Components and Techniques of Integrated Pest Management Threshold Determinations for Soilborne Pathogens

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ABSTRACT
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Thresholds are levels of pest and pathogen stress to a crop that are used as a basis for management decisions. By definition, the threshold has an underlying economic basis and is a function of the relationship between the biological stress and crop value and the relationship between cost and stress reduction. Development of threshold levels usually involves determining parameter values for models that describe these relationships. The nature of the models may vary with the length of the planning horizon and the volatility of the biological systems involved. Parameter values are affected by biological, economic, and environmental conditions of the production system.

The term threshold is variously used and defined in integrated pest management (IPM). Literally, threshold indicates the point at which some effect begins. In IPM, it is used to describe 1) the point at which damage is first seen (also called the damage threshold or tolerance limit); 2) the point of first economic loss for a given control cost (the point at which the value of the crop loss is equal to the cost of control, also referred to as the discrete-choice threshold) (15); and 3) the point of maximization of profit (the point at which the difference between crop value and pest control cost is greatest). Note that the threshold is a measure of biological stress imposed by the pest or pathogen. It may be quantified in terms of population densities of individuals or as some measure of disease or damage severity. Essentially, the threshold is a decision point, as appropriately defined for the particular usage, and it is constant for the boundaries and constraints specified. In the general sense, however, the threshold for a particular crop and pest combination is not static but is influenced by the favorability of the environment for both pest and host plant and by current economic conditions (management costs and crop values). Furthermore, it will vary with location, season, and phenological status of the crop at the time the decision is being made.

There are longer term temporal considerations related to thresholds. The threshold determined for a single growing season may differ from that when the decision horizon is extended over several growing seasons. Management of a pest to a specific level to maximize profits in a single growing season may exacerbate problems for subsequent growing seasons, resulting in a suboptimal management decision for the long term.

CONCEPTS AND MODELS

Within the definition of the threshold concepts described, there are two major component functional relationships. Each of these relationships has parameters that may be known with varying levels of certainty (15). The damage function is the mathematical description of the relationship between plant yield and biological stress (population densities, disease

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severity, etc.) and may be used for explanatory and/or predictive purposes. The basis for a rational approach to economic threshold decisions for pest and pathogen species lies in the expectation that a relationship between numbers of the pest organism and the yield or value of the crop can be determined.

Although soilborne pathogens may pass through several generations during a single crop season, they generally spread only slowly from plant to plant because of relative immobility and the impedance of the soil medium. Consequently, their epidemiology shows many of the characteristics of simple-interest diseases (19). For threshold determinations in annual crops and relatively short-range decisions, simple deterministic models have been used. Frequently, these are critical-point models relying on a single observation of the plant and pest system as a basis for predicting the future behavior of the system (5,7). The application of critical-point models descriptive of the relationship between pathogen densities and crop yield has utility in annual cropping systems because many management alternatives for soilborne organisms require preplant decisions (5,7). Because the soilborne population is present at the time of planting, it is not necessary to consider the phenological state of the crop at an unpredictable time of pest invasion, as might be the case with an aboveground pathogen. Infection is likely to occur relatively predictably at a certain stage of plant development or under defined environmental conditions.

For perennial crops or more dynamic pathogen systems, a more detailed consideration must be given to the temporal relationship between pathogen and plant. This relationship can be influenced by plant age, reintroduction, and buildup of nondetectable initial levels of the pathogen with time and seasonal effects that have an impact on temperature-dependent development rates. Here, multiple-point models to predict the behavior or trajectory of the system are based on a series of observations over time. Analytical descriptions of disease progress curves and disease severity have been developed by relating yield reduction to cumulative propagule counts or symptom expression (2,4,16). Frequently, losses are closely related to the area under the disease progress curve (1,19) or to multiple observations of disease severity at various stages of host development (18). Serial observations of disease allow determination of the rate of change in the pathogen population and of the rate of increase of damage to the crop (12,13).

Noling and Ferris (13) applied the multiple-point approach to the root-knot nematode (*Meloidogyne hapla* Chitwood) in an alfalfa cropping system. The nematode stress dosage received by the crop is conceptualized in terms of nematode degree days (NDD), a stress-unit index that reflects nematode population densities through time and their physiological activity relative to temperature conditions. NDDs are calculated as a product of each root-colonizing stage density and the degree-day units that each stage has been in contact with the alfalfa root, summed across all stages and time. The rate of increase of the "area under the population progress curve" relative to degree days is the "dosage rate." The second part of the functional relationship to be developed is the "damage rate," i.e., the rate of increase in crop damage or loss relative to the rate of increase of nematode dosage. Both rates are nematode-, host-, and environment-specific. They are calculated by multiple-point observation of nematode population densities and crop loss. The economic threshold is achieved at the NDD where the value of cumulative loss in yield is equal to the management cost necessary to suppress the population or to the opportunity costs of planting an alternative crop or resistant cultivar (12,13).

The second functional relationship, which is a component of the threshold determination, is that between management intensity or cost and level of management or population reduction achieved (7). For any management procedure, the cost-effect relationship is seldom linear. Progressively greater amounts or application costs of pesticide are required to achieve equal increments of control as the population is reduced to lower levels. Similarly, crop rotation to a nonhost crop may result in pest population reduction of 50% the first year but only of 50% of those remaining the second year. By determining the nature of control cost relationships, as affected by environmental and economic conditions, the population level reduction that allows loss in crop value equal to management cost (or other threshold definition) can be calculated.

The Seinhorst (17) model is an example of a deterministic, critical-point, simple damage function (Fig. 1), where curve A represents a relationship between nematode (pathogen) density and expected crop value. The control cost function (curve B) represents the cost of controlling an initial population to various lower levels (7). If a static control cost is applied (a standard dosage recommendation), then the discrete-choice economic threshold (15) could be calculated as that population level at which the value loss on curve A is equal to the cost of the management option. The optimizing threshold (point F) is the level to which the nematode population should be reduced at a cost (point G) determined by the shape and position of the control cost curve (B). At this point, the benefits of the treatment are maximized (point H minus point G). Curve E represents the difference between the crop value and control cost lines for

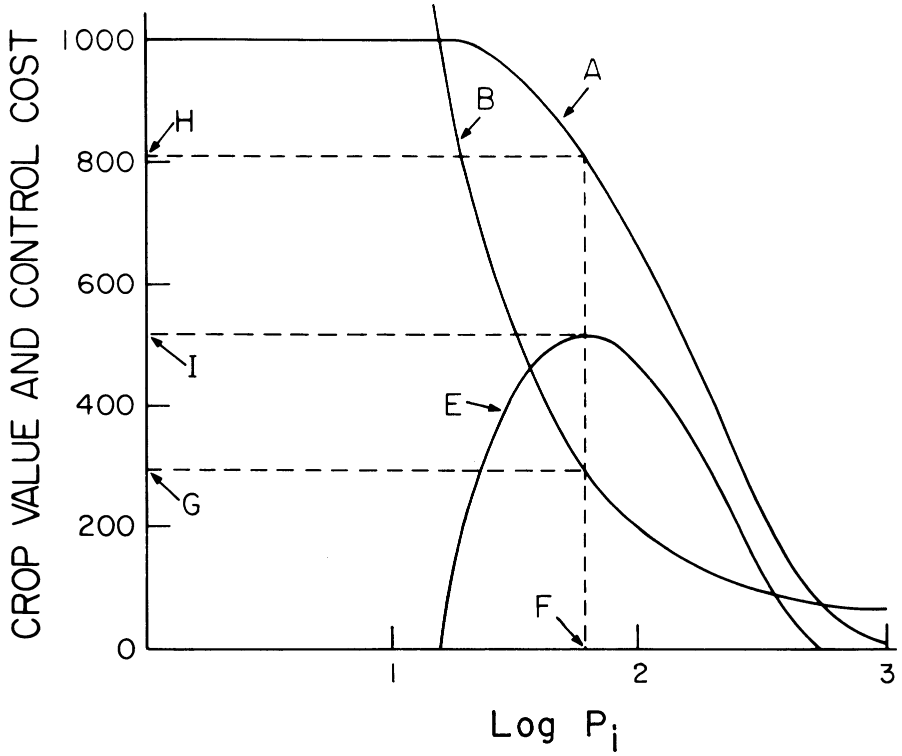

Fig. 1. Determination of the economic threshold by maximizing the difference (curve E) between the nematode damage function (curve A) and the control-cost function (curve B). The optimizing threshold is the population level at which the derivatives of the damage function (curve C) and the control-cost function (curve D) intersect (7).

various nematode population densities, indicating the population density (point F) at which benefits (point I) are maximized. These considerations relate to the economics of the current crop year, not to effects on succeeding crops. Variable production overheads should also be considered in the damage function as they may shift the crop value curve so that control treatments are never profitable.

In many agricultural production systems, crop rotation is the only economic means of managing soilborne pathogens, usually because resistant cultivars are not available and crop values are too low to justify costly pesticide treatments. In this case, the economic threshold is described by a discontinuous step function (5,7) whereby population or propagule reduction is considered in discrete steps at the end of each crop season. The optimum number of years for rotation to reduce the population level can be determined if the seasonal reduction under a nonhost crop and the relationship between propagule densities and expected value of the primary crop can be estimated. The economic threshold is reached when returns from the primary crop would be equal to or greater than those of the alternate crop.

An economic threshold for perennial crops must consider total net revenues or losses over an extended time horizon, as illustrated by the areas under the hypothetical production curves (Fig. 2). Soilborne pathogens can influence total losses by extending the length of time to first harvest, reducing yields, and shortening the productive life of the crop (12). The analytical framework for the economic threshold uses pathogen-free or resistant crop returns as a benchmark for attainable yield (20). Damage functions relating crop yield reductions at each harvest to nematode stress describe the rate at which cumulative profits for the two production curves diverge or converge with postplant nematode management practices (cross-hatched area, Fig. 2) (12). This allows economic threshold decisions to be made for both preplant and postplant management options. The point at which production costs equal crop value and net revenues for the crop reach zero (points 3 and 4, Fig. 2) identifies the time at which crop termination is economically justified. In practice, this point should never be reached because the crop will be terminated when the revenues reach the value of the next best alternative use of the land.

The criterion for choice among nematode management options, including no management, is maximization of annual net revenues over the productive life of the crop or over a specified planning horizon. The difference between production functions for nematode-managed and unmanaged systems (Fig. 2, curves 4 and 1, respectively) measures the returns on investment for a management practice (areas C + D + E + G − B). Net revenues for both managed and unmanaged scenarios are initially negative because of establishment and maintenance costs (areas A + B or A + C, Fig. 2) incurred before the onset of profitable production (point 1 or 2, Fig. 2). These negative revenues (costs) include land preparation, irrigation, fertilization, and pest control costs. Even though the production function for managed systems may show higher initial production costs (area A + B), it may result in positive net revenues more rapidly (point 1, Fig. 2). The unmanaged production function (curve 1) may have a lower establishment cost but result in a longer period to positive net returns (point 2, Fig. 2). The real costs of managing pests in perennials, considering only preplant options, is represented by any positive difference between areas B and C. The cost of the management option itself may be inadequate as a benchmark for evaluating its profitability because additional costs may be incurred in bringing the stressed plants into production (area C). The objective of any management practice is to achieve an increase in area F (Fig. 2) through long-term reduction of pathogen stress. The areas under production curve 4 and 1 (both positive and negative) represent cumulative profits generated during the productive life of the managed and unmanaged crops. The greatest return on investment is indicated by the maximum average annual return for the managed cropping system.

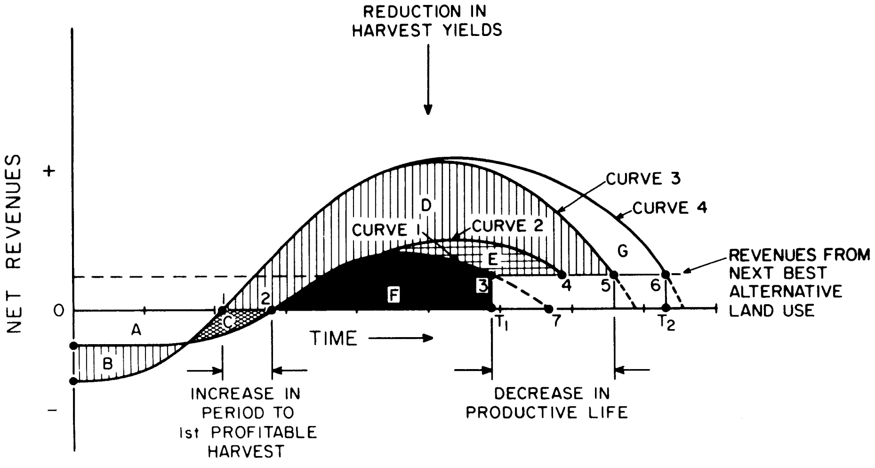

Fig. 2. Hypothetical production functions describing net revenues in a perennial crop for preplant and postplant nematode management practices (12,13).

The concept of optimal control has been expanded beyond the profit-maximizing decision to include consideration of various pest control practices at different levels of intensity at a single point in time. In these expanded models, optimal control considers the timing and dosage of multiple-pesticide applications and the application of decision theory for considering risk (3,6).

PARAMETERIZING FUNCTIONS

Field-applicable damage functions are appropriately developed in the mesocosm and macrocosm (sensu Odum [14]). Mesocosm situations may be provided by small bounded field plots (microplots) with some environmental control (soil moisture, nutrition, etc.). The macrocosm is represented by small field plots and whole-field trials where conditions are those of practical agriculture. Theoretical models can be tested and validated in greenhouse experiments, but for advisory purposes and as a basis for economic threshold decisions, they must be parameterized under field conditions. Generally, for parameterizing damage functions, it is necessary to have a series of plots representing many initial population levels. Such levels may be generated by soil manipulation, partial treatment of soil, or appropriate rotation patterns. In each case, there is a danger of incorporating another variable into the experiment through the manipulative procedure.

A balance must be struck between the number of plots required to develop the damage function and the minimum size of the plot acceptable for yield measurements on the particular crop. In the field, it may be possible to capitalize on the aggregated pattern of soilborne pathogens by randomly locating the series of plots across the field. There is a high probability that a large range of initial population densities will be encountered. Problems associated with this type of experiment include locating the plots at harvesttime, developing a harvest strategy compatible with that of the grower's requirements, and practical considerations concerning equipment.

Management cost functions are also appropriately developed at the field level. In their simplest form, they may represent differential levels of pesticide dosage and the impact on pathogen management and crop yield. They may also be formulated by consideration of damage functions for a range of crop species relative to the prevailing pathogen population. In this case, it will be necessary to develop pathogen-multiplication functions for the various crops so that the impact of cropping sequence on the pathogen population may be predicted.

FUTURE DIRECTIONS

Biotechnological advances will provide improvements in species and race-level identifications for soilborne pathogens through the use of monoclonal antibody and gene probe techniques. Improved sampling methodology and recognition of horizontal, vertical, temporal, and textural determinants of pathogen spatial pattern are enhancing the accuracy and reliability of predictive systems (8–10). Improvements in precision and efficiency of pathogen population assessment and recovery systems are evolving with technological advances. The reliability and cost of sampling programs, a limiting factor in the development and use of damage functions, is under investigation (8,10,11). The risk component associated with the use of damage functions has been expressed in terms of probability levels associated with estimating both pest population density and yield (8). Refinements in understanding of yield variation resulting from physical, chemical, and biological characteristics of the soil, genetic characteristics of the pathogen and host, and specific cultural practices will contribute to crop management prescriptions for varying environmental settings.

The real utility of predictive systems is determined by whether the information will improve production economics. Adoption of new strategies is functionally related to profit and risk. Field-level perception of the problems, quality and accuracy of the information, predictability and reliability of the damage functions, feasibility of alternative management practices, and uncertainty in implementation of new technology are all important determinants of grower adoption. If alternate pest control practices are to be implemented, they must be designed with clear and convincing evidence, considering the economics at the individual farm level, the effectiveness of the program, and the heterogeneity of the environment. Acceptance uncertainty is complicated by seasonal, geographical, and edaphic variation, cultural practices, and market conditions that influence the shape and form of the damage and control cost functions. Further success in the implementation and adoption of the evolving technology may be contingent on additional research, academic instruction, and increased effort to demonstrate, communicate, and extend the information that formulates the basis for threshold determinations.

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