

Chapter 6

MODELING AND COMPUTERIZED DECISION AIDS

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INTRODUCTION

Entomologists have long recognized the challenge to acquire relevant information and effectively use it for problem solving; however, the complexities of entomological problems have frustrated these efforts. Insect problems in agriculture rarely are due to the occurrence of single species, a fact that is particularly true in cotton. Instead, they involve communities of plants and animals. Understanding multiple species and their interactions are difficult undertakings, partly because the methods of study have not been well defined. The same difficulty holds true in applying useful information to problem solving. Notwithstanding, events of the last forty years have provided new opportunities to gather and apply information.

During the period between 1920 and 1930, the boll weevil, *Anthonomus grandis grandis* Boheman, greatly curtailed cotton production in the Southeast, forcing it to the weevil-free areas of the West (Frisbie *et al.*, 1989). The situation changed after World War II, and the rapid development of agricultural chemicals and on-farm mechanization dramatically altered cotton production and pest management throughout the Cotton Belt. Initially, chemicals were relatively cheap and, as they increased in number and efficacy, farm production and profits rose. Mechanization, improved varieties and high inputs of pesticides, fertilizers and water brought on a "green revolution" in all of agriculture. At the same time, these changes institutionalized a near single-tactic approach to pest management. Inevitably, the heavy dependence on chemicals changed the way of doing business in crop production, agricultural research, extension and the chemical industry. Alternative management approaches, and the acceptance of some pest losses common before the war, were forgotten in a new generation.

The benefits of a single-tactic management system were soon being weighed against developing problems. These problems intensified over the years and included the destruction of nontargeted species (including beneficial arthropods, fish, birds and mammals) and the buildup of secondary pest populations. Pesticide resistance resulted in control failures, greater chemical usage, and increasing costs of control. Environmental contamination, such as that found in groundwater, ultimately led to public health concerns and pesticide registration cancellations. These serious consequences sparked a strong and lasting debate within the political, scientific, agricultural and lay communities that challenged farm management practices and its heavy reliance on chemicals. Increasingly, the unilateral approach to pest management came under attack because of the associated social, economic and environmental costs involved. To those who made their living from agriculture, the unsettling question arose—what to do next?

Managers of food and fiber resources often deal with insect pests in one of two ways: through direct control at times of crisis (e.g., during insect outbreaks) or through direct control when no control is needed (e.g., when insect populations are below thresholds or at endemic levels). In the first case, managers are willing to accept the risk of insect attack, a situation sometimes found in forestry because of the relatively low crop value. In the second case, managers are unwilling or unable to accept risk. They usually deal with crops of high value such as those found in production agriculture. Cotton is an excellent example.

Unfortunately, both management strategies are inappropriate, and economics are only partly to blame. Management problems often result from a lack of knowledge or an inability to access and effectively use existing knowledge. Thus, having information available in a general sense and not being able to access or use it effectively is a dilemma which affects all levels of crop production. This dilemma has hindered the application of integrated pest management (IPM) as it was originally conceived. Unlike single-tactic approaches, IPM requires a great deal of integrated information on the dynamic status of crops, insects, pest impact, control tactics and cost/benefits to determine the appropriate management alternatives. The inability to integrate, interpret and transmit meaningful information quickly to those who can use it has had no adequate solution until recently.

Just as synthetic chemicals transformed agro-management after World War II, another transformation in crop and pest management began in the late 1960s. By this time the political and social climate favored a major increase in research funding directed toward developing new approaches to agroecosystem management. In 1972, the National Science Foundation, Environmental Protection Agency (EPA), and the United States Department of Agriculture (USDA) sponsored a massive commitment to integrated pest management on six major cropping systems in the United States: alfalfa, apple, citrus, cotton, soybeans, and pine forests. Cotton was studied under the "Huffaker Project" (1972-1978), along with alfalfa, apple, citrus and soybeans. This project was replaced by the Consortium for Integrated Pest Management (CIPM) project which excluded citrus and was funded by the EPA from 1979-1981 and the USDA, CSRS (Cooperative State Research Service) from 1981-1985 (Frisbie, 1985).

These multidisciplinary research projects involved about 250 scientists from numerous universities, state experiment stations and federal laboratories across the country. Their primary goal was to develop socially and ecologically sound management systems that optimized the costs and benefits of crop production and protection. Such management systems would require a great deal of information on the various important components of the agroecosystem—on the dynamic status of the crop, pests and beneficials; on the environment; and, on the costs and benefits of making alternative management decisions. In addition, the information on the various system components had to be formulated in such a manner as to explain component interactions. Systems science and mathematical modeling were proposed to unify and describe the complex dynamic components and their interactions. Advancements in computer technology made this approach feasible.

SYSTEMS ANALYSIS AND POPULATION MODELING

Computers were emerging as a revolutionary new technology during the 1950s, with applications first in research and later in business. Like the rest of the research community, agricultural scientists quickly identified applications for this powerful tool. One prominent use was in areas of population ecology and modeling, fields heavily dependent on numerical analysis. By the early 1960s, a systems approach was gaining acceptance as the means for understanding, describing and studying crop ecosystems (e.g., see Watt, 1961, 1966; Clark *et al.*, 1967; Getz and Gutierrez, 1982). Watt (1966) defined a biological system as a group of interacting and interdependent components forming a unified whole. Components under study could be the cell, organism, population or community. IPM investigators endorsed the population level of organization because the combined effects of individual pests on a crop could best be explained using this level of complexity.

The processes of describing, explaining and controlling system behavior over time are collectively called systems analysis (Curry and Feldman, 1987). Getz and Gutierrez (1982) defined systems analysis somewhat differently, although appropriately for this discussion, as the application of quantitative and qualitative techniques that enhance the understanding of interactions among components of a crop-pest system and their relationships to the environment and management practices.

MATHEMATICAL FOUNDATIONS OF POPULATION MODELING

Reviews describing the mathematical foundations of population modeling in natural and agroecosystems are provided by Getz and Gutierrez (1982) and Curry and Feldman (1987). Early investigators interested in modeling interactive populations proposed a system of differential equations (Lotka, 1925; Volterra, 1926; Nicholson and Bailey, 1935). These models were not adequate to describe system components and their interactions because they ignored the age structure of populations and considered all individuals to be equal. Leslie (1945) developed a convenient mathematical form to describe the various age classes of a population using matrix algebra, but this discrete time approach modeled the mean value of population growth; e.g., indi-

dividuals of a cohort (those born at the same time) have identical rates of development. Using a system of partial differential equations, von Foerster (1959) proposed a continuous time model with age-dependent population growth.

Gutierrez *et al.* (1980, 1985) provided a historical review of specific modeling efforts in cotton. Early work concentrated on understanding plant physiology, especially as it relates to respiration and photosynthesis. This work led to the development of the cotton model, SIMCOT II — primarily a USDA, Agricultural Research Service (ARS) effort that provided mechanistic detail of the growth and development of a single (average) plant (Baker *et al.*, 1972; Jones *et al.*, 1974; McKinion *et al.*, 1974). This model predicted discrete numbers of squares and bolls (fruit) produced by a plant. Fruit production of a population of plants was estimated simply as the number of fruit per plant times the number of plants in the population. Because insects normally show oviposition and feeding preference to fruit of certain age classes, IPM investigators required that the number of fruit per area vary continuously among plants in the population. SIMCOT II ignored the continuous age structure in the cotton crop and thus was not endorsed, although some of the physiological parameters were used in the ensuing IPM models. For this reason, and because of the high degree of interaction among IPM research groups, later cotton models were very similar in structure and generally were based on a system of von Foerster-type equations.

These crop models basically described a population of plants of different ages, each plant comprised of sub-populations of roots, stems, leaves and fruit of differing ages. Cohorts of leaves produce photosynthate at age-dependent rates which is allocated to respiration, reproduction, vegetative growth and reserves. Mortality of plant organs occurs as a function of age and extrinsic factors, such as insect herbivores (plant-feeding insects). The underlying patterns of plant growth and development are determined by weather, nutrition and water. Arthropod pests affect the plant by attacking the carbohydrate supply side (e.g., defoliators and most diseases), the demand side (e.g., squares or bolls) or both sides of the photosynthetic production/allocation process.

Three major cotton/insect modeling groups were established during the IPM projects of the 1970s and 1980s. These interdisciplinary research teams were located at the University of California, Mississippi State University, and Texas A&M University. Some were made up of both state and federal (ARS) personnel. Each developed its own cotton model, which are remarkably similar in general structure. They concentrated on particular pest species, developing population models that were integrated with the cotton models. Another group at North Carolina State University also made early contributions to the insect modeling effort. An independent ARS effort developed SIMCOT II and later GOSSYM, but this effort was not involved with insect modeling until recently.

COTTON INSECT MODELS

This section summarizes the prominent population models that describe cotton insect pests found in the United States. It also lists some process-level models not

incorporated in the population models. Model descriptions are not complete in listing or detail. No attempt is made to evaluate model performance (the degree to which they represent the "real world"). The section is organized alphabetically by insect name, followed chronologically by model citation.

BEET ARMYWORM, *Spodoptera exigua* (Hübner)

The beet armyworm was introduced into North America during the nineteenth century and presently is found throughout the western and southern regions of the United States (Hogg and Gutierrez, 1980). The species feeds on multiple hosts (polyphagous) and has multiple generations each year (multivoltine). It overwinters as adults and is only able to survive in areas where the winters are mild (apparently it does not diapause). The excellent migratory ability of the insect permits expansion into favorable areas. Females oviposit eggs in clusters that are covered with scales. Young larvae feed gregariously near the egg cluster and gradually disperse as they grow. Pupation occurs in the soil.

The insect is a secondary pest of cotton. Besides being a defoliator, it attacks plant terminals and squares. There is one population model of beet armyworm, developed by Hogg and Gutierrez (1980) at the University of California.

Hogg and Gutierrez (1980) — This model stresses beet armyworm flight phenology (the timing and patterns of flight activity) under California conditions. It contains descriptions of births and deaths through time and thus can be classified as a population model. Important processes described in the model include immature development and mortality, oviposition, adult longevity and female flight activity. The model uses a Leslie matrix structure.

Oviposition of the beet armyworm does not commence until the third day of adult life. An exponential function is used to describe the cumulative percent oviposition relative to adult age (measured in degree days above 50F [10C]). Total fecundity varies with temperature, female size and the host on which the insect was reared; however, for modeling purposes an average value of 900 eggs per female is used.

A linear, degree-day (DD) model is used to describe the relationship between development rates and temperature. The model is parameterized with data from constant temperature experiments, with larvae reared on artificial diet. Development times of larvae and pupae are combined because the precise timing of pupation could not be determined once larvae entered the soil (to pupate). The lower threshold of development is estimated by regression methods at 54F (12.2C).

Age-dependent survivorship of eggs and larvae is modeled with an exponential function, using a constant age-specific mortality rate. Survivorship of adult females is both age- and temperature-dependent.

Hogg and Gutierrez (1980) studied the possible effects of three variables (wind, moonlight and night temperature) on female flight activity. High winds dampened moth catches in traps, but it occurs infrequently during the summer and thus was not included in the model. Moonlight was not correlated with trap catch. The influence of night temperatures (in degree-days) on trap captures (percent of maximum catch) is

described by an exponential equation. The lower and upper threshold values for flight are set at 60.1F (15.6C) and 90F (32.2C), respectively.

The model is initialized with light trap data in the early season and predicts the subsequent pattern of moth captures through time. Predictions compared favorably to light trap catches for the San Joaquin and Sacramento Valleys. The model performed poorly for the cooler Salinas Valley. The investigators noted that differences in model performance by location are due to a lack of understanding and description of one or more of the variables influencing flight, population growth or development.

Process Models Not Associated With The Population Model — Gutierrez *et al.* (1975) modeled the combined effects of defoliation by beet armyworm and the cabbage looper, *Trichoplusia ni* (Hübner), on cotton growth and yield. Like beet armyworm, the cabbage looper is a secondary noctuid pest of cotton that may reach outbreak proportions following pesticide use. In this model, females show ovipositional preference to leaves of an intermediate age class (between 840 and 1500 degree-days Fahrenheit). Larvae attack and consume these leaves first, and when they are all consumed, larvae move to both younger and older leaves. Larvae consume leaves at an age- and time-dependent rate. The amount of leaf dry matter required by the larval population is a product of the number of larvae in different age cohorts and the daily rate of consumption by larvae in each cohort. The rate of consumption varies exponentially with larval age. The number of larvae in the population is based on field counts, and this value is used as a model input. The computer results indicated that moderate defoliation causes only slight yield reductions. The investigators concluded that either the model is incorrect, grossly insensitive, or that larval feeding has a physiological effect not accounted for in the model.

BOLL WEEVIL, *Anthonomus grandis grandis* Boheman

The boll weevil is native to Central America where it is host specific to plants of the tribe Gossypieae of the family Malvaceae, which includes several species of cotton. This insect forms a unique relationship with its host (Gutierrez *et al.*, 1979a). In the United States, it is an obligate monophagous species (feeding restricted to one kind of plant) dependent on commercial cotton for its survival. Recently, the eradication program has eliminated the boll weevil as a pest from Virginia, the Carolinas, Georgia, Florida, Arizona and California.

The boll weevil has a multivoltine (completes more than one generation each year) life-cycle. Newly emerged adults prefer feeding on pollen of open flowers. After a day or so, its elongated rostrum enables the adult to penetrate the flower bud (square) and feed on immature anthers before bud opening. Females search cotton plants, showing ovipositional (egg laying) preference to flower buds measuring about 0.118 to 0.354 inches (3 to 9 millimeter) diameter (Lincoln *et al.*, 1963). Pristine squares normally are selected for oviposition, but when they are scarce, oviposition may occur in squares containing an egg or in cotton bolls (Walker *et al.*, 1977; McKibben *et al.*, 1982; McGovern *et al.*, 1987). The insect has three larval instars that feed cryptically

(unseen) in squares or bolls. In response to a developing weevil (second and third instars), fruit generally are shed from the plant after about five to nine days (Coakley *et al.*, 1969; King and Lane, 1969). The loss of fruit from the plant results in significant changes in the microhabitat of the developing weevils. This can lead to high mortality. The weevil has few natural enemies; however, the parasite *Bracon mellitor* Say attacks third instar larvae and can cause from 5 to 50 percent mortality to first generation larvae (Bottrell, 1976). Fire ants also suppress weevil populations in certain areas (Sterling, 1978).

Currently there are five population models of the boll weevil. They were developed by the USDA,ARS in Arizona (Fye and Bonham, 1972), North Carolina State University (Jones *et al.*, 1977), the University of California (Wang *et al.*, 1977 and Gutierrez *et al.*, 1991a) and Texas A&M University (Curry *et al.*, 1980).

Fye and Bonham (1972) — Using insectary data on adult longevity and fecundity (egg-laying capacity) (Fye, 1969), Fye and Bonham (1972) described the cumulative percent oviposition of females emerging from overwintering sites and those of later generations as functions of adult age. Daily oviposition of the population is mathematically described using these estimates, together with the mean lifetime fecundity per female and the number of females emerging each day.

A linear regression model is used with a rate summation approach to determine development times as a function of temperature. Model coefficients are obtained from data on colony weevils reared on artificial diet from eggs to adult emergence (Fye *et al.*, 1969). Input temperatures driving the model vary according to the location of the infested squares. For example, several equations describe the temperature in squares on the plant or in squares on the ground as functions of air temperature (for upland or extra long-staple cotton). The proportion of infested squares aborting through time is determined from a cumulative function. Separate temperature equations are used for weevils in bolls because these weevils normally cannot emerge until the boll matures and opens (a unique feature of Arizona weevil populations). For this reason, a temperature-dependent boll maturation routine is provided.

Fye and Bonham (1972) described temperature-dependent mortality of immature weevils in squares on the plant (before abscission) and immatures in squares on the ground (after abscission). Noting that 35 percent of the punctured squares on plants fail to abort, they postulated that eggs are killed by temperatures above 100F (37.8C). For weevils in squares on the ground, percent mortality is described as a function of the time spent above 100.4F, the lethal temperature (Fye and Bonham, 1970). Descriptive equations estimate adult longevity of weevils emerging from overwintering sites and those of later generations [data from Fye (1969)]. Estimates of daily mortality are used with daily emergence to calculate the number of weevils in the population.

Jones *et al.* (1977) — This comprehensive behavioral and mechanistic model calculates the number of squares and bolls damaged by adult weevils on a given day. Reproducing females are treated separately from non-reproducing females and males

(Jones *et al.*, 1975a,b). Factors considered in the model are fruit availability; the number, age and sex structure of the weevil population; and the searching, feeding and oviposition behaviors of the weevil.

Feeding and oviposition only occur during daylight hours (Cushman, 1911). Average hourly feeding rates vary with female age and depend on the mean number of eggs oviposited per hour, the amount of food ingested per oviposition event, the total ingestion per hour and the mean ingestion per feeding event. Oviposition depends on the availability of eggs in the oviduct, preferential site selection of fruit and the availability of sites in the field [determined by their cotton model, COTCROP (Jones *et al.*, 1980)]. Individual females make one puncture per fruit and do not discriminate against previously punctured sites (e.g., selection of a site is not affected by the number of punctures already present at the site). After oviposition, females move to another site before feeding or ovipositing again. Weevils may feed without ovipositing, depending on their energy balance. Searching for an oviposition site commences only when a mature egg is available in the oviduct. Egg production rates differ from oviposition rates. The time to complete an oviposition event is constant, but searching time varies with fruit density and searching rate.

Females preferentially select food and oviposition sites in this order: (a) squares older than 10 days, (b) squares 5 to 10 days old and bolls less than 7 days, (c) bolls 7 to 19 days old, and (d) plant terminals and leaves. Initially, females accept only class (a) sites, but if these sites are not encountered after a certain time of searching, other sites of lower ranking are accepted. Searching occurs randomly and assumes that fruit are uniformly distributed in the field. The data used to develop these submodels are derived from numerous sources—Hunter and Pierce (1912), Mitchell (1967), Lloyd *et al.* (1961), Mitchell and Cross (1969), and Mitchell *et al.* (1973).

The submodels do not account for known environmental influences (such as temperature and food type) on any of the processes (such as egg production rates, oviposition, feeding and searching rates). Many parameter values are undefined due to the lack of experimental data. Because the data to parameterize and validate the models are difficult to obtain, the individual process models are largely unvalidated.

Jones *et al.* (1977) used the exponential equation of Moore (1972) to predict the mean development times of eggs, larvae and pupae as a function of temperature. The inverse of predicted time is used to calculate the mean developmental rate because time cannot be accumulated under variable temperatures. The model does not describe decreasing rates above the optimum (the temperature at which development is the fastest), but rather it approaches an asymptote at high temperatures. The investigators may have selected this model because the data on which it is based (Bachelier and Bradley, 1975; Bachelier *et al.*, 1975) do not extend beyond the optimum for most life stages. The lower threshold of development is 57.9F (14.4C) (Hunter and Pierce, 1912). To account for variability in development times among individuals of the same age group, development times vary between ± 2 standard deviations of the mean. A cumulative normal distribution is then used to predict the probability that an insect completes development (of a given stage) in any time period.

Temperature-dependent mortality of boll weevil larvae and pupae is described using a relationship based on the hours spent above or below an optimum temperature. Model constants are derived using the experimental data of Bachelier *et al.* (1975). Daily predation and parasitism are held constant for each stage and are estimated from the data of Hunter and Pierce (1912). Insecticides kill only adults at a constant rate and only on the day of application. The influence of temperature on adult longevity is treated the same as other life-stage transitions [model coefficients are determined using data of Isely (1932)].

Wang *et al.* (1977) — These investigators emphasized the role of nutrition on weevil reproduction, describing the oviposition period and the rate of egg production as functions of the nutritional history of the female [data from Isely (1928) and Cushman (1911)]. The nutritional status of a weevil depends on the number of squares, small bolls and large bolls available to its parent at the time of oviposition, and the preference the ovipositing female has for these sites. Females are fecund between the ages of 265 and 1000 degree-days (measured in degrees Celsius), but the actual oviposition period varies with nutritional history. For example, the ovipositional period of square-reared females is 1.5 times longer than that of females reared on small bolls. The egg production rate also changes as a function of the insect's nutritional history. Overall, females produce an average of 200 eggs in their lifetime, but square-reared females produce four times as many eggs as females reared on small bolls. Oviposition ceases when only large bolls are available.

A linear, degree-day approach is used to estimate development times under fluctuating temperatures. Data for square-reared weevils (Bachelier *et al.*, 1975) and diet-reared weevils (Roach, 1973) are used to calculate the mean number of degree-days (265) from egg to adult emergence. The lower threshold of development is 53.6F (12C) (Fye *et al.*, 1969). Transition times of individual life stages are not considered, nor are the development times of individuals in the population.

Wang *et al.* (1977) proposed a discrete model to describe weevil mortality. Using data of Cushman (1911) and Sterling and Adkisson (1970), the probability of death is 0.37 (37 immatures expected to die per 100) for all immatures combined, 0.43 (43 adults expected to die per 100) for adults between the ages of 265 and 720 degree-days, and 0.2 between 720 and 1110 degree-days. These probabilities are modified by the insect's nutritional history. For example, adults reared on squares live 1.5 times longer than those reared on bolls (Isely, 1928).

Wang *et al.* (1977) defined the maximum rate of boll weevil immigration per acre as 0.704 (704 boll weevils per 1000 expected to enter an acre of cotton). Immigration (entering a field) occurs only in adults of a specific age. Emigration (leaving a field) varies with the supply/demand ratio of oviposition sites in the field.

Curry *et al.* (1980) — Curry *et al.* (1980) modeled the cotton crop/boll weevil system using a von Foerster (1959) framework modified by a system of partial differential equations which were solved by iterative numerical methods (Feldman and Curry, 1983). A distinguishing characteristic of this model is the incorporation of stochastic

elements of reproduction, development and mortality. The model uses four-day time steps for cohort aggregation. Hourly temperatures are used to drive the individual life-process models (e.g., development, reproduction, emergence).

The percentages of weevils emerging from overwintering sites (Hinds *et al.*, 1909) and weevils colonizing cotton (Walker and Niles, 1971) are described with linear functions of cumulative DD above 43F (6.1C) after March 1. No reproduction occurs in the field until the cotton contains squares that are at least one-third grown. Normally, only one egg is allocated per fruit.

Oviposition is estimated using an age-dependent reproductive profile and temperature-dependent rates. For example, each adult cohort that completes development over a four-day period is given a reproductive profile that is developed using the techniques of Curry *et al.* (1978a) and data of Isely (1932) and Cole (1970). This profile is integrated between the starting and ending development dates of each cohort and yields the fraction of total reproductive potential for each time period. This fraction is multiplied by the temperature-dependent lifetime fecundity associated with the period. Values are summed across all cohorts to yield an egg-laying potential of the population given unlimited oviposition sites.

The number of eggs actually oviposited depends on the number of acceptable fruit per acre and a female's searching coefficient (a model constant). This approach approximates some of the complex behavior described in the model of Jones *et al.* (1975b), which was not used because the influences of environmental variables on relevant processes were not defined (Cate *et al.*, 1979) and some of the basic parameters were not measured (Curry *et al.*, 1980). Ovipositing females show preference for fruit of different sizes. Given stable preference probabilities for each size class, the availability of fruit in the field (determined by their cotton model) determines the resulting distribution of deposited eggs. Size classes are declared as: (a) small squares less than 0.276 inches (7 mm) in diameter, (b) one-third grown and large squares greater than 0.276 inches, (c) small bolls less than 0.945 inches (24 mm), and (d) large bolls greater than 0.945 inches. Relative preferences for these size classes are 0.354, 0.85, 0.469 and 0.534, respectively. This work is based on the model of Cate *et al.* (1979), which was validated using several sets of field data including that of Jones *et al.* (1975b).

Curry *et al.* (1980) predicted development times of weevil cohorts using the approaches of Sharpe and DeMichele (1977) and Sharpe and Hu (1980) to describe development rates as a function of temperature and nutrition (e.g., squares vs bolls), and Sharpe *et al.* (1977) to describe the variation in development times among individuals in the population. The nutritional component of the model describes the differences in nitrogen content between squares and bolls. This difference affects both mean development times and the variation in development times among individuals feeding on the two food sources. The approach is supported by data from Isely (1932), Cole (1970), and Bacheler *et al.* (1975). Two developmental stages are modeled because of their differing microhabitats — egg through pupa in the fruit (immature stages combined) and the free-living adult stage.

Several mortality factors are represented in the model. They are (a) nonspecific density-dependent (e.g., parasitism and predation), (b) nonspecific density-independent [e.g., egg viability and a cell proliferation response of the infested square (Hinds, 1906)], (c) the effects of desiccation and temperature on immature weevils, and (d) the effects of insecticide applications on adults. Because little information is available on the nonspecific density-independent factors, their effect is assumed constant with respect to immature age. The impact of parasites on third instar larvae is described using a general approach. For example, percent parasitism is a function of larval density per acre, the maximum percent mortality attributed to the parasite when host density is not limiting, and the number of larvae at which one-half the maximum mortality is achieved.

A detailed biophysical model of square drying and associated immature weevil mortality is included in Curry *et al.* (1980). This model considers the physical changes occurring in infested fruit after abscission. While on the plant, the microhabitat within the fruit is assumed uniform. Fruit begin to dry with abscission, and the drying process is modeled as a function of fruit size, cotton variety and the condition of the microhabitat (DeMichele *et al.*, 1976). Curry *et al.* (1982) extended the bud-drying model to account for the interactions among relative humidity and temperature on immature mortality. This model describes the time required for an infested fruit of a given size to dry to a critical mass. The critical mass is defined as the minimum food needed for successful larval development. A larva must pupate before the quantity of food is reduced to the critical mass. To accomplish these tasks, development times, bud abscission times, air and soil temperatures at different locations are determined by the model. For example, temperature of infested fruit varies with fruit location (e.g., hanging on the plant after abscission or fallen to the ground) and the fraction of total daily solar radiation received at these locations (e.g., full sunlight, partial shade or full shade). Fruit that fall to the ground are distributed between and beneath plants. Other details of the crop environment are provided.

A general framework for modeling temperature-dependent stochastic longevity of adult insects is given by Curry *et al.* (1978b). Due to inadequate data for the boll weevil, this approach could not be used. Rather, longevity is estimated as 64.4 percent survival per four-day period, based on studies of Sterling and Adkisson (1970). Insecticides, when applied, kill 95 percent of the adult population.

To represent the onset of diapause, the number of non-reproductive adults in the population is based on crop phenology using a time-delay relationship between the proportion of squares and bolls attacked. For example, a cumulative normal distribution describes the proportion of non-reproductive adults in the population as a function of the proportion of eggs oviposited in bolls (relative to squares) two weeks earlier [data from Sterling and Adkisson (1978)].

Gutierrez *et al.* (1991a) — These investigators modeled the population dynamics of the boll weevil in Brazil on two long-season cotton varieties. The weevil was first reported in that country in 1981. They incorporated stochastic development of imma-

tures and adult longevity into the model of Wang *et al.* (1977). This was accomplished by using distributed maturation times to simulate populations of the weevils, cotton (Gutierrez *et al.*, 1984; 1991b), and their interactions. Details of this approach are described under the pink bollworm model of Stone and Gutierrez (1986a).

Weevils may feed multiple times on squares and bolls, but generally they deposit only one egg per square in contrast to multiple eggs per boll. Because multiple attacks may occur on a single fruit, the functional response model of Frazer and Gilbert (1976) is used to describe the number of fruit attacked due to feeding and oviposition. In this submodel, attack rates vary with (a) fruit availability corrected for weevil preference, (b) the maximum demand for feeding and oviposition sites required by the population, (c) time measured in degree-day Celsius, and (d) a weevil searching parameter that depends on plant size. Weevils emerging from bolls are assumed to be in diapause and therefore do not become reproductive. Oviposition begins when females are 285 degree-days old and end at different ages depending on the availability of squares. Insecticides are assumed to kill adults at a rate of 90 percent on the day of application, decaying to zero percent 3.5 days later.

Some interesting aspects of weevil biology are reported from Brazil that differ from those in the United States. For example, in Brazil the weevil shows only a slight preference for squares over bolls (expressed in the model as 1.1 vs 0.9, respectively). Fruit age (e.g., squares vs bolls) apparently has little effect on weevil development times in Brazil and therefore is not considered in the model. The time from weevil attack to square shed is greater in Brazil, and large squares and bolls do not abscise at all. These events may be due to the humid Brazilian conditions. They served as reasons for not modeling larval mortality due to the square drying [as found in the model of Curry *et al.* (1980)].

Process Models Not Associated With The Population Models — Several process models have been developed that are not associated with the population models discussed above. Barfield *et al.* (1977) produced a stochastic temperature-dependent model of development for the boll weevil parasite, *Bracon mellitor*. McKibben *et al.* (1982) developed a model of weevil oviposition behavior. This latter model indicates that females discriminate against squares containing an egg by rejecting as many as five punctured squares while searching for one that is pristine.

Using the boll weevil as an example, Feldman and Curry (1984) modeled temperature-dependent mortality of insects using separate rate and distribution functions. Due to the lack of data on the precise timing of weevil death, a uniform distribution is used to apportion mortality throughout the life of the immature weevil. This approach alters the predicted pattern of survivorship when compared to mortality taking place only during the emergence portion of the development period.

Stone *et al.* (1990) developed a degree-day model of spring emergence and overwinter survival of the boll weevil. Spring emergence varies as a function of the number of degree-days above 43F (6.1C) accumulated from January 1 and two indices of winter severity. These indices are used to predict overwinter survival.

Culin *et al.* (1990) and McKibben *et al.* (1991) developed models of boll weevil dispersal.

BOLLWORM, *Helicoverpa zea* (Boddie) AND TOBACCO BUDWORM, *Heliothis virescens* (F.)

These two noctuid species (members of the Noctuidae family) number among the most serious pests of agricultural crops in the Cotton Belt. They attack cotton, corn, tomatoes, soybeans, grain sorghum, alfalfa and other crops (Sterling, 1979). The worldwide importance of the *Helicoverpa/Heliothis* complex in agroecosystems was reviewed by Fitt (1989).

More than a century ago, Boddie (1850) wrote that the bollworm, better known as the corn earworm (thus the species name, *zea*), is a versatile pest which "is an anomaly in the natural history of insects." The anomaly refers to its destruction of cotton, a plant which is attacked only secondarily (that is, only when it becomes "necessary"). Bollworms overwinter 2 to 6 inches (5 to 15 cm) below the soil surface as pupae and emerge in the early spring as adults. Newly emerged moths disperse, mate and oviposit on diverse wild plants and may complete several generations before attacking cotton early in the summer. A female can oviposit from 250 to 1500 eggs during a lifespan of 3 to 12 days. The eggs are deposited on any part of the cotton plant, but tend to be placed individually in the upper third of the canopy on the upper leaf surfaces or in the terminal. Eggs hatch in three to five days, with the larvae feeding progressively on larger-sized squares and bolls for the next 12 to 15 days, molting through five to six instars before pupating. Moths emerge approximately two weeks after pupation.

The tobacco budworm was first reported as a pest on cotton in the United States in 1934, but it probably was overlooked before this time because of its close resemblance to the bollworm (Folsom, 1936). Like the bollworm, budworms are polyphagous (feed on many plants) (Neunzig, 1969). The two species have similar life cycles; however, the seasonal abundance is often dissimilar (Brazzel and Newton, 1963; Snow, 1964; Snow and Brazzel, 1965). Traditionally, budworms are more resistant to pesticides than bollworms and thus are more difficult to control.

The bollworm/tobacco budworm were among the earliest cotton insects to be modeled. Three research groups developed population models: (a) a joint USDA, ARS and Texas A&M University effort (Hartstack and Hollingsworth, 1974; Hartstack *et al.*, 1976a; Hartstack and Witz, 1983), (b) those at North Carolina State University (Stinner *et al.*, 1974a, 1977a,b), and (c) at Mississippi State University (Brown *et al.*, 1983). Their work reflects the distinct geographical and biotic differences found in each region (Fitt, 1989).

Hartstack and Hollingsworth (1974), Hartstack *et al.* (1976a), Hartstack and Witz (1983) — One of the earliest models describing cotton insects is MOTHZV. According to Hartstack and Hollingsworth (1974), this model was developed to help decide when to monitor the bollworm and budworm and when to apply chemical and biological control agents. The model is comprehensive, encompassing more than 16

subroutines including simple crop models for cotton, corn and sorghum (Hartstack and Witz, 1981a). The earliest version, MOTHZV-1, was expanded into MOTHZV-2, which represented a detailed and ambitious approach to modeling an agroecosystem (Fitt, 1989). A later version, MOTHZV-3, enhanced the cotton model and added a larval damage subroutine. A life-table approach is the bookkeeping system used by the model to account for changes in insect numbers and transitions between life-stages. For each day of the simulation, the model describes changes in the numbers of eggs, larvae, pupae, non-ovipositing adults and ovipositing adults.

In the early part of the season, MOTHZV is initialized with the number of moths caught in pheromone traps or with field counts of eggs. When used as part of the management model, TEXCIM (see below), field counts of larvae can be used to start the model. Once initialized, the model simulates the population abundance of several generations throughout the season using long-term temperature averages to drive the model. It simulates bollworm and budworm populations individually or combined. For the most part, however, the biological processes of the two species are not modeled independently.

Specific subroutines accommodate the use of pheromone trap captures as initializing values. For example, descriptive equations of trap efficiency convert trap captures into moths per acre. Another subroutine describes the influence of crop phenology (stages of plant growth and reproduction) on movement of moths between crops. For example, the predicted numbers of moths migrating out of corn or sorghum are stored for later use. Other factors include the influence of moonlight on ovipositional behavior and the impact of cloud cover on decreasing moonlight (Hartstack *et al.*, 1976a; Hartstack and Witz, 1981b).

Average temperature during the three hours after sunset is used to determine the probability of oviposition on a given night. For example, if this temperature falls between 72 and 77.9F (22.2 to 25.5C), the probability that a female will oviposit is 1.0 (100%); if the temperature falls below 55F (12.8C) or above 95F (35C), the probability is near zero. A second influence of temperature on oviposition applies a method of curve fitting, known as piecewise linear regression, to describe the effects of adult longevity (in days) on proportional daily egg production at various constant temperatures. Two additional variables influence oviposition. One determines the attractiveness of ovipositing females to other crops relative to cotton. For example, corn during silking is attractive to the bollworm but not the budworm. The other factor accounts for the proportional reduction in oviposition during periods of full moon. To obtain the total number of eggs laid per day per moth, the product of these four factors is weighted by the maximum daily egg production (set at 300 for the bollworm and 400 for the budworm).

Temperature also influences development times (in Celsius degree-days) and thus generation time from adult to adult. The lower and upper thresholds of development for eggs and larvae are 54.7F (12.6C) and 91.9F (33.3C), respectively. Eggs require 40.5 degree-days to complete development. An adjustment factor determines differences in egg development for the two species. Small larvae (first to third instar) require

81.7 degree-days, large larvae (fourth and fifth instar) require 120.6 degree-days. A nutritional factor adjusts for differences in the bollworm development feeding on cotton, corn or sorghum. The entire life cycle is completed in 484.9 degree-days. A normal distribution is used to describe developmental variability among individuals in each life stage.

Parasitism, particularly by the egg parasite, *Trichogramma* spp., is an important cause of egg mortality and is considered in the model using four options. In the first option, the number of parasites must be provided for each day of the simulation. To determine the percent parasitism to eggs, these values are used in an empirical model developed by Knipling and McGuire (1968). With the second option, daily percent parasitism must be supplied. Option three uses estimates of maximum percentage in corn for the bollworm, which is adjusted by the model as this crop matures. In the fourth option, the parasitism rate is a function of the number and age of adult *Trichogramma* spp. and of temperature. It also uses the numbers of egg predators in the Knipling and McGuire model. If ovicides are used, mortality rates are input as constants under this option. A background rate of 4.5 percent per day accounts for unexplained mortality to eggs.

Larval mortality due to predators is based on the exponential function of Knipling and McGuire (1968). A similar model (Knipling, 1971) is used to describe parasitism of small larvae. For the bollworm in corn, the number of surviving larvae is modified by cannibalism. A residual, daily mortality rate is given as four percent. Separate inputs for larval mortality resulting from insecticides are provided. As noted above, adult mortality is temperature dependent, but an additional daily rate of 15 percent is also imposed.

The cotton model SIMPLCOT [derived from a model by Wilson *et al.* (1972)] simulates the typical fruiting pattern of the plant. It describes the number of new fruit per plant per degree-day, the probability of fruit survival per degree-day, and the yield per acre. Soil type, fertility and moisture are assumed to be non-limiting. Cohorts representing the different ages of fruit are not stochastically distributed. Short, medium or long-season varieties are modeled by adjusting the parameters controlling fruiting rate. Other adjustments control different growing environments. A feedback mechanism permits regrowth of cotton (i.e., compensation) following simulated insect losses.

The damage subroutine of MOTHZV determines changes in yield caused by bollworm/tobacco budworm larvae. The numbers of small and large larvae are weighted (normalized) by their physiological age divided by 8.5. This calculation provides the "equivalent number of 8.5 day-old larvae" within the two cohort groups (e.g. small and large larvae). This weighting factor is based on data from Townsend (1973), who showed that 8.5 day-old larvae damage one fruit per day. The probability that an equivalent larva will find a square or boll is described by an exponential function of fruit density. This probability is adjusted by larval preference. For example, small larvae attack only squares, but large larvae attack both squares and bolls (with a preference for squares) depending on the proportion of bolls in the fruit population. The adjusted probabilities are used to parameterize an exponential function that calculates damaged squares and bolls per acre.

Other papers discussing improvements to and applications of MOTHZV include Hartstack and Witz (1981b), Sterling *et al.* (1989a) and Witz *et al.* (1981).

Stinner *et al.* (1974a, 1977a,b) — The modeling work in North Carolina was conducted concurrent to that of MOTHZV. Each research group provided unique contributions that complemented the other. Distinguishing features of the North Carolina model, HELSIM (HELiothis SIMulation), include intraspecific competition among bollworm/tobacco budworm larvae and the influence of patchy, small fields of mixed crop diversity on insect dynamics. The model has at least two versions: HELSIM-1 includes both the bollworm and the budworm; HELSIM-2 focuses on the impact of multiple cropping systems on population dynamics of the bollworm. HELSIM-2 makes use of contest-type intraspecific competition, and the role it plays in altering the timing of populations beyond that predicted by physiological time alone. HELSIM developers recognized that food availability sets the upper limits on insect population growth. Thus the model describes the number, type and quality of feeding sites available per hectare, as well as the spatial abundance of the principle hosts. The impact of these resources on population growth is modified by weather and natural enemies. The model uses difference equations to move individuals from one stage to the next (e.g., from one larval stage to the next, day by day), as opposed to the life-table approach of MOTHZV.

A prominent submodel of HELSIM involves the ovipositional response of the bollworm to various host plants in North Carolina (Johnson *et al.*, 1975). Four agronomic crops—cotton, corn, soybean and tobacco—are included. A spatial grid of crop types and associated crop-growth habits (up to 14 combinations) are used to simulate the movement of moths between crops (Hartstack *et al.*, 1976a). Ovipositional preference for these hosts and their spatial and temporal abundance (e.g. in relation to space and time) provides the basis for partitioning eggs among the different crops. HELSIM assumes a 1:1 sex ratio. Temperature determines the length of the pre-ovipositional period, fecundity and the temporal oviposition pattern. The data of Isely (1935) are used in describing these relationships.

Two algorithms describe development as a temperature-dependent, stochastic process. The first applies the development rates of the fastest, the median and the slowest individuals in the population held at different constant temperatures. A non-linear function is fitted to the development rate *vs* temperature data sets for the three groups of insects. Daily field temperatures are used to drive the three rate equations independently, and the predicted rates are summed to unity (1.0) to determine development times. Thus, a rate-summation approach is used to predict the development times of three different portions of the population. A cumulative distribution is then fitted to the three predicted development times plotted against their respective proportion of the population. Data of Isely (1935) are used to parameterize the larval development submodel. Other data on local insect strains and conditions are used for its validation.

HELSIM provides greater detail on larval cannibalism than does MOTHZV. In fact, cannibalism is the dominant mortality factor when larvae are found on corn. The cannibalism subroutine calculates the spatial distribution of larvae among ears of corn. This subroutine determines the probability that a larva will come into contact with

another at the same site. Cannibalism occurs when more than one larva is found at a given site. When high population densities are present, cannibalism alters survival and the timing of generation peaks. Generation times can be reduced up to 18 percent by this factor because older larvae can eliminate large proportions of small larvae that hatch from eggs oviposited later.

The abundance of natural enemies varies according to host-plant type and its phenological state. This effect tends to dampen density-dependent numerical responses and alters the functional response of natural enemy populations. Because bollworm/tobacco budworm moth populations disperse, there is a temporary release of insect populations from natural control. While these and other influences are recognized in HELSIM, they are simply lumped into a value that describes daily mortality as function of crop type, maturity and time.

The work in North Carolina motivated several innovations that not only improved HELSIM but also had broader applications to other insects. The first of these innovations involves the use of non-linear functions to describe temperature-dependent development rates (Stinner *et al.*, 1974b). Later improvements incorporated developmental variability among individuals in the population (Stinner *et al.*, 1975). These algorithms may have been the first applications of a non-linear, stochastic approach to modeling insect development in population models. Another innovation is the descriptive model that predicts the spring emergence of bollworm populations in North Carolina (Logan *et al.*, 1979). The emergence model includes the effects of soil type as well as the interactions between soil type, temperature and soil moisture in influencing the post-diapause development and survival of overwintering pupae. This work influenced the development of an expert system for building pest simulation models (Logan, 1988).

Brown *et al.* (1983) — An initial bollworm/tobacco budworm model called HELSYS (Harris *et al.*, 1976) was developed by the Mississippi group; however, changes in personnel led to the abandonment of this model. Later work produced an alternative model, CIM-HEL (Cotton and Insect Management-Heliothis), which built upon MOTHZV and to a lesser extent HELSIM. CIM-HEL emphasizes bollworm/tobacco budworm feeding on cotton, with larval preferences for fruiting forms derived from studies by Wilson and Gutierrez (1980) and Nicholson (1975). The detailed approach to larval feeding, along with the use of the boll weevil model of Jones *et al.* (1975a,b, 1977) and the cotton model, COTCROP (Jones *et al.*, 1980), led to the development of the management model, CIM (see below).

Unlike MOTHZV which separates the two species only when necessary (Hartstack *et al.*, 1976a), CIM-HEL models each species individually. According to the Mississippi group, separation of the two species is justified because of their significant differences in development, fecundity and resistance to insecticides. CIM-HEL uses discrete time-steps in degree-days; however, the output of the model is given in calendar (Julian) days. Bookkeeping on the number of individuals per life stage and the timing of life stage transitions is performed using a Leslie matrix approach.

CIM-HEL is initialized using the numbers of insects in each life stage, or alternatively, the numbers of adults entering the field in the spring (Murphey, 1980). The model applies the fecundity subroutine of MOTHZV without its moon-phase effect (Murphey, 1980). Development is temperature-dependent using the linear, degree-day approach (measured on a Celsius scale). Developmental variability among individuals is also simulated. Eggs require 50 degree-days to hatch. Data on larval development are obtained from Hogg and Calderon (1981), with the bollworm requiring slightly longer to develop than the budworm (310 vs 300 degree-days, respectively). Female pupae of both species develop faster than males; however, because only females influence population growth (Hogg and Gutierrez, 1980), their rates alone are used in the model. Pupae of both species develop in about 235 degree-days.

Egg and larval mortality result from predators, other natural causes and insecticide applications. The predator/parasite population is not modeled explicitly but, on occasion, very simple population models for predators/parasites are used (Brown *et al.*, 1979a). The numbers for predators/parasites are supplied from field samples as an exogenous variable (Brown *et al.*, 1979a; McClendon and Brown, 1983). Therefore, egg and larval mortality are proportional to the numbers of predators/parasites supplied. CIM-HEL models the recovery of predator/parasite populations following an insecticide application. This task is done using a step function that has an 80 percent decrease in their numbers on the day of application. A linear function is used to describe their recovery rate over a 14-day period.

Larval mortality due to insecticides is based upon a table of supplied values that describe daily mortality for each larval stage (first to sixth instar). The values differ for each species. Larval mortality from insecticides on the day of application decreases from about 95 percent for first instar to less than six percent for sixth instar. Daily mortalities by instar are reduced on the second and third days post-application to simulate residual insecticide mortality. Additional daily mortalities are three percent for eggs and pupae and 15 percent for adults. Data from Hogg and Nordheim (1983) are used to parameterize larval survival rates in CIM-HEL.

Empirical relationships are used to describe and couple the feeding behavior of bollworm/tobacco budworm with the Cotton Crop Model, COTCROP (Brown *et al.*, 1979b). This crop model was derived from SIMCOT II specifically for interfacing with insect models. Unlike SIMPLECOT used in MOTHZV, COTCROP is a detailed process-oriented, physiological plant model. Growth rates of plant organs depend on temperature, age and the availability of carbohydrate and nitrogen reserves. This modeling capability permits the comparison of crop practices such as irrigation and fertilization to insect management tactics. Conforming to other IPM modeling groups, Mississippi researchers held to the view that "one must vary the number of fruit ... per area in a continuous manner" in order to model insect feeding on cotton (Brown *et al.*, 1983). Thus, COTCROP simulates the growth of plants in one square meter areas, rather than the average plant. The number of fruit eaten per day per larva is a linear function of larval age. Larval fruit preference is influenced by both fruit and larval age.

The estimate of feeding damage is stored in an array so that the cotton model can appropriately schedule the abscission date of damaged fruit.

Process Models Not Associated With The Population Models — HELDMG (HELiothis DaMaGe) (Thomas, 1989a,b) is a bollworm/tobacco budworm damage model coupled to the cotton model, GOSSYM (Baker *et al.*, 1983). This model also uses the damage function from MOTHZV (Hartstack and Witz, 1983), and the larval fruit-preference equations of Wilson and Gutierrez (1980). Using inputs from either scouting reports or MOTHZV (as part of TEXCIM), HELDMG simulates the within-plant distribution of larval damage. The model apportions the projected number of damaged fruit on the plant in order to adjust the fruit distribution of GOSSYM. Thus, a platform is provided that can be used to study the effects of larval damage on cotton growth and yield. Explicit management options for bollworm/tobacco budworm control are not specified; rather, the user has to decide if the forecast of bollworm/tobacco budworm damage is severe enough to take action.

Other models include: (a) a regression equation describing the population buildup of bollworms (Butler *et al.*, 1974), (b) a sex pheromone emission model (Hartstack *et al.*, 1976b), (c) genetic suppression models of the tobacco budworm (Makela and Huettel, 1979; Levins *et al.*, 1981; Roush and Schneider, 1985), (d) a distribution model of bollworm development times (Sharpe *et al.*, 1981), (e) a damage reduction model of bollworm/tobacco budworm on cotton (Young and Wilson, 1984) and (f) an emergence model for overwintering bollworm/tobacco budworm (McCann *et al.*, 1989).

COTTON FLEAHOPPER, *Pseudatomoscelis seriatus* (Reuter)

The fleahopper is a key pest of cotton in Texas and adjoining states. The insect is polyphagous (feeds on multiple plants) and multivoltine (more than one generation per year), with five to eight generations per year. It overwinters as diapausing eggs, which often are found in the fall on stems of the wild host, woolly croton, *Croton capitatus* Michx. Eggs begin to hatch on warm spring days and continue do so for up to two months. Rainfall triggers egg hatch. Typically, the first two generations are found on wild hosts, with adults of the second generation moving to cotton after the preferred hosts senesce.

Proper management of this insect is important for several reasons. While on cotton, it feeds on pinhead squares causing them to abort. Poorly-timed insecticide applications against the insect can release other pests from natural control, resulting in additional losses in production and increases in control costs. The fleahopper is an important predator of bollworm/tobacco budworm eggs, and is a food source for polyphagous predators, particularly spiders (Hartstack and Sterling, 1986). These last two characteristics make modeling this insect unique in comparison to other cotton insects. One population model developed at Texas A&M University exists for the species (Hartstack and Sterling, 1986).

Hartstack and Sterling (1986) — The Texas cotton fleahopper model predicts fleahopper abundance through time and cotton fruit losses caused by the insect. These

forecasts are designed to help producers make management decisions on fleahopper control. The model can stand alone or be used as part of the comprehensive management model, *TEXCIM* (see below). The fleahopper model is coupled to the cotton model, *SIMPLECOT*, which assigns fruit to cohorts according to their physiological age. Temperature and rainfall are the principle variables affecting fleahopper diapause, spring emergence, development and oviposition.

The model simulates the number of eggs entering diapause in the fall as a function of calendar date. The probability of diapause is described by a linear function, with no eggs entering diapause before September 1 and all eggs entering after October 11. Temperature and rainfall are used to estimate the timing of spring emergence. The emergence pattern of nymphs provides one approach for initializing the fleahopper population model. The number of nymphs observed in a field provide an alternative approach. Using these inputs, the model predicts changes in population density through time for the F_1 and subsequent generations.

A degree-day approach is used to predict development times of eggs and nymphs as a function of temperature. The lower threshold of development is 58.2F (14.6C) and the upper threshold is 92F (33.3C) (Sterling and Hartstack, 1979). This approach is integrated with the distribution method of Sharpe *et al.* (1977) to determine developmental variability among individuals in the population. The model uses "physiological days" as the basic time step, which are defined as the degree-days (Celsius) per calendar day divided by 13.3 degree-days. The development times of eggs and nymphs are 9 and 7.2 physiological days, respectively.

Females oviposit a maximum of 20 eggs per day, depending on temperature and female age. Eggs are oviposited between 62.6F (17C) and 95F (35C). Females are reproductive during the ages of 1.6 and 13.5 physiological days. If female age is between 3.5 to 6.09, the probability of oviposition is 1.0 (100%). For ages <3.5 or >6.09, the probability of oviposition is determined by two linear functions, one for each interval. The sex ratio of adults is set at 0.5.

To indicate potential insect problems, fleahopper abundance through time is compared to the fruiting curves provided by *SIMPLECOT*. The damage rate of both nymphs and adults is 0.5 squares per day for squares younger than five days. Older squares are not damaged. An exponential function is used to estimate the number of damaged squares per day as a function of insect numbers and the density of susceptible fruit. This damage function is similar to that used by *MOTHZV* to describe bollworm/tobacco budworm damage (Hartstack and Witz, 1983).

The number of fleahopper nymphs dying each day is temperature- and age-dependent. Mortality increases when temperatures are above 84.9F (29.4C) or below 75F (23.9C) (Gaylor and Sterling, 1975). Adult mortality increases with temperature and physiological age. Adults live 376 degree-days (or about 28 physiological days).

Mortality by insecticides is determined by a table of values. These mortality values range from 5 to 20 percent for eggs, 90 to 99 percent for nymphs, and 70 to 99 percent for adults. A residual effectiveness of each insecticide, typically less than 4.3 days, is also provided. The type of insecticide, the number of applications and the day of appli-

cations are specified before the population model is run. The mortality rate due to the various insecticides are estimates and caution is recommended in their use. The nymph and adult insecticide mortality rates are modified by the aging process.

Fleahopper mortality is also dependent upon field counts of the numbers and types of fleahopper predators. The efficiency of each predator group is weighted, with spiders given the most weight. If field samples are not available, default predator levels and types can be selected, along with default estimates of the timing of natural enemy abundance. The predation rate is based upon the predator model of Knipling and McGuire (1968). The maximum daily predation rate of eggs and nymphs is five percent.

PINK BOLLWORM, *Pectinophora gossypiella* (Saunders)

The pink bollworm is not native to North America but was introduced into Mexico in 1911 and spread to the United States in 1916. Presently, it is found in cotton growing areas west of the Mississippi River, where it is a pest in Arizona and California. The insect is confined to malvaceous plants; cotton and okra are the only two cultivated crops in the United States attacked. Adults are small moths (Microlepidoptera) that are active in the predawn hours. Females release pheromones to attract males. Bolls are the preferred oviposition (egg-laying) site, but prior to bloom, eggs may be found on all plant parts. Development occurs within a single fruit. Generally only one larva survives per square, but several can survive in a single boll. Feeding in squares is directed to the anthers, whereas in bolls preference is shown to lint and seeds. Pupation occurs in the soil or in lint, and pupal mortality can be high from extremes in soil temperature or moisture. The insect overwinters as a mature larva in the soil or in dried bolls.

Population models have been developed by Larson and Huber (1975), Gutierrez *et al.* (1977a), Stone and Gutierrez (1986a), and Hutchison (Unpublished manuscript, W. D. Hutchison, Department of Entomology, University of Minnesota, St. Paul, MN). Larson and Huber (1975) adapted the western lygus bug, *Lygus hesperus* Knight, model of Watson (1973) to pink bollworm. This model does not explain the mechanisms behind process-level events, but is purely descriptive.

Gutierrez *et al.* (1977a) — Gutierrez *et al.* (1977a) developed a detailed model using a von Foerster (1959) approach to represent the population of pink bollworm. The model calculates the age structure of the population in degree-days Celsius and applies a complex net mortality function that depends on age, time, density, temperature and the net immigration-emigration rate of adults into the population. At any point in time, the population consists of adults emerging from diapause, eggs, larvae, pupae and adults emerging from squares or bolls.

The model describes cumulative percent emergence of adults from diapause using Gompertz equations fitted to the field data of Rice and Reynolds (1971). Oviposition rates vary with female age, with more eggs deposited earlier in the adult life than later. Maximum fecundity (egg-laying capability) is 240 but the actual value per female

depends on the nutritional history of the insect. For example, the fecundity of females emerging from diapause is scaled by 0.66. Scaling factors of 0.8 and 1.0 are given to females that fed on squares and bolls as larvae, respectively.

Accumulated degree-days above 50F (10C) (Butler and Hamilton, 1976) are used to calculate the development times under fluctuating temperatures. The field data of McLaughlin (1974) provided estimates of the range of development for each life stage: eggs from 0 to 83 degree-days (in Celsius), larvae from 83 to 233 degree-days, pupae 233 to 450 degree-days, pre-reproductive adults 450 to 478 degree-days, and adults 478 to 794 degree-days, respectively. This was verified in the laboratory on artificial diet. Fruit age, determined by their cotton model (Gutierrez *et al.*, 1975, Wang *et al.*, 1977), influences food selection as well as development rates of newly emerged larvae. For example, larvae show little preference for very young squares, bolls or flowers. A square supports only one larva, while a boll supports up to 15. Development rates vary with age of the fruiting structure using scalars that adjust degree-days accumulation (Lukefahr, 1962).

Temperature and photoperiod influence diapause initiation of pink bollworm (Albertos, 1974). These factors are used to calculate the percentage of first instar larvae that go into diapause. Individuals that go into diapause are treated as emigrants in the population since they do not develop beyond the prepupal stage.

Mortality factors are described for various life stages. Predators reduce eggs and newly hatched larvae by five percent on bolls and 15 percent on foliage. Only 82 and 92 percent of newly emerged larvae locate squares or bolls, respectively, on which to feed. Once the fruit is attacked, pink bollworm larvae are immune to predator attack. Adults die in an age-dependent manner.

Data from Brazzel and Gaines (1956) are used to describe pink bollworm damage to cotton. Percentage loss of lint, seeds, and reduced quality are described as exponential functions of the number of larvae per boll (details of these submodels are not provided by the authors).

Stone and Gutierrez (1986a) — These investigators modified the pink bollworm model of Gutierrez *et al.* (1977a) in two significant ways. First, they incorporated developmental variability among individuals into the model (stochastic development) for both cotton and pink bollworm. For example, fruit of a given cohort ages according to a Gamma probability density function describing the mean and variance of development times. This function is also used to describe the probability of pink bollworm completing development, applying the constant temperature data of Hutchison *et al.* (1986) to parameterize the model for each larval stage. The model also enhances the nutritional influence of the host on larval development. Instead of incorporating nutrition as a correction factor for the aging process (Gutierrez *et al.*, 1977a), Stone and Gutierrez (1986a) expanded the concept of physiological time to include the nutritional influences of the host on pink bollworm development. The nutritional value of the fruit (represented as a scaling multiplier for developmental rate of the infesting larva) varies as a continuous function of fruit age (measured in degree-days). Thus, the

aging rate of a larva at any particular time not only depends on temperature but also on the nutritional value of the fruit.

Hutchison (Unpublished manuscript, W. D. Hutchison, Department of Entomology, University of Minnesota, St. Paul, MN) — Hutchison used the degree-day approach to describe the mean development time of pink bollworm life-stages and the distribution approach of Logan (1988) to describe the variation in individual development times. The data of Hutchison *et al.* (1986) are used to parameterize the models (with lower and upper threshold values of 51.6 and 90.5F [10.9 and 32.5C]). The data of McLaughlin (1974) are used to validate the models. A logistic equation describes cumulative oviposition as a function of physiological age (in degree-days). The maximum fecundity of females varies with nutrition according to the formula used by Gutierrez *et al.* (1977a). Unlike other pink bollworm models, this model describes the probabilities of a time delay in oviposition attributable to sublethal dosages of three insecticides (using data of Hutchison *et al.*, 1988).

Process Models Not Associated With The Population Models — Butler and Hamilton (1976) used the function of Stinner *et al.* (1974b) to model pink bollworm larval and pupal development as a function of temperature. Butler and Watson (1980) developed a model that estimates daily survival of adults as a function of temperature. Gutierrez *et al.* (1981) improved the diapause induction and spring emergence models proposed in their earlier work (Gutierrez *et al.*, 1977a). Their analysis showed that the environment experienced by individuals at the time of diapause induction and spring emergence influences the combined pattern of adult emergence in the spring.

TARNISHED PLANT BUG, *Lygus lineolaris* (Palisot de Beauvois), AND WESTERN PLANT BUG, *Lygus hesperus* (Knight)

Plant bugs are polyphagous (feed on many plant species), multivoltine insects found on a wide variety of agronomic crops and weed species. The tarnished plant bug, *Lygus lineolaris*, is widely distributed throughout North America, occurring on cotton from the Carolinas to Texas. *Lygus hesperus* (western plant bug) is found in the West, primarily in Arizona and California. Cotton is not a preferred host of either species, but adults migrate into this crop after the primary hosts have matured, died out, or are harvested. In the East, *Lygus* spp. typically develop large populations on early-season annuals; in the West, alfalfa and safflower are reserve crops. Young squares that are attacked will abort, but loss of older fruit is uncommon. The pest status of these species is debated. Some studies show that common densities observed in cotton do not reduce yields or quality (Falcon *et al.*, 1971; Gutierrez *et al.*, 1975). However, large migrating populations can cause severe damage (Gutierrez *et al.*, 1977b).

A population model of the tarnished plant bug in cotton and a wild host was developed by Fleischer and Gaylor (1988). Watson (1973) and Gutierrez *et al.* (1979b) modeled the western plant bug in cotton (the Watson model was not available for review). Gutierrez *et al.* (1977b) developed a population model for the western lygus bug in alfalfa.

Fleischer and Gaylor (1988) — These investigators studied nymphal development and survival, and adult longevity and fecundity of the tarnished plant bug on several hosts including cotton. A Leslie matrix approach is used to model the insect on cotton and the wild host annual fleabane, *Erigeron annuus* (L.). This model describes a population of individuals of differing age classes; each age class has a reproductive rate and a probability of surviving to the next class. The dynamics of the model are determined iteratively (repetitively) according to a matrix equation, whereby the age distribution of individuals at any time is a function of time, varying birth rates and death rates. The model is parameterized using life-table data collected in the laboratory at 79.7F (26.5C). This simple model indicates greater population growth of the tarnished plant bug on annual fleabane than on cotton. The model is not integrated with a model of the host.

Gutierrez *et al.* (1979b) — These researchers simplified the western plant bug model of Gutierrez *et al.* (1977b), which applied a matrix approach similar to that of Fleischer and Gaylor (1988). The model does not consider reproduction, development or other life processes explicitly, or the mechanisms that influence these processes. Rather, it uses two empirical functions to describe field observations. For example, they found that the number of western plant bug adults in standard sweepnet samples increases exponentially with the number of cotton squares in the field. To adjust for sweepnet inaccuracies, the predicted number of adults given by this function is multiplied by 3.65 (after Byerly *et al.*, 1978). Using the fruiting subroutines of their cotton model (Gutierrez *et al.*, 1975; Wang *et al.*, 1977), the number of adults through time is estimated as a function of available squares. The number of nymphs in the population is a function of the number of adults, given a 200 presumed degree-days Fahrenheit time delay for egg development. Development time of eggs is estimated as 200 degree-days above 53.5F (11.9C), and the time for nymphs is 400 degree-days. The net immigration rate into cotton is a constant, set at 0.01.

Insecticides presumably kill all plant bugs at the time of application. After application, it takes 200 degree-days for adults to reinfest the field. Between 200-800 degree-days, the rate of increase for adults is 1.4 times normal due to a suppressed natural enemy complex. Nymphs also benefit from the decline in natural enemies after a spray, increasing 2.27 times the norm.

Plant bugs injure small squares, with adult females causing about twice as much damage as males. The average rate is 0.028 squares per degree-day for females vs 0.0134 for males (Gutierrez *et al.*, 1977b). According to the investigators, the injury resulting from nymphs occurs at a rate of 0.0142 squares per degree-day. These results contradict the belief that nymphs cause twice the damage as adults.

Process Models Not Associated With The Population Models — Fleischer and Gaylor (1988) used linear models to describe development rates as a function of temperature for the tarnished plant bug nymphs reared on nine hosts, including cotton. No significant differences in the slopes or intercepts of these equations are found. This suggests that a single model fitted to the pooled data may represent development adequately on all hosts.

Butler and Wardecker (1971) modeled the western lygus bug development rates as a function of temperature using a linear model. Strong (1971) simulated the mating behavior of the insect on alfalfa. Mangel *et al.* (1985) applied analytical methods to examine changes in the numbers of squares and western lygus bug in the field through time. Although there was an inverse correlation between squares and western lygus bug numbers during certain weeks of squaring, no evidence is presented supporting their assumption that the relationship was due to the insect.

SPIDER MITES, *Tetranychus* spp.

Three mite species attack cotton in the United States. In the West, where mites rank among the most important arthropod pests, the strawberry spider mite, *Tetranychus turkestanii* Ugarov & Nikolski, occurs chiefly in the early season; the twospotted spider mite, *Tetranychus urticae* Koch, occurs in the mid-season; and, the Pacific spider mite, *Tetranychus pacificus* McGregor, dominates during the late season. In most areas outside the West, outbreaks of the twospotted spider mite occur chiefly during dry summers. Mites damage the plant through leaf feeding and by injecting phytotoxins which affect stomatal conductance, leaf resistance, transpiration and net photosynthesis (Marcano, 1980).

We are not aware of any population models for spider mites in cotton. Wilson *et al.* (1985) developed a spider mite forecasting model that determines sampling times and cotton damage potentials. This model is integrated into a rule-based expert system, CALEX, for making pest management decisions in California (see below).

MODEL APPLICATIONS

Population models have been used for understanding and describing the cotton/insect system and, to a limited degree, for managing it. We discuss general applications followed by specific instances and case studies.

GENERAL APPLICATIONS

Initial steps in the modeling process are to define the boundaries of the system under study and identify the components and their interactions that are essential to its operation. In this way, a mental or conceptual picture is formed of how the system works, or how we believe it works. These steps provide organization, structure and direction to research. They help to: (a) identify important topics for study, (b) assemble known information on each topic, (c) determine where the information fits in the scheme of things, and (d) determine what should be done next. Therefore, the modeling process focuses research on relevant questions about the nature and behavior of the system. This value does not change once the model is formulated. It then becomes a powerful tool for directing research through sensitivity analysis, which helps identify the components (parameters) that must be measured with greatest precision.

Models can be used to test scientific hypotheses, an application with relevance to management as well. For example, many of the simulation models developed from the

IPM projects provide a method for devising and evaluating effective management strategies or for evaluating the potential pest status of a species (examples are provided below). The tasks of devising and evaluating new strategies are useful only if the strategies can be implemented, and models provide a method for accomplishing this task as well. As we will examine later in this chapter, computer-based systems provide an excellent way to implement comprehensive crop/pest management strategies. New strategies can be very complex, and even experts have difficulty evaluating the agroecosystem as a whole. All management options may not be known, and the changing nature of events in the field are not always straightforward or intuitive. Computer-based systems have the power to integrate, analyze, interpret, hypothesize and deliver complex information on the important components of the agroecosystem. These components include crop dynamics, pest population dynamics, treatment tactics, impacts and cost/benefit analyses.

Models can promote the effective use of agricultural chemicals through proper timing of applications and by recommending the most efficient products (or combination of products) and dosage rates. This use of models should reduce pest resistance problems and extend product durability and efficacy. Concurrently, alternative methods of control with less economic and environmental impact should become viable options that can be used with greater confidence (less risk). Models may be used to develop and test potential new agricultural products, such as some of the genetically-altered new cotton varieties (e.g., those containing a *Bacillus thuringiensis* protein effective against lepidopterous pests). They can provide a concise summary of the proposed mode-of-action of a tactic or strategy, and then be used to evaluate the tactic before costly field evaluations are initiated.

SPECIFIC APPLICATIONS

Some of the comprehensive simulation models described in this chapter have been well tested and provide good descriptions of the biological systems they represent. For these reasons, they have been used to evaluate management strategies consistent with IPM objectives — to improve crop production and reduce pest damage by augmenting natural enemy populations, using host-plant resistance and cultural modifications, and by evaluating a species' pest status or dynamic spray thresholds. Other models address what Newsom (1980) called "The next rung up the ladder", which involves the management of multiple pest species that occur simultaneously. While these "mega-models" represent progress, much work remains. As noted by Gutierrez and Wilson (1989), the development of management models in cotton is a recent event; one that could only take place after the models accurately represent several sets of independent field data. This validation process is not easy, for often time-consuming experiments reveal gaps in our understanding of biological relationships.

CIM (Cotton and Insect Management) — Mississippi scientists developed the cotton crop model, COTCROP (Jones *et al.*, 1980), integrating it with simplified versions of the bollworm/tobacco budworm and boll weevil models (Brown *et al.*, 1983;

Jones *et al.*, 1977), yielding a comprehensive tool for managing insects primarily through insecticides (Brown *et al.*, 1983). CIM simulates the daily changes in the crop and insects from crop emergence to harvest. Initial insect densities of both pests and predators are supplied by the user. Other model inputs include soil characteristics, date of crop emergence and harvest, plant population density, nitrogen and insecticide applications and daily weather data. Model outputs include daily records on the crop, insect densities by life stage, and a summary report provided at the end of the simulated growing season. This report includes the yield estimate, the number and cost of insecticide applications and the net dollar return (Brown and McClendon, 1982; Brown *et al.*, 1983). By varying the historical weather data, soil types and insect densities, different insect management strategies can be evaluated.

CIM was developed specifically for devising, evaluating and improving insect management strategies in Mississippi (McClendon and Brown, 1983; Murphey, 1980). For example, using simulation and field results, researchers developed a dynamic threshold strategy for managing small bollworm/tobacco budworm larvae. This concept was tested against the recommended threshold of the time (1979). The dynamic threshold varied with the changing status of the crop. The results indicated that the dynamic threshold could reduce the number of insecticide applications without a loss in yield, thereby increasing profits. In general, insecticides were applied earlier using this threshold, and late-season applications were avoided for fruit that would not mature.

Besides its use in developing management strategies, CIM has a specialized application as a teaching aid in the model COTGAME (Pieters *et al.*, 1981). Presently, CIM is not widely used in production systems due to the lack of a user-friendly interface, documentation and training of potential users.

Curry *et al.* (1980) — The Texas cotton/boll weevil model of Curry *et al.* (1980) is comprehensive and well-tested and provides good biological descriptions of the system. It was used to evaluate pest management strategies consistent with IPM objectives. For example, the model was used to investigate a variable treatment-level threshold for the boll weevil similar to the dynamic threshold described above. The variable treatment-level threshold gives priority to early-season fruit and decreases protection for late fruit (Curry and Cate, 1984). This approach adjusts treatment levels according to the following schedule: one percent damaged buds until first bloom, 25 percent until first 12-day-old bolls and 75 percent for the remainder of the season. Simulation analysis indicated that the variable treatment-level threshold improved control with fewer treatments, increased cotton yields and reduced the possibility of secondary pest outbreaks when compared to the standard 10 percent punctured-square threshold or the approach proposed by Walker and Niles (1971). The last approach calls for three applications at four-day intervals starting with the occurrence of one-third grown squares.

Curry and Cate (1984) also used the model to evaluate the impact of natural enemies compared to insecticide control, both alone and in combination with a 20 percent decrease in weevil development rates resulting from hypothetically altered host resistance. In the former case, natural enemies provide less control than insecticides; in the

latter, the combined effects produced excellent control without the use of insecticides. Additional model analyses examined combinations of other possible benefits resulting from altered host resistance, e.g., decreases in reproductive rates and increases in mortality rates of the weevil.

In an optimization study using the model, an economic analysis was conducted of multiple insecticide applications directed at the weevil in the absence of bollworm/tobacco budworm (Talpaz *et al.*, 1978). The analysis used a cumulative Weibull function to determine kill rates as a function of insecticide amounts. The results indicated that insecticide applications should be timed to coincide with critical windows during the development of the crop. Dosage rates, however, are sensitive to price changes in insecticide and cotton.

DEMHELIC (DEcision Model for HELiothis In Cotton) — This model collates information from diverse sources (Brown *et al.*, 1983; Gutierrez *et al.*, 1975; Hartstack *et al.*, 1976a, 1982; Hartstack and Witz, 1983; Room, 1979; Stinner *et al.*, 1974a; and Wang *et al.*, 1977) into a decision tool for bollworm/ tobacco budworm management (Hopper and Stark, 1987). It emphasizes the use of natural enemies as opposed to insecticides which disrupt natural enemy populations. A secondary objective is to minimize other negative influences of insecticide use, such as pollution, pest resurgence and secondary pest outbreaks. It does not employ population models *per se*.

A distinguishing feature of DEMHELIC is the use of small spatial (of or relating to space) and short temporal (of or relating to time) horizons. For example, the authors maintain that the spatial variation in bollworm/tobacco budworm populations is too great to permit accurate predictions within fields. This view is in contrast to that adopted by TEXCIM. Model corrections are made weekly or twice weekly using scouting data from the field. These brief horizons are also used because the effects of current management practices on bollworm/tobacco budworm populations and natural enemies are not well understood. For these reasons, DEMHELIC makes extensive use of sampling data on predator/parasite density, bollworm/tobacco budworm density and feeding damage, cotton growth patterns and weather. The program provides ranked management options to the user.

Gutierrez *et al.* (1979b) — Using optimization procedures with simulation results, these investigators analyzed the impact of western lygus bug on Acala cotton yields in California, both with and without the use of pesticides. Their results indicated that the insect is not a pest of cotton under most circumstances; rather, it often enhances yields. Yield enhancements occur because only very young squares are shed after injury from lygus, and this loss causes minimal impairment of the plant's ability to compensate. Pesticide applications against the insect reduced yields rather than increasing them. Reduced yields in combination with the cost of treatment lowered profits compared to simulation results with no treatment. The use of pesticides against lygus may also cause a resurgence of secondary pest species after the destruction of beneficials. In some cases, significant injury and economic losses can occur when large numbers of the western lygus bug migrate into cotton from cut hay.

Gutierrez *et al.* (1991a) — Using simulation analysis, Gutierrez *et al.* (1991a) examined the impact of the boll weevil on long-season Brazilian cottons compared to a short-season Texas variety. The analysis indicated that Brazilian cottons do not compensate as well for fruit losses due to nitrogen stress or the weevil. Instead, they allocate more photosynthate to vegetative growth rather than new fruit production. The Texas variety, bred to avoid weevil damage, produces greater yields than the Brazilian cotton because of its greater fruiting rate (which allows for the replacement of some shed squares), lower loss rate per fruit (fruit are smaller in size) and faster maturation times. The investigators concluded that cottons bred for maximum compensation for the boll weevil should require less insecticide for weevil control and return greater profits.

Stone and Gutierrez (1986b) — These investigators developed a management model for the pink bollworm by integrating pesticide and pheromone (gossyplure) routines into their cotton/pink bollworm model (Stone and Gutierrez, 1986a). The pesticide submodel assumes a maximum kill (to all adults and eggs on the foliage) at the time of the application; thereafter, the death rate decreases exponentially with time. The pheromone submodel reduces mating by applying gossyplure from discrete point sources (emitting devices). The number of active sources in the field depends on the number applied per acre (a model input), the loss rate of sources that drop off plants (a function of degree-days since application), and the number of applied sources that adhere to the foliage (a scalar computed from the cotton model output). The release rate of pheromone per unit area is described as an exponential decay curve. If the concentration of pheromone is above a minimum threshold, no mating occurs; if it is below the threshold, the effectiveness of the pheromone in reducing mating is a ratio of the actual concentration to the lower threshold.

Using the model, Stone *et al.* (1986) analyzed the economics of pheromone use for pink bollworm control, compared to and in conjunction with insecticides. This analysis indicated that early-season use of pheromones in combination with insecticides applied at low thresholds is the most profitable, especially at low pink bollworm population densities. The model has been used in the Palo Verde Valley of California (Gutierrez and Wilson, 1989).

TEXCIM (TEXas Cotton Insect Model) — TEXCIM (Sterling *et al.*, 1992) is a comprehensive collection of cotton insect and crop simulation models joined to an economic assessment package (also see Chapter 7, this book). A primary function of this integrated program is to provide crop managers with sound economic advice for making pest control decisions. This task is accomplished by comparing the costs and benefits of controlling multiple pest species over the duration of a growing season on a field-by-field basis. The program has undergone five revisions, each adding greater functionality through new or altered components, improved robustness through broader validation, and ease-of-use through editors, charts, and a windowing environment. Originally designed for use in Texas (available through the Texas Agricultural Extension Service), cooperators are now located in different cotton growing states and in several foreign countries. The present release (version 5.0) contains insect simulation models for the cotton fleahopper (Hartstack and Sterling, 1986), bollworm

(Hartstack *et al.*, 1976a), boll weevil (Curry *et al.*, 1980) and pink bollworm (Gutierrez *et al.*, 1977). It uses the plant model, SIMPLECOT (Wilson *et al.*, 1972).

The manner and extent to which TEXTCIM has adapted and applied extant simulation models is unique in cotton. The integration of individual simulation models, developed by numerous researchers during the 1970s and 1980s, is not a trivial task. As summarized in this chapter, these models are often large and detailed. For this reason, such a consolidation will likely not be duplicated. Rather, TEXTCIM may ultimately find additional value as part of other computer-based management systems presently under development. One such cooperative effort involves another Texas research group, in which TEXTCIM is being linked to a newer model, Integrated Crop Ecosystem Management Model, ICEMM (Benedict *et al.*, 1991; Landivar *et al.*, 1991). ICEMM contains the crop simulation model, TEXTCOT, which is a modification of GOSSYM (Baker *et al.*, 1983). Unlike SIMPLECOT, TEXTCOT is a physiologically-based model that accounts for photosynthetic production and allocation. This foundation provides greater realism to the cotton model and allows linkage to models of other herbivore pests such as sucking insects. For example, simulation models for the cotton aphid (Xie and Sterling, 1987) and sweetpotato whitefly (von Arx *et al.*, 1983) now reside in the integrated system. Also, the original bollworm model in TEXTCIM has been modified to form a new tobacco budworm model. TEXTCIM/ICEMM provides expanded advice on economically optimal crop management with regard to insecticides, fertilizers, irrigation, and plant growth regulators. It accomplishes this task by estimating the costs of these agronomic inputs, as well as the costs of consultants, insurance, interest, pest resurgence, pest resistance, on-farm health and environmental effects. These costs are compared to potential benefits derived from the use of the input(s), and if benefits exceed costs, the program recommends application.

REASONS FOR LACK OF FARM USE OF POPULATION MODELS

A vast amount of knowledge on agricultural systems came out of the research efforts of the 1970s and early 1980s, and much of this knowledge is summarized in the cotton crop/pest models. Despite the emphasis on implementing alternative management practices, most IPM models have not been used beyond their original research roles. With few exceptions, this research effort has served agro-management only indirectly. The application of population models to problem solving at the farm level was not fully realized for several reasons. We discuss below reasons specific to cotton. Coulson *et al.* (1990a) defined the problems associated with the development and operation of computer-based systems in forest pest management, which are similar to those encountered in agricultural systems.

Pyrethroids were introduced commercially into cotton in 1978. As this group of new compounds became more available and cost-effective over the next several years, the liberal use of insecticides was reinstated as the primary means of pest control. This result diminished the urgency to develop and apply alternative management strategies during the early 1980s. It was apparent that as long as insecticides remained practical, efforts to integrate pest management models into agriculture would be difficult.

By 1985, the "Huffaker and CIPM" projects that supported the research and development of the IPM models ended. Interdisciplinary teams conducting the research had recruited and retained excellent people during the tenure of these projects. However, without national backing, the administrative and financial support needed to preserve project continuity was lost. Many projects could not maintain adequate funding, resulting in their partial or entire disbandment. Accumulated knowledge, expertise and the momentum to accomplish the overall objectives were lost. The funding of pest management research returned to business as usual — encouraging discrete research projects with explicit short-term objectives leading to as many publications as possible. Given these constraints, it was very difficult to maintain interdisciplinary research teams working on system models. As Coulson *et al.* (1990a) stated it, "... the multidisciplinary format and centralized management approach for IPM research in forestry (and agriculture) have been virtually abandoned."

Not only did the simulation models go unfinished, but more importantly, so did the process of developing management interfaces for them. Adapting research models for farm use was a new and undefined task. Early attempts began in the mid-1980s but these were largely unsuccessful. Initial user/system interfaces were inflexible. They did not consider the manager's point of view or his way of doing business, hence they were not well accepted. The systems did not solve problems or make decisions *per se*; rather, they presented reports which had to be interpreted by the user.

Computer hardware was not ready for on-farm application of models. Most models were developed on mainframe or mini computers located at universities. These computers were the only machines that had the power to run the large models of the day. When attempts were made to distribute the models on these computers, access was difficult, costly and inconvenient for distant users. When personal computers (PC) became available in the early 1980s, they initially had limited power and prohibitive costs for individual farm use. Some models were written in computer languages that were incompatible with PC use (such as APL), and these had to be translated into FORTRAN as PCs became the machines of choice.

There was no organized method for delivering computer technology to user groups in agriculture until the late 1980s. Initially, interpreting model output was difficult and usually required research specialists. For the most part, researchers did not have the inclination to work with lay persons, and cooperative extension services were not capable of delivering this technology because of the lack of computer hardware and trained personnel. Solutions for delivering, supporting and maintaining computerized decision aids are still evolving. It is now clear, however, that resolution of these issues will require a partnership between the developers and practitioners, with an intermediary providing the link between research and application (Coulson *et al.*, 1990a). The intermediary could be an extension specialist, consultant or a technology transfer group similar to the one established for the GOSSYM/ COMAX/WHIMS system (see below). Ultimately, the resolution of these issues will determine the utility of pest management models on the farm.

There were problems with the simulation models themselves, perhaps best summarized by Gutierrez and Wilson (1989). They stated that "populations of organisms grow when birth and immigration rates are greater than death and emigration rates, and *vice versa*. The major problem in population ecology and IPM has been to define the reasons why these rates change over time and the consequences of that change on the population dynamics of pests, host plants and natural enemies. The complexity of even the simplest system has long stymied the development of 'realistic population models' for any species in nature."

The problem is not one of estimating the timing of insect life-history events. The models accomplish this task rather well. Rather, it is one of describing realistic age-specific birth, death and net immigration-emigration rates. It is extremely difficult to estimate changing abundance of populations through time and space. Take mortality for example, there are numerous biotic and abiotic factors that lead to the demise of pests; but methods for studying and quantifying their single and combined effects are not well defined. Nor do we have the ability to accurately predict future weather variables such as temperature that drive the models. These problems persist today.

INTEGRATED SYSTEMS

Stone (1989) argued that classical simulation models are inadequate as the unifying principle in IPM because they are not able to model the management process and integrate the diverse kinds of knowledge gained from the IPM projects. He believes "the process of IPM *is* management," and therefore, modeling the management process should be a major objective of IPM research. Stone (1989) called for the development of knowledge-based systems as the unifying paradigm (exemplary model) of IPM. These computer programs are designed to mimic human reasoning, the basis of decisionmaking, and can facilitate the integration of dissimilar types of information. Expert systems (ES) are the best-known examples of knowledge-based systems.

In general, expert systems have several attributes not provided by simulation models alone. These attributes include ease of incorporating management recommendations, developmental flexibility and a "user-friendly" interface for mathematical models. An "expert-in-a-box" approach is taken, capturing the knowledge of an expert (or experts) in the problem domain. A typical expert system consists of working memory, a knowledge base and an inference engine. Working memory holds the information specific for individual problems as they arise; this information is usually elicited from the user. The knowledge base is where the expertise resides, generally in the form of facts, rules (productions) and/or "frames" (Minsky, 1975). Facts are assertions about the state of the problem domain such as "the temperature is above 90F" or "there is an average of four weevils per pheromone trap." Facts provide the basic ability to represent simple, declarative knowledge.

Rules are made up of an antecedent (the "if" part) and a consequent (the "then" part). The knowledge they encode is heuristic in nature: "IF condition A exists, THEN action B should be carried out". The "action B" can represent addition (or "assertion")

of an inferred value to the knowledge base, performance of a procedure or mathematical function or advice to the user regarding the results of an evaluation.

Frames are efficient structures for storing related knowledge. Each frame consists of one or more "slots", which contain the slot name and one or more values. For example, the frame "cotton plant" might have the slots "plant height", "number of leaves" and "number of nodes" with their associated values. Most frame constructs allow a variety of items such as procedures (called methods or demons) or groups of related rules, to be put in slots. Frames allow data and associated methods to be stored together. It is thought that human beings store knowledge in conceptually similar structures, called "schemas" (Stillings *et al.*, 1987). Composite frame-and-rule-based expert systems provide powerful representational and reasoning mechanisms.

Pest management has proven to be a particularly fertile area for the application of expert systems technology. Subject areas range from rangeland grasshopper control (Kemp *et al.*, 1988) to grape pest management (Saunders *et al.*, 1987) and pesticide risk analysis (Messing *et al.*, 1989). At present, there are four expert systems for managing cotton pests in the United States. The systems are COTFLEX (Stone *et al.*, 1987; Stone and Toman, 1989), CALEX/Cotton (Plant *et al.*, 1987; Plant, 1989a), GOSSYM/COMAX/WHIMS (McKinion and Olson, 1992; Olson and Wagner, 1992), and CIC-EM (Bowden *et al.*, 1990).

COTFLEX, CALEX/Cotton and GOSSYM/COMAX/WHIMS are similar in scope, with pest management being a component of the larger farm-level system. They are designed to accommodate both simulation models and rule-bases as knowledge sources. CIC-EM, on the other hand, is a stand-alone expert system that models cotton pest management in Mississippi. It is not coupled to simulation or other management models. The details of this expert system are summarized first.

CIC-EM (Cotton Insect Consultant for Expert Management) — CIC-EM (Bowden *et al.*, 1990) is a classic rule-based expert system that deals with the management of cotton arthropod pests in Mississippi. Thirteen pests are included: thrips, cutworms, plant bugs, boll weevils, bollworms/tobacco budworms, aphids, spider mites, western flower thrips, *Frankliniella occidentalis* (Pergande), bandedwinged whiteflies, *Trialeurodes abutilonea* (Haldeman), cabbage loopers, *Trichoplusia ni* (Hübner), beet armyworms, yellowstriped armyworms, *Spodoptera ornithogalli* (Guenée) and fall armyworms, *Spodoptera frugiperda* (J.E. Smith). The knowledge contained in the program was acquired primarily from a cotton entomologist at Mississippi State University. As the result of interviews with the expert, various scenarios for pest problems were assembled, as were management recommendations for solving these problems. Because of the many possible problem scenarios, a program was written to examine the scenarios and construct a set of rules for each. This program, called the Knowledge Acquisition Program, constructs and displays the scenarios, and allows the expert to enter his recommendation. Using a pattern-matching algorithm that scans the scenarios for regularities, Knowledge Acquisition Program constructs rules that are then used in the knowledge base. Over 5,200 problem scenar-

ios were evaluated to yield 750 rules. The rules are partitioned into 13 sections along taxonomic lines.

CIC-EM evaluates a problem via question-and-answer interaction with the user. Ten to 14 questions are asked before generating a recommendation. A consultation begins with a request for the planting date and current date. The program then moves into the crop-stage identification module, where the user selects one of eight possible stages of crop phenology. After determining the crop stage, CIM-EM requests the name(s) of the pest(s) to be controlled. There are help sessions and pictures to aid in pest identification. Finally, the program invokes the rule-base partition(s) that pertains to the chosen pest(s). Using these rules, conclusions are reached which consist of recommendations and a list of pesticide application rates.

COTFLEX (COTton Farm-Level EXpert) — COTFLEX contains “advisors” in three areas of cotton production (Stone and Toman, 1989). The Farm Management Advisor and Farm Policy Advisor are small rule-bases that call and analyze the results of simulation models. The Pest Management Advisor is a more complex rule base, reflecting the nature of the pest management problem. This problem has two important features. First, pest management decisions have a strong temporal component that requires understanding of past and expected trends in crop and pest status. Second, because the agroecosystem is complex, it is impossible to enumerate all possible problem situations.

To address the temporal issue, COTFLEX stores field histories in frames. (In purely rule-based systems, the storage of related facts is inefficient for more than nominally complex situations.) From this standpoint, COTFLEX is a hybrid rule-and-frame-based system. Frames are used to store complex data and knowledge, and rules are used to perform reasoning tasks based on this information. Probably because rule-and-frame-based development environments (so-called shells) were not available at the time of initial COTFLEX development, Stone and Toman (1989) modified an existing rule-based system (CLIPS, developed at NASA) to accommodate frames. There are now many commercial shells to facilitate the development of these systems [e.g., ART-IM (Inference Corp., Los Angeles, California) and Nexpert Object (Neuron Data, Palo Alto, California)].

Model-based reasoning techniques are used in COTFLEX to deal with the inability to specify *a priori* all possible problem situations. When the system does not know the answer to a problem (i.e., when the problem is inadequately specified), it can examine a so-called “deep model” of the problem domain. This model can provide mechanistic detail about the operation of the system that is not easily embodied by “if-then rules”. One form of model-based reasoning is the use of COTTAM (Jackson and Arkin 1982), a cotton simulation model. COTTAM provides COTFLEX with estimates of cotton phenology. A second variety of model-based reasoning is provided in rudimentary form via a rule base that embodies causal relationships within the agroecosystem.

CALEX (CALifornia EXpert) — This program exists in two versions: CALEX/Peaches (Plant *et al.*, 1989) and CALEX/Cotton (Plant *et al.*, 1987; Plant, 1989a,b).

More so than COTFLEX, CALEX is an "agricultural expert system shell", with inference engine, user interface, rule-language and related system components specialized for the development of management aids for agroecosystems. Thus, the knowledge in each version is specialized for a specific crop. Within each version, tasks are divided like those in COTFLEX — each has different knowledge modules and associated models. We concentrate on CALEX/Cotton, specifically the arthropod-pest component (Plant and Wilson, 1986). The system contains modules for spider mites and plant bugs.

There have been major revisions in the way CALEX makes recommendations for these two pests. These revisions illustrate the rapid changes taking place in computerized decision aids in agriculture. The original methodologies are discussed in Plant (1989a) and the innovations in Plant (1989b).

In the original version of CALEX, knowledge is stored entirely as rules (Plant, 1989a). For example, the spider mite module contains about 30 rules on in-season scouting and treatment (Plant and Wilson, 1986). The program uses a regression scheme devised by Wilson *et al.* (1985) who found that the number of infested leaves increases asymptotically over time to 100 percent. The rule base attempts to fit a non-linear regression curve to data provided by the user. CALEX recommends in-field scouting a few days before the date of the predicted economic threshold (50 percent infested leaves). If insufficient data are available to fit the curve, simple heuristics (rules-of-thumb) are used to recommend scouting and treatment.

Plant bugs are handled with a smaller rule base that divides the season into two parts, early and mid-to-late (Plant and Wilson, 1986). Early-season treatment is recommended if the projected damage is severe enough that the crop might not have time to compensate. Mid-to-late season rules follow the University of California IPM manual for cotton (Anonymous, 1984).

Recognizing the uncertainty involved in agricultural decision making, CALEX applies certainty factors as antecedents to rules. The conclusions drawn from these rules are displayed as categories, based on the value of the derived certainty factor (c); e.g., most likely to occur ($c = 1.0$), very likely ($1.0 > c \geq 0.75$), reasonably likely ($0.75 > c \geq 0.50$) and possible ($0.50 > c \geq 0.25$). Conclusions with $c < 0.25$ are not displayed. This approach provides the user with knowledge of all reasonable conclusions.

CALEX views agricultural management as the planning and scheduling of in-season tasks, called "actions" (Plant, 1989a). For instance, a scouting trip to the field is scheduled when spider mites become a potential problem. Scouting for mites consists of walking through the field and counting the number of infested leaves in a sample (Wilson *et al.*, 1985). Obviously, field conditions can influence the ability to accomplish this task. Thus, other management actions directed at the field may come into conflict. For example, a field may be difficult or impossible to work in during or shortly after an irrigation event. Irrigation conflicts with scouting, and so does the application of pesticides and fertilizer. In the first version of CALEX, this problem is handled by a simple prioritization scheme with higher priority actions scheduled first. Irrigation has the highest priority, and so the program schedules this activity first. If the best day for scheduling a lower priority action (such as scouting) occurs when the field is wet, the action is rescheduled.

Although the original CALEX often worked well, it had three deficiencies (Plant, 1989b). First, rule bases are inherently unstructured; there are no explicit links between related items. This makes for needlessly inefficient storage and access of information that can naturally be arranged in related groups. Also, it is difficult to incorporate procedural knowledge in a rule base. Second, there are more complex interactions between actions than just time conflicts, and a simple prioritization scheme is inadequate for handling them. For example, spider mites may favor lush vegetation, prompting a recommendation to reduce irrigation in the face of high sub-threshold mite infestations. Finally, management recommendations are synthetic — they require integration of results from multiple lines of reasoning into a coherent output. The production-rule model does not efficiently deal with this type of problem.

To address these issues, basic design changes were implemented in CALEX (Plant, 1989b). Frames are now used to facilitate the storage of related knowledge in one place in the system. Frames also allow for efficient storage of, and access to, procedural knowledge in the form of methods. These procedures are stored in slots and can be accessed and activated as readily as any other piece of knowledge. For example, a mite activity frame contains data-set slots, influence-list slots (containing a list of all factors that influence an activity), and methods such as “above threshold” and “scouting date”.

Farm management involves multiple objectives that are often carried out by different individuals. To deal with these problems, CALEX uses ideas from the artificial intelligence field of multi-agent planning (Konolige and Nilsson, 1980). The activities are treated as semiautonomous entities; all communication between them is accomplished through a central structure known as a blackboard. A critic module examines the blackboard and each activity to determine if there are conflicts between them before a schedule is finalized. To implement this structure, an object-oriented design was adopted. In object-oriented programming, program modules are self contained, autonomous and communicate with each other via messages. Each program unit does not need to know anything about the inner workings of the others.

GOSSYM/COMAX/WHIMS — GOSSYM/COMAX (/Cotton Management eXpert) represents the longest continuous research effort directed at building and applying a cotton simulation model. Experimental work began in 1964 and continues today with a collaborative insect modeling effort (Williams *et al.*, 1990). The cotton models developed during the IPM projects have their biological origin in SIMCOT II, a forerunner to GOSSYM. GOSSYM was the first cotton model to run with the assistance of an expert system, COMAX (Lemmon, 1986). While the IPM models have not been widely used by individual farmers, GOSSYM/COMAX is on many farms beltwide. The successes of this system prompted the formation of a specific group to address issues of technology transfer. The GOSSYM/COMAX Information Unit (GCIU), funded by Federal Extension Service, trains system users, promotes the transfer of the model from the research group to extension service personnel, consultants, and producers, and conveys user sentiments back to the research group for further research and development.

rbWHIMS (rule-based Holistic Insect Management System) is the pest management component of GOSSYM/COMAX/WHIMS (Olson and Wagner, 1992). It takes advantage of recent advances in software development technology, especially in the area of object-oriented programming (OOP). The idea of object-oriented programming is not new in agriculture. COTFLEX (Stone and Toman, 1989) has object-oriented elements, as does CALEX (Plant, 1989b). Sequeira *et al.* (1991) developed an object-oriented cotton model, and another is under development under the auspices of the cotton production modeling project (Sequeira and Olson, 1993). The advantages of object-oriented paradigm fall into two categories: functional and epistemological (Olson *et al.*, 1990a). The functional features are well documented (Thomas, 1989) and facilitate the maintenance and modification of complex computer systems. They are not discussed in detail here.

Epistemological (or representational) advantages stem from two facts (Olson *et al.*, 1990a). First, in a pure object-oriented paradigm system, the fundamental unit is the object. Objects consist of procedures and data. As such, the object is similar to a frame — the procedural and declarative code (i.e., the related data) are stored together as objects and accessed through a common interface. There is one critical difference, an outside procedure can directly access and modify the data in a frame. This is not the case with an object where only an object's methods can access and/or modify its data. Object orientation is intuitively pleasing because it is similar to the way we view the world — as a collection of objects, not as a collection of functions as in conventional programming techniques.

Another advantage of object-oriented paradigm, particularly with respect to modeling biotic systems, is that systems of objects can be defined hierarchically. Objects lower in the hierarchy are specializations of those at higher levels, and they “inherit” methods and sometimes data from objects above. This structure is important, because the organization of natural systems can be viewed hierarchically. The modular nature of methods, coupled with the hierarchical structure, allows detail to be represented and manipulated at multiple levels in the organization of the agroecosystem.

rbWHIMS was developed to take full advantage of the features of object-oriented programming. It contains three principal components: WhimsModel, WhimsManager and a Graphical User Interface. WhimsModel contains a static, qualitative model of the cotton/pest ecosystem (rbWHIMS does not model ecosystem dynamics explicitly, although simulation components are under development). Objects present in WhimsModel represent major components of this ecosystem. There are population objects that embody all of the pest species handled by rbWHIMS. Field, crop and management-unit objects model these aspects of the system.

As the name implies, WhimsManager manages the operations of rbWHIMS. It controls the interactions between the system and the user (through the Graphical User Interface), the accessing and operation of the rule bases and the consolidation of information and issuing of reports. Like CIC-EM, COTFLEX and CALEX, the mechanism by which rbWHIMS evaluates data and renders decisions is by the “if-then” decision rule. Unlike these systems, however, rbWHIMS is not a production-rule system.

In the production system model, the knowledge base is composed of a fact component (the fact base) and a rule component (the rule base). The fact base holds information about the specific problem being addressed, and the rule base contains the decision rules elicited from an expert. The inference engine searches the rule-base until a rule is found that matches the fact base (Waterman, 1986). When a rule is executed, one of two things happen: either a recommendation is given to the user (and the process stops), or the rule changes the information in the fact base. If the latter occurs, the inference engine searches the knowledge base again, finding the state of the fact base to be different. Therefore, a different rule will match the known facts and will, in turn, be fired. In other words, the state of the fact base determines the order in which the program executes. This characteristic gives the production system much of its power and flexibility. However, the cost in terms of program size and execution speed can be significant. An inference engine is a necessary component of the application, and repetitive searches of the knowledge base are time-consuming.

Due to the nature of cotton pest management, the developers of rbWHIMS decided that a production system approach was not needed. All the information required to make a recommendation is known in advance, as is the order in which the information is used (i.e., the order in which the rules will fire). Thus, an inference engine, *per se*, is not a part of rbWHIMS. Instead, the data needed to render a decision are collected by an object contained in WhimsManager. After manipulation, the data are passed to the rule base contained in WhimsModel, which is segmented into tree-like objects called RuleTrees. Each pest species has a set of Rule Trees. The cotton crop is divided into eight distinct, phenological plant growth stages (Williams *et al.*, 1991); and each Rule Tree is valid for one or more of these stages. RuleTrees write their recommendations to a Blackboard.

The third major component of rbWHIMS, the Graphical User Interface, provides a mouse-driven, windowing interface for the system. It is implemented in Microsoft Windows 3.1 (Microsoft Corporation, Redmond, Washington). The Graphical User Interface provides data-entry capability, menus for controlling the operation of rbWHIMS and a report-generator. The user enters field scouting information through on-screen forms displayed by the interface. These data are then used to update the state of WhimsModel. When the user requests a recommendation, a report is written that summarizes the scouting data and the recommendations provided by the system.

rbWHIMS is written in C++, an object-oriented variant of the C programming language. It currently provides management advice for the Midsouth on cutworms, boll weevils, bollworms/budworms, bandedwing whiteflies, early- and late-season plant bugs, early- and late-season thrips, spider mites, aphids, and the armyworm complex fall, beet and yellowstriped armyworms. It underwent field evaluation in 1991 and 1992, and a formal pilot test began in 1993.

The WHIMS project also has a companion sampling research effort designed to provide precise field estimates, at the least cost, for use in the model. This research is adapting innovative techniques for use in agriculture. For example, a method of scouting pest populations is under development using Bayesian statistical methods (Willers

et al., 1990). Also, an expert system component will apply Bayesian probabilities to evaluate the precision of the scouting data used in the model. This information will increase the confidence (certainty) of decisions provided by the model.

COTFLEX, CALEX and GOSSYM/COMAX/WHIMS illustrate a growing trend in the development of agricultural expert systems. Because of the complex nature of agroecosystem management, a simple rule-based format has proven inadequate. System developers are turning to advanced techniques from artificial intelligence and other branches of computer science to aid in managing large, complex bodies of knowledge. This trend is discussed below.

THE FUTURE OF MODELING COTTON PEST MANAGEMENT

The future of modeling in cotton pest management appears bright, although the models of today and tomorrow are extended in definition beyond the pure simulations of a decade ago. The on-farm successes of GOSSYM/COMAX (McKinion *et al.*, 1989) indicate that if systems are easy to use and provide a valuable service, their acceptance will be forthcoming. The organizational and synthetic abilities of computers enable large amounts of knowledge to be placed at the disposal of farm managers. Knowledge-based systems, with their ability to integrate and interpret diverse information, provide the basis for delivering powerful farm-management applications.

Jones (1989) surveyed agricultural expert systems to assess the overall viability of this technology in agriculture. He divided the existing applications into five varieties: heuristic expert systems, real-time expert systems, model-based expert systems, expert databases, and problem-specific shells. Heuristic (rule-based) expert systems are those that, in Jones' words "come close to the original concept of an expert system based on the 'seat-of-the-pants' knowledge of a tried and true expert." Although Jones (1989) predates Bowden *et al.* (1990), CIC-EM is clearly of this type. The second variety, real-time expert systems, use expert knowledge to monitor sensor data and to control instrumentation. Model-based expert systems link expert systems to simulation models to facilitate the use of the model. COTFLEX (Stone and Toman, 1989) and GOSSYM/COMAX/WHIMS (McKinion and Olson, 1992) represent this type. The fourth variety, the expert databases, link expert systems with databases to assist in the retrieval and organization of certain classes of information. Finally, problem-specific shells provide a framework within which to develop agricultural expert systems. CALEX (Plant, 1989a) falls under this category.

Jones (1989) identified heuristic (rule-of-thumb) expert systems as the least effective of the five categories for addressing agricultural management. He attributes this to the type of problem domain chosen in agriculture. When the problem is sufficiently narrow and well defined, the pure heuristic approach tends to be successful. When the domain is ill-defined and broad, the classic expert system is less viable. This attribute of rule-based systems is well known. Waterman (1986) defined a viable expert system domain as one that is narrow and well-defined. The problem domain of CIC-EM

(Bowden *et al.*, 1990) appears to be broad; there are about 750 rules for thirteen pest species. However, because the rule-base is partitioned, CIC-EM is more akin to thirteen small systems that fit the classic, narrow-domain mold. Similarly, rbWHIMS (Olson and Wagner, 1992) partitions the knowledge base (into Rule Trees) along species lines and crop stage.

Many of the tasks within agroecosystem management are too complex for the classical heuristic approach (Olson *et al.*, 1990b). Agro-management requires integration and use of advice from multiple, sometimes conflicting, experts. Further, the manager must synthesize knowledge from diverse fields. As Plant (1989b) pointed out, agroecosystem management is synthetic, and rule-bases are simply inefficient at representing such problems.

In the face of the intricate nature of agroecosystem management, builders of integrated decision-support systems in agriculture are taking advantage of developing technologies from areas of computer science, particularly artificial intelligence. As we have seen, recent systems reflect this trend in areas of object-oriented programming, causal modeling, multi-agent planning and uncertainty in decision making. In all likelihood, these trends will continue. For example, the area of causal (or qualitative) modeling (Weld and de Kleer, 1990), briefly mentioned under COTFLEX, continues to be developed in natural resource management (Schmoldt, 1991). Much of what we know about any biotic system is non-quantitative. It consists of relationships like "organism A increases as organism B decreases" or "temperature effectively limits the growth of organism C". Although these relationships are easily captured as mathematical functions, the data to parameterize these functions are often not available or, if available, are only valid for the locations and conditions under which they were collected. Olson *et al.* (1990a) maintain that qualitative relationships are often sufficient for modeling purposes, especially if the aim is not to predict actual system quantities.

Uncertainty is another area being explored in decision-support systems. Olson *et al.* (1990b) summarize the issues in natural and agricultural management, where uncertainty results from inexact measurement of system quantities or limited knowledge of system mechanisms and behavior. The Bayesian techniques under development in GOSSYM/COMAX/WHIMS address the former issue, where techniques assess the reliability of scouting information used in the model and help determine the confidence of decisions made by the model. As we have seen, CALEX/Cotton uses a certainty-factor scheme to assess the second type of uncertainty — that associated with limited knowledge. Elsewhere, Schmoldt (1991) applies fuzzy-logic techniques (Zadeh, 1965) to simulate red pine growth. Using these techniques, a causal model is developed that incorporates uncertainty in the knowledge of red pine growth and physiology. Olson *et al.* (1990c) propose another combined qualitative modeling/uncertainty technique for use in pest management systems, the Bayesian belief network (Pearl, 1988).

Spatial reasoning is another area of rapid development in decision support systems. Entomologists have long recognized that pest problems usually exhibit landscape-scale dynamics. In cotton, the only arthropod pest that is host specific in the United

States is the boll weevil. For many pests, cotton is an alternate or secondary host. These pests develop on other crops and wild hosts scattered throughout the landscape. Often they move sequentially among crops; some even migrate long distances. Therefore, the spatial and temporal scale of multiple cropping systems are important from a pest management perspective. Geographic information systems are an important tool for quantifying, modeling and manipulating this type of information.

A geographic information system is basically a database for storing spatially-registered information (Star and Estes, 1990). This information is classified by type, and stored in thematic layers. For example, a common layer contains elevation data; another layer might contain soils information, and a third might hold vegetative data. The information in each layer is spatially registered — that is, each bit of information about the layer's theme is correlated with an area that is located in some coordinate system. Each layer can be overlaid on other layers in any combination. Thus, inferences about the correlations between different values of each theme can be made. Geographic information systems usually contain sophisticated mapping features so that correlations can be visualized. They also offer, to a greater or lesser degree, software packages that allow analysis of spatial characteristics and the rectification of digital images with known coordinates.

Geographic information systems are presently being used in natural resource management, and in the past few years development has begun in support of pest management. Integrated computer systems that contain geographic components include HOPPER (Kemp *et al.*, 1988; Berry *et al.*, 1991) and the Jack Pine Budworm Decision Support System (Loh *et al.*, 1991). In HOPPER, a geographic information system helps predict the level of rangeland grasshopper infestations in conjunction with a management rule base and simulation models. The system for jack pine budworm uses a geographic information system, simulation models and a knowledge-based system to handle separate tasks. These components are linked by a database/interface that provides a common language and "look-and-feel" for all components. In cotton, a stand-alone geographic information system describes boll weevil populations in Mississippi (Smith *et al.*, 1993).

While the computer software developments mentioned above are moving agricultural models forward, they have been made possible by equally impressive progress in computer hardware. The rate of advancement has been astonishing, with no change in sight. Presently, PCs operate at about 100 MHz clock speeds and cost as little as \$2,500. Whereas it was once thought that computer speed and cost might limit model size and application, these concerns are no longer issues of importance.

Perhaps no other research program better documents the maturation of pest management models than the Southern Pine Beetle project at Texas A&M University. This effort spans more than two decades and illustrates the continuous changes in computer hardware and software that have driven model development and application. Experimental work on beetle population dynamics began in the early 1970s as part of the IPM project. By 1980, this research led to the development of the simulation model, TAMBEETLE (Coulson *et al.*, 1989a). The first applied product, the Southern

Pine Beetle Decision Support System, SPBDSS (Rykiel *et al.*, 1984), followed in 1984. This interactive program was designed to help forest managers solve unstructured pest problems by integrating numerous models and data-bases within a single framework. It did not solve problems directly, rather only supplied managers with supplemental information for decision making. The system lacked heuristic knowledge from experts, and this shortcoming (among others) led to the development of the Integrated Southern Pine Beetle Expert System, ISPBEX (Flamm *et al.*, 1991). ISPBEX presently contains simulation models and a treatment advisor. The advisor contains a rule base and two data bases that archive information from a national forest on beetle infestations and the red-cockaded woodpecker (an endangered species that influences beetle management). During its development, interest in beetle population dynamics shifted from single (within-spot) to multiple (among-spot) infestations. This interest led to the development of an intelligent geographic information system by the late 1980s (Coulson *et al.*, 1990b). In this system, rules are used to automate decisions based on the spatial relationships identified by the geographic component. As the integrated system enlarged, however, problems arose in connecting and maintaining the disparate components. Recognizing this, Coulson *et al.* (1989b) introduced the Knowledge System Environment, a framework that provides a protocol for connecting and interpreting diverse sources of information. Such a protocol makes it possible to add new components to extant systems.

Although we cannot predict the exact nature of agricultural models of the future, history provides important insights into their development and use. For all practical purposes, models will not be limited by computer hardware and software. In fact, the rapid technical changes in these areas are driving model development. If for no other reason than this, models will continue to increase in size and complexity, integrating new components that increase their function and ease-of-use. Today, and in the future, the factor limiting model development and use is reliable information on the dynamic biological and physical components of the agroecosystem. Reliable information is central to our ability to describe system behavior and draw sound conclusions (advice) from the models. In this sense, we have not progressed very far from the 1970s. Support of basic experimental research is essential if computerized decision aids are going to increase in function and value.

CONCLUSIONS

Sound decisionmaking in agriculture is difficult because of the complex and dynamic nature of the biotic, edaphic, climatic, economic, social and political systems involved. Decisions are often based on information that is incomplete, inaccurate, outdated or simply not available. When reliable information is available, it often describes distinct features of the production system, independent of other related factors. In formulating decisions, it is up to the farm manager to put this information into context with associated facts. Because of man's limited knowledge and experience with all aspects of the cropping system and difficulty in combining and evaluating the impact

of multiple, interacting variables on different aspects of the system, decisions are often deficient or even ill-advised. By nature, man prefers limited information on which to derive simple solutions; after all, the easy approach to problem solving is convenient, more-or-less effortless and often saves money in the short-term. Unfortunately, simple solutions rarely resolve complex problems adequately.

We demonstrate other attitudes that frustrate efforts to solve complex problems. For example, pending problems are frequently dealt with in a restrained manner, and we avoid taking action to the very last. In this sense, we are crisis-oriented. In agriculture, what constitutes a crisis with regard to pest management has been altered over the last 40 years and can be described by the general cliché, “the only good bug is a dead bug.” This conviction is particularly apparent in high-value crops because of the potential losses that can result from arthropod pests. The situation demonstrates an interesting paradox. Whereas we usually are slow to address problems, this often is not the case in agriculture. Many times managers “shoot first and ask questions later” (e.g., resort to direct control when no control is needed). Just as our perception of and response to pending problems are learned, so too can our attitudes and behaviors be modified.

Clearly, individuals (and corporations) must solve problems in a cost-effective manner if they are to prosper in a competitive world marketplace. Unfortunately, experience teaches us that the quick-and-easy approach to problem solving does not always produce sound and lasting results, especially when all aspects of the production system are concerned. Consider the environment for example. What constitutes responsible problem solving from an economic and environmental standpoint is not always clear. Business considerations involving these two issues often come into conflict, with the latter losing out to the former. We are aware of this conflict more today than ever, with numerous actual or potential environmental problems in the news — industrial by-products degrading the air and water, global warming altering the climate and vegetative patterns, acid rain spoiling the lakes and forests, a diminishing ozone layer threatening public health, hazardous waste dumps littering the landscape, and a loss of topsoil degrading fertile farm lands. The fact is, there has been widespread abuse of the environment, and we can no longer be complacent of its quality. Who is responsible for its safeguard? The problem is one of scale — numerical, temporal and spatial. Individual farmers must address immediate problems (within a growing season) on a particular field(s). Within this context and to that farmer, most solutions have significant economic impact but trivial environmental impact. Unfortunately, most arthropod pest problems are regional in nature, and the management practices directed against them are usually identical. Over the years, the combined actions of all individuals in a region do have impact, and the problems arising from our ubiquitous and heavy use of agricultural chemicals constitute an excellent case in point (refer to the **Introduction** section of this Chapter).

The farmer traditionally understands man’s relationship to, and dependence on, the environment. His choice of professions symbolizes this fact, which today is ironic because agriculture has become so synthetic. Man’s desire to separate himself from and control nature, as opposed to integrating and working with it, is pervasive in mod-

ern society. Partly as a result, agriculture has changed from a way of life (a practiced philosophy) to a way of living (an enterprise).

In his classic monograph, *Insects and Climate*, Uvarov (1931) presents lasting insight into the nature of pest problems in agriculture. He states, "entomologists of the present day are no longer satisfied with merely recording the outbreaks of insect pests and with devising means for their control. They realize more and more that their chief aim and highest ambition must be to foresee and to prevent outbreaks. In order ... to do this, all conditions accompanying and causing outbreaks must be thoroughly investigated and elucidated; in other words, the epidemiology of insect pests must be the central problem of ... research, which should be carried out from the ecological point of view. The ecological conception of economic entomology consists in the recognition of the injurious insect as an integral part, and even as a product, of its environment."

One of the primary goals of entomologists is to predict pest outbreaks far enough in advance to avert disaster through proper management of pest and host (crop) populations. Surveys, or scouting, have traditionally been combined with intuitive reasoning to perform these tasks, but it is clear from the above passages that we have long dreamed of doing better. We have new opportunities to achieve this goal; however, to take advantage of them, some changes are required. The changes will not only alter our way of doing business, but our way of thinking about crop and pest management. For example, producers (and consumers) must be willing to accept some losses from agricultural pests if they are to manage populations effectively and responsibly. It is preferable to accept small losses from several pest species than significant losses from single species. This strategy does not necessarily imply greater risk.

It is unreasonable to expect producers to unilaterally alter their way of doing business without others doing the same. It is the responsibility of the entire agricultural community to provide viable, alternative management options that will ensure a competitive advantage to U.S. farmers. Computer models of crop production and management will assist in this task by providing better use of information on all aspects of the cropping system. By their very nature, these models will be complex and will require sustained, interdisciplinary efforts in their development and testing. For these reasons, modeling endeavors should not be viewed simply as research "projects", with definitive beginnings and endings. We have made this mistake before. Rather, they should be viewed as an approach to planning, conducting and transferring research knowledge. Such endeavors will provide a comprehensive and dynamic set of strategies for optimizing the costs and benefits of crop production and protection. Commitment to this approach should be widespread and lasting.

SUMMARY

This chapter charts the history of cotton pest modeling, describing the events and models leading up to the present. Examples of future systems, as we see them, are also proposed. The application of systems analysis to the study of agroecosystems, and the development of mathematical models to describe the population biologies of interacting plants and animals in these systems, has an interesting past. Cotton modeling has its origins in the 1960s and continues today with the development and application of computerized decision aids for farm management.

There have been many contributors to this fledgling science from across the Cotton Belt. Early researchers, such as the interdisciplinary teams of the "Huffaker" and "CIPM" Projects, used population models as a unifying principal of IPM. These simulation models were applied primarily as research tools, often for devising and evaluating new pest management strategies. In recent years, with the advent of economical and fast personal computers running advanced software systems, new applications have extended this technology to farm use. Simulation models are now being used in conjunction with expert systems of varying degrees of complexity. These integrated systems are designed to assist farm producers and advisory specialists in making ecologically sound decisions that optimize the costs and benefits of cotton production and protection.

Arthropod pests will continue to compete with man for food and fiber resources, and multiple tools will be needed to meet this challenge. Computers are one of these tools, and will serve an important and ever expanding role in crop management of the future. As with any new technology, however, there has been reluctance by some to embrace the modeling approach, to alter old ways of thinking and doing business. To date, their caution may be justified; the development and application of complex modeling systems have not been trouble-free. Nevertheless, the technology will prevail because useful innovations always do. The strong advocates of this approach have recognized its actual and potential value to research, education and management. Their tenacity and vision represent a challenge to all those in agriculture — to cooperate in building viable management systems that will enable U.S. farmers to maintain a competitive advantage yet be conservators of the environment.