 4.2	Drought	7.2 ± 1.0	2.2
		Cutworms	56.1 ± 7.1	17.6
		Root maggot	1.5 ± 0.4	0.5
		Other[a]	0.8 ± 0.3	0.3
		Total	65.6 ± 7.1	20.6
Preheading	253.6 ± 6.0	Cutworms	8.6 ± 1.1	2.7
		Root maggot	9.6 ± 1.7	3.0
		Flea beetles	0.3 ± 0.1	0.1
		Rodents	1.3 ± 1.0	0.4
		Clubroot	1.3 ± 0.8	0.4
		Other[a]	0.9 ± 0.2	0.3
		Total	22.0 ± 4.5	6.9
Heading	231.6 ± 7.1	Cabbage caterpillars	29.4 ± 1.0	9.2
		Root maggot	0.6 ± 0.1	0.2
		Clubroot	3.2 ± 1.6	1.0
		Soft rot	0.4 ± 0.1	0.1
		Total	33.6 ± 1.7	10.5
Harvest	198.0 ± 6.7	Cabbage caterpillars	18.4 ± 2.2	5.8
		Clubroot	5.5 ± 1.8	1.7
		Soft rot	3.0 ± 0.5	0.9
		Total	26.9 ± 2.1	8.4
Yield	171.1 ± 7.1		148.1 ± 4.5	46.4

[a] Miscellaneous factors such as frost, hail, and mechanical damage.

Source: Harcourt (1970). Courtesy of D. G. Harcourt and the Entomological Society of Canada.

cides are used. Benefit/risk analysis provides a means for assessing the relevant economic benefits versus the risks in pest control. The consideration and assessment of benefit/risk is fundamental to pest management. A grower carefully considers the hazard of a highly toxic pesticide and takes action to ensure safety for himself and his workers in handling and in application. Similarly, a grower must consider the effects on society and on the environment of a pesticide that is applied. Higley and Wintersteen (1992) propose estimating environmental costs of using pesticides through contingent valuation, that is, opinion surveys used by economists for estimating the value of nonmarket goods, such as environmental quality. Results from the model these authors have developed indicate that use of environmental EILs (Economic Injury Level) could reduce pesticide use and improve pesticide selection.

The use of insecticides when they are not needed is contrary to pest-management philosophy. The treatment of 1 million acres when only 100,000

Table 1.3 Operating Statistics for a Planting of Early-Market Cabbage, Ottawa, 1968

Growth Period	Potential Revenue ($/acre)	Hazard	Loss of Revenue ($/acre)
Establishment	$813.96	Drought	18.36
		Cutworms	143.05
		Root maggots	3.83
		Other	2.04
		Total	167.28
Preheading	$646.68	Cutworms	21.93
		Root maggots	24.48
		Flea beetles	0.76
		Rodents	3.32
		Clubroot	3.32
		Other	2.29
		Total	56.10
Heading	$590.58	Cabbage caterpillars	74.97
		Root maggot	1.53
		Clubroot	8.16
		Soft rot	1.02
		Total	85.68
Harvest	$504.90	Cabbage caterpillars	46.92
		Clubroot	14.03
		Soft rot	7.65
		Total	68.60
Operating profit	$436.30		

Source: Harcourt (1970). Courtesy of D. G. Harcourt and the Entomological Society of Canada.

acres needs protection imposes risks that exceed the benefits. Furthermore, chemical treatment is seldom a process so efficient that all the input is fully utilized. As a rule, more than 90% of the insecticide applied to control insects does not hit the target pest, and becomes incorporated into the environment in various ways. Parasitoids and predators are reduced. Persistent pesticide residues concentrate in foods and in the environment. These additional unwanted nonmarket effects are called *externalities*. Externalities have adverse economic, ecological, and sociological consequences. An example is the magnification of DDT in fish in Lake Michigan, from about 0.000002 ppm in the water to as much as 15 ppm or more in game fish, so that the U.S. Food and Drug Administration (FDA) has declared these fish illegal for commercial sale for human consumption (see Chapter 6). Another example is the presence of persistent residues in soil at levels high enough that subsequent crops grown in these soils may be legally unacceptable in the marketplace. The oil in soybean grain and the waxy rind and seeds of pumpkins can contain objectionable residues of lipid-soluble pesticides when these crops are grown on soils that were treated in previous years and still contain residues of organochlorine insecticides (Bruce et al., 1966, 1967).

Insecticides are not the only pesticides causing unwanted environmental and sociological problems. The Illinois Environmental Protection Agency tested 129 surface water drinking supplies in 1991 and 128 supplies in 1992. It found that over 100 community water supplies contained either atrazine or alachlor, which are commonly used herbicides in corn fields. The level of atrazine exceeded EPA's drinking water standard of 3 parts per billion (ppb) in 17 communities during both 1991 and 1992. None of the communities had detections exceeding the limits of 2 ppb alachlor, although one community had a sample in 1991 that equaled that level (WATERlines, 1993).

D. Tolerance of Pest Damage

Complete freedom from insect attack is neither necessary in most cases for high yields nor appropriate for insect pest management. Nearly all plants can tolerate a substantial degree of leaf destruction without appreciable effects on plant vigor. One needs only to examine the holes, blotches, and mines in the leaves of healthy forest trees to appreciate this statement. Quantitative studies of the degree of damage versus reduction in corn yield are urgently needed so that thresholds can be established for allowable damage. In assessing this factor it should also be remembered that an important exception occurs in the case of plant diseases transmitted during a brief feeding period, sometimes as short as 15 seconds, by an insect vector.

1. Economic Injury Level This quantitative measure of insect pest density determines whether an insect component of an agroecosystem is to be classified as a pest. Without an estimate of the pest density that can be tolerated without significant crop loss, there can be no reasonable safeguard against either overtreatment with insecticides or unacceptable crop damage. This determination of the economic injury level, which can vary during the cropping season in plants grown from seedling to maturity, is critical in defining the ultimate objective of any pest management program and in delineating the pest population level below which damage is tolerable and above which specific interventions are needed to prevent a pest outbreak and to avert significant crop injury.

The concept of the economic injury level (EIL) was first articulated by Stern et al. (1959), who defined it as the "lowest population density that will cause economic damage." Other definitions include "a critical density . . . where the loss caused by the pest equals the cost of available control measures" (NAS, 1969). Headley (1972) defined the EIL as the "pest population that produces incremental damage equal to the cost of preventing damage." Thus, the EIL predicts future crop damage (yield loss) based on present pest densities and/or crop injury. Pedigo and Higley (1992) emphasized that the EIL, although conveniently expressed as a level of pest density, is actually a level of injury indexed by pest numbers. Consequently, it can be expressed in injury units or injury equivalents.

Where crop injury and yield loss are linearily related a generalized EIL model has been proposed by Pedigo et al. (1986):

$$\text{EIL} = \frac{C}{VID}$$

where EIL = number of insects per production unit
C = cost of management activity per production unit
V = market value per unit of yield (for example, $ per lb)
I = injury units per pest production unit (proportion of defoliation per insect per acre)
D = damage per unit of injury (yield loss per acre or proportion defoliated)

Although it is generally assumed that the efficiency of the pest-control intervention approaches 100%, this is not always the case and an additional factor K = proportional reduction in pest attack can be factored into the denominator. Other refinements may also be included to compensate for the externalities of environmental quality costs from pesticide application (Higley and Wintersteen, 1992). Thus, the environmental EIL becomes:

$$\text{EIL} = \frac{\text{PC} - \text{EC}}{VDIK}$$

where PC = pesticide and application costs
EC = environmental costs
D = yield loss as a function of total crop injury
I = crop injury per pest density
K = proportionate reduction in injury from pesticide use

2. *Economic Threshold* The economic threshold (ET) is the most important parameter in pest-management decision-making and represents the "action threshold" for decision-making in applied control. ET is the density of a pest population that will justify treatment. It was first defined by Stern et al. (1959) as the "pest density at which control measures should be applied to prevent an increasing pest population from reaching the economic injury level (EIL)." The ET typically represents a pest density lower than that of the EIL to allow the initiation of control measures so that they can take effect before the pest density exceeds the economic injury level. These relationships are shown in Fig. 1.3. There are four categories of economic thresholds:

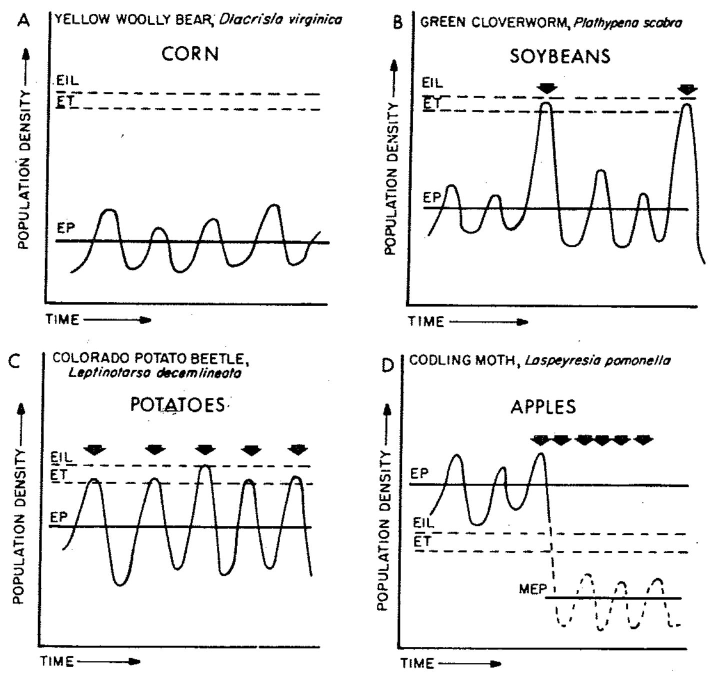

Figure 1.3 Economic injury levels (EIL) and economic thresholds (ET) for typical insect pest situations: EP, equilibrium position; MEP, modified equilibrium position; arrowheads, pest-control intervention. (Modified after Stern (1965).)

1. *Nonthresholds* The pest population is always greater than the EIL; typical of vegetable and fruit crops with extreme cosmetic requirements, where applied control is used as a crop production insurance, or where crops are highly susceptible to transmission of insect-borne diseases.
2. *Nominal thresholds* The relationships between pest injury and crop damage are undetermined so that EIL values cannot be calculated. This is the situation for the majority of small vegetable and fruit crops. Estimated ETs based on experiment station and extension research and producer experience will reduce the indiscriminate use of insecticides and aid in the development of IPM programs.
3. *Simple thresholds* ET values are calculated from EIL values based on generalized insect injury and crop response data. These ETs are those that are currently considered the best current practice for important commercial use.
4. *Comprehensive thresholds* ET values are calculated from dynamic EILs developed from research involving variations in economics, pest injury, and crop response over the life of the crop phenotype. Such ETs are currently under development for major crops.

These theoretical relationships are important in establishing the basis for the determination of sound EIL levels that will ultimately reduce unnecessary pesticide use. The fundamental relationship between pest and crop injury (*V*), crop damage per injury unit (*I*), and proportionate reduction in pest attack (*K*) are well understood for only a few major crops and specific pest species. Moreover, the externalities involved in determining the environmental costs (EC) associated with pesticide use vary greatly with the use of individual pesticides and their integration with other pest-control interventions, such as biological control and cultural control. These are, as Pedigo and Higley (1992) put it, "an almost infinitely expanding web of benefits and costs associated with pesticide use. . . . [U]nfortunately trying to identify all of these costs and benefits is likely to entangle us within a web of confusion," within which the great benefits of the EIL concept to applied entomology may be lost.

3. General Equilibrium Position The general equilibrium position is the average population density of an insect population over a long period of time, unaffected by the temporary interventions of pest control. The population density fluctuates about this mean level as a result of the influence of density-dependent factors such as parasitoids, predators, and diseases. The economic injury level may be at any level from well below to well above the general equilibrium position. Insects can be grouped in four general categories in this regard, as shown in Fig. 1.3.

1. Many insect species feed on cultivated crops without ever reaching densities high enough to cause economic injury (Fig. 1.3*A*) and consequently are rarely if ever noticed. Familiar examples include the following: the cowpea aphid, *Aphis craccivora* Koch, on alfalfa; the yellow woolly-bear, *Diacrisia* (= *Spilosoma*) *virginica* (Fabricius), on corn; and the painted lady, *Vanessa cardui* (L.), on soybeans.
2. Another large group of insects are occasional pests (Fig. 1.3*B*), which exceed economic injury levels only when their population densities are affected by unusual weather conditions or the injudicious use of insecticides. Examples include forest insect pests such as the fall webworm, *Hyphantria cunea* (Drury), which becomes epidemic in 5- to 10-year cycles; the green cloverworm, *Plathypena scabra* (Fabricius), on alfalfa or soybeans, and the white-lined sphinx, *Hyles lineata* (Fabricius), of California deserts. At their peaks of population density some sort of intervention, usually insecticides, is required to reduce their numbers to tolerable levels.
3. A third group of insects has economic injury levels only slightly above the general equilibrium position (Fig. 1.3*C*), and intervention is necessary at nearly every upward population fluctuation. These insects are perennial pests, for example, the gypsy moth, *Lymantria dispar*, in

hardwood forests; the cotton boll weevil, *Anthonomus grandis* Boheman; the Colorado potato beetle, *Leptinotarsa decemlineata* (Say); and the Mexican bean beetle, *Epilachna varivestis* Mulsant, on beans. The general practice is to intervene with insecticides whenever necessary to produce a modified average population density well below the economic injury level (Fig. 1.3*C*).

4. Severe pests are found in a group of insects having economic injury levels below the general equilibrium position (Fig. 1.3*D*). Classic examples include the codling moth, *Cydia* (= *Laspeyresia*) pomonella (L.), on apples; the corn earworm, *Heliothis zea,* on sweet corn; the asparagus beetle, *Crioceris asparagi* (L.), on asparagus; and the artichoke plume moth, *Platyptilia carduidactyla* (Riley), on artichokes. Regular and constant interventions, usually with insecticides, are required to produce marketable crops.

The same insect pest attacking several crops may have greatly differing economic injury levels. *Heliothis zea* feeding on alfalfa never reaches a population density sufficient to cause economic injury and belongs in category 1. However, like the cotton bollworm, *Heliothis zea,* is a major pest of cotton, has an economic threshold of four larvae per plant (Stern, 1965), and generally requires insecticidal treatments several times yearly; thus, it belongs in category 3. *Heliothis zea* attacking sweet corn is a severe pest; it has an economic threshold approaching zero population density and falls in category 4.

Determining the economic injury level and economic threshold is generally a complex matter based on detailed operation of pest ecology as it relates to bioclimatology, predatorism, diseases, the effects of host-plant resistance, and the environmental consequences of applied control interventions. The economic injury level concept is flexible and may vary from area to area, crop variety to crop variety, and even between two adjoining fields, depending on specific agronomic practices (Reynolds, 1972). The economic injury level decreases as the value of the crop increases and is also a function of consumer standards. Thus, for tree fruits, sweet corn, asparagus, potatoes, cut flowers, and the like the threshold may be very low: A single codling moth, scale insect, or earworm attack drastically affects the consumer acceptance of produce. Changes in marketing developments, such as the rapid growth of the frozen-food industry, and FDA laws regulating the presence of insect fragments in canned food products can produce decisive changes in economic injury levels for vegetable and fruit crops. The economic injury level is inversely related to the product price and directly related to the cost of control (Headley, 1972).

For the individual grower, assuming no external costs, Rabb (1972) has suggested the following factors as essential for determination of the economic injury level:

1. Amount of physical damage related to various pest densities
2. Monetary value and production costs of the crop at various levels of physical damage
3. Monetary loss associated with various levels of physical damage
4. Amount of physical damage that can be prevented by the control measure
5. Monetary value of the portion of the crop that can be saved by the control measure
6. Monetary cost of the control measure.

From this information it is possible to determine the level of pest density at which control measures can be applied to save crop value equal to or exceeding costs of control. This simplified approach, however, does not consider important externalities, such as increasing soil pesticide residues, which may make subsequent crop production less profitable, or ecological effects on natural enemies, which may result in the increased frequency of pesticide intervention or in outbreaks of secondary pests. Therefore, economic injury levels for individual insect pests are almost always higher than superficial evidence suggests. In pest management great care must be taken not to equate the visual threshold with the action economic threshold, where the level of pest population is such that intervention must occur to prevent the population from rising above the economic injury level.

A special category of economic injury level must be applied to insects serving as vectors of plant and animal diseases. Here a single insect attack may cause the death of a valuable tree, a domestic animal, or a human. Examples include the smaller European elm bark beetle, *Scolytus multistriatus* (Marsham), and Dutch elm disease; tsetse flies, *Glossina* spp., and African trypanosomiasis; and *Aedes aegypti* (L.) and yellow fever. Economic values can scarcely be set for the costs of such depredations, and the economic injury level approaches zero population density.

CASE HISTORY

The soybean, a valuable protein and oil crop, is utilized worldwide as human food and as a supplement in livestock feeds. Brazil and the United States are the largest producers of soybean for domestic use and export. Many harmful as well as beneficial species of insects inhabit soybean fields. Fortunately, not all pest species appear in a field at the same time and the nature of the damage caused by insect pests depends on the plant part attacked and when attack occurs during the plant's growth cycle. The biology of a pest species and the dynamics of its life cycle meshed with the plant's susceptibility to injury at various stages during its growing period are critical in developing economic thresholds.

In Fig. 1.4, Kogan and Kuhlman (1982) have illustrated the complex of insect pests that can attack soybean in Illinois during the cropping season. A plant's