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Simple Decision Aids fo

Researchers use quantitative procedures to describe and predict pest behavior, crop production, or, occasionally, pest and crop interaction, yet remarkably few of these procedures have been implemented in growers' management programs. We want to address this problem by describing how research approaches can be adapted to pest management programs, using the example of a simple "decision aid" for practical control of cedar apple rust, caused by *Gymnosporangium juniperi-virginianae* Schw.

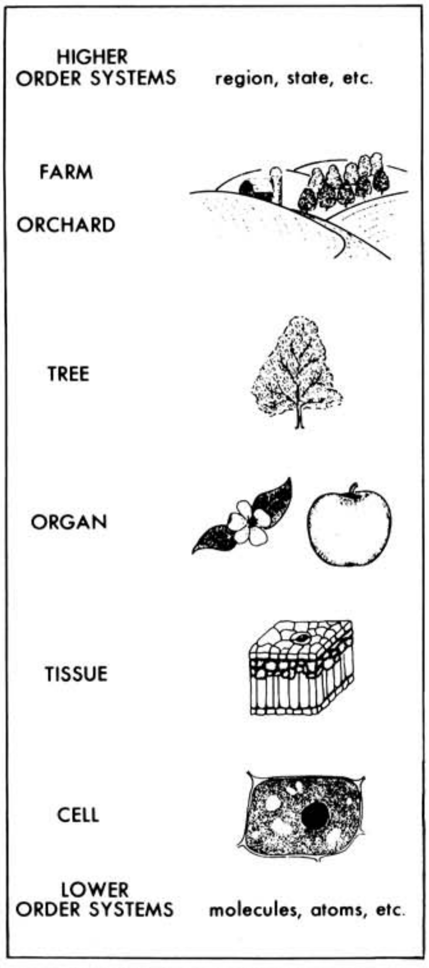

Fig. 1. Hierarchy of an apple ecosystem.

Aids for the Decisionmaker

The decisionmaker at the farm level, ie, the farm production or pest manager, tries to maximize the economic yield of a crop. Desired yields are realized through a management strategy that outlines practices for ensuring a healthy crop and tactics for minimizing injuries from pests. Tactics, to be effective, must be adjusted for crop age and canopy and for changing economic, sociologic, and ecologic constraints. Beset with numerous kinds and degrees of tactics in a given strategy, a decisionmaker gathers information to make the necessary choices for some course of action. Decision aids can be used to organize the information base.

Equations, nomograms, rules of thumb, schedules of management practices, or combinations of these are decision aids. In their most sophisticated form, decision aids are synonymous with management models. In our example, we use a set of graphs illustrating the interactions between pest and crop and outlining the critical periods when tactical choices should be made. Lotka (4) endorsed such visual displays 60 years ago, referring to them as "working models."

Management decisions must be based partly on physical elements. These elements can be holistically viewed as part of a "system." In our example, the system is an apple farm. The farm can be depicted in a spatial hierarchy (Fig. 1) (8).

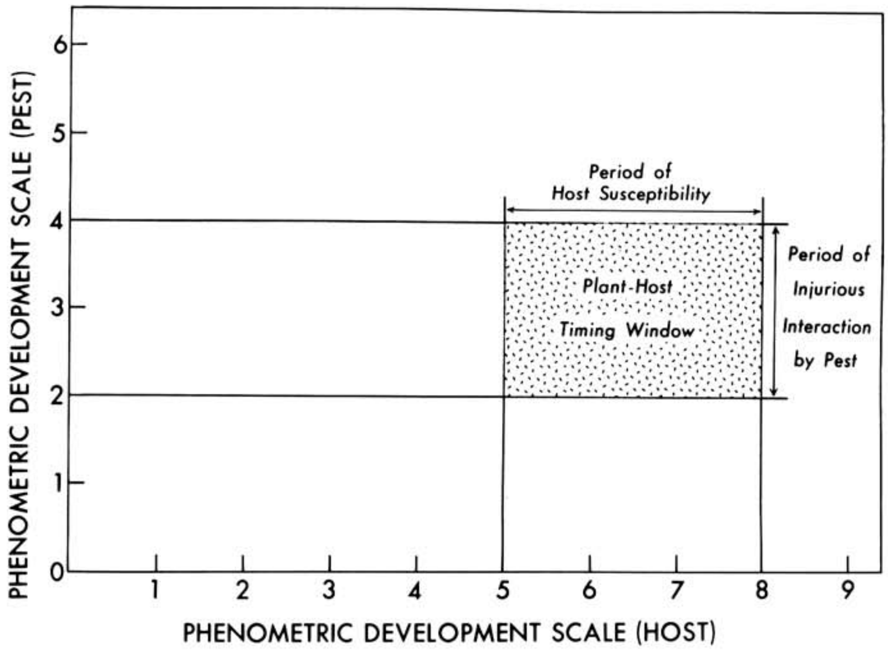

Fig. 2. Management timing window for a pest-plant interaction based on phenological events.

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ractical Control of Pests

Decision aids can be developed for any of the hierarchical levels, the choice of level depending on the current understanding of how the elements of interest are causally related to each other and to their immediate environment. For example, the apple maggot pest damages fruit and thus affects the apple farm system at the organ level.

We must also be concerned with time. One successful approach to establishing time boundaries is to schedule management activities in terms of easily observable events, such as crop or pest development stages or phenophases (9). When graphically presented on the appropriate time scale, chronologically ordered phenophases can delineate a "timing window" of plant-pest interaction. A generalized timing window is depicted as the intersection of periods measured along pest and plant host phenometric time scales (Fig. 2). The phenophases defining the leading edge of the window on both time scales "trigger" or signal the decisionmaker to consider implementing a pest management tactic (3,9). The trailing edge of the timing window in Figure 2 marks the point where pest control is no longer a consideration because the decision period has passed and the decisionmaker must bear the consequences of the decision made—or not made.

The requirement of readily observable pest phenophases to define a timing window is rarely met in plant pathology studies. Microscopic pathogens do not provide easily discernible triggers. For example, a trained technician and a microscope are needed to determine the stage of maturity of ascospores of the apple scab fungus. In this instance, the timing window is best determined from a combination of growing degree days (calculated from climatic data) and intensive microscopic surveillance centered around the time when total degree days or some other model predicts ascospore maturity.

The hierarchy of a farm system and the concept of a timing window provide a spatial and temporal framework for organizing information important to decision making in crop production. Our example of cedar apple rust shows the utility of identifying such a framework to construct decision aids.

The Cedar Apple Rust Example

In regions of the United States where susceptible *Juniperus* species (usually eastern red cedar, *J. virginiana*) grow in proximity to apple trees, spots may

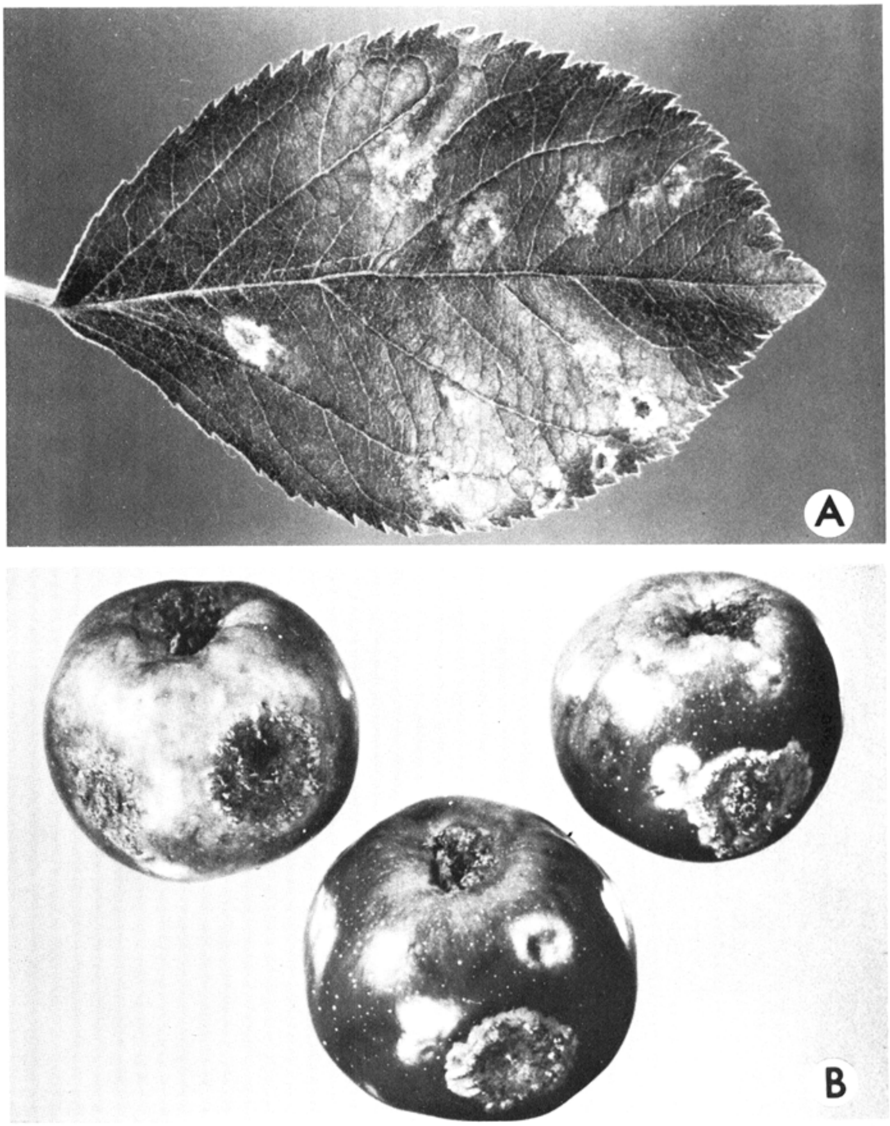

Fig. 3. Typical symptoms of *Gymnosporangium juniperi-virginianae* on (A) leaf and (B) fruit of susceptible apple cultivar.

develop on leaves and fruit of apple cultivars susceptible to cedar apple rust (Fig. 3). All growers are concerned about the reduced marketability of blemished fruit, and the risk-conscious ones also feel that the foliar lesions are debilitating to both bearing and nonbearing trees.

Production goals are to maximize net revenue on fruit produced for the fresh market. Long-term strategies, such as planting resistant cultivars and removing the alternate host (red cedars) within the immediate area, are implemented at the outset, to the degree market, economic, and political constraints allow. Short-term strategies entail timely, efficient use of fungicides for balancing potential incremental production revenues against expected incremental control losses.

Short-term Strategies Basis

The decisions necessary for short-term strategies to control cedar apple rust are based partly on two interrelated biological and environmental events: 1) time when apple tissues are susceptible and inoculum is available and 2) time when climate favors infection. These events should be observed at the organ level of the farm system, but resources and time constraints force many farmers to monitor at a higher spatial level of the hierarchy. Certain simplifying assumptions must be made to link the different levels of observation.

- Assumption 1: All fruit and all leaves of equal age on a tree are equally susceptible.
- Assumption 2: Trees of the same cultivar in an orchard are equally susceptible.
- Assumption 3: Orchards of the same cultivar on a farm are equally susceptible.

These assumptions reduce the number of organ-, tree-, and orchard-level observations necessary to make farm-level decisions. The assumptions may be tailored differently from farm to farm. Assumption 3, for instance, might not work on a farm where some orchards are in environmental settings slow to dry after a rainfall.

Even with a manageable number of observations, proper instruments and equipment are necessary to make the desired weather measurements. At the farm level, investment in on-site instruments may be justified. These may be as simple as a continuous recording thermograph and a leaf wetness meter.

Other information necessary for farm-level decisions includes knowledge of the susceptibility classes for cultivars (1), the time needed to implement tactics, the positive and negative features of alternate fungicides to control the disease, and the availability of fungicide application methods. For our example, we will assume that we need 6 hours to prepare equipment and spray the trees and that we have an after-infection (kickback) fungicide that can control the fungus when applied within 48 hours of infection onset. Some promising kickback compounds are being evaluated (7).

Now the stage is set for developing decision aids for cedar apple rust.

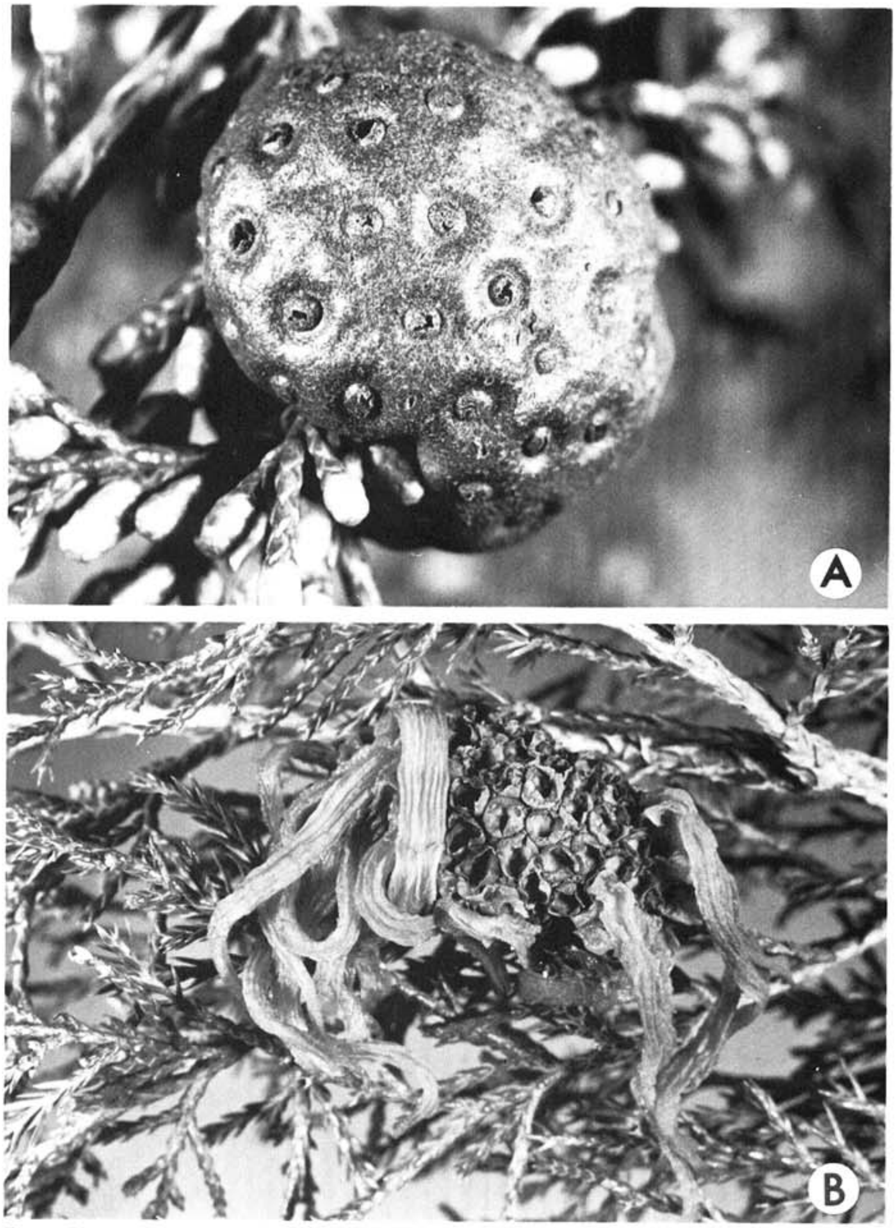

Fig. 4. Phenological stages of *G. juniperi-virginianae* representing the temporal boundary of basidiospore production: (A) First horn and (B) dark horn.

The Three Graphic Aids

The graphic decision aids used for cedar apple rust are all timing windows for major events contributing to development of disease. The first and most general decision aid is a timing window bounding the period when apple fruit and leaves are susceptible and the cedar galls are capable of producing infectious spores. Apple fruit are susceptible to rust infection between the generative (flower to fruit) phenological stages of tight cluster (TC) and petal fall (PF). Leaves are susceptible from the time they emerge from beneath the bud scales until terminal shoot growth stops, with greatest susceptibility during the first 4–8 days. These two phenological stages are referred to as green tip (GT) and bud set (BS). TC and GT constitute the timing-window triggers for fruit and leaf susceptibility.

Phenological stages of the cedar gall are easily observable, and therefore triggers for a decision concerning inoculum availability are readily identifiable. Galls that will produce telial horns the current year have small indentations on the surface and look like small golf balls. The first indication that a gall will extrude a horn is when the indentations start to swell and crack (Fig. 4A). This stage is called first horn (FH). Teliospore (hence basidiospore) production ceases in late spring or early summer and can be identified by failure of wetted galls to produce a spore print when laid on a paper towel for 30 minutes or when wetted horns are no longer bright orange and abscise from the gall (Fig.

4B). This stage is called dark horn (DH). There are no reinfections during the growing season because the aeciospores produced on apple can only infect the alternate host, cedar.

The apple and cedar apple rust phenometric time scales can be combined to form the first graphic decision aid (Fig. 5). With host susceptibility along the abscissa and time of inoculum availability along the ordinate, the graph depicts the timing window for potential infection. Calendar time scales for Geneva, NY, are included in Figure 5 as points of local reference. When both phenological times are within the bounds of the timing window, the potential for infection of apple fruit and/or leaves exists.

The second decision aid is based on the time scale of the weather-related variable of leaf wetness. Because two phases of the phenology of *G. juniperi-virginianae* depend on free moisture and different temperature regimes, the wetting process is divided into 1) basidiospore formation and 2) infection. Temperature determines the hours of wetting necessary for basidiospore formation (2). If the coordinate of average temperature and hours of leaf wetness lies within the shaded window (Fig. 6), teliospore germination has occurred and the potential for infection has been initiated.

The third decision aid, a timing window for controlling infections by the cedar apple rust fungus, is constructed in two steps. First, the wetness period for basidiospore formation determined from the second decision aid is subtracted from the total wetness period, resulting in the hours of leaf wetness after basidiospore formation. This period is represented by values along the abscissa of the third decision aid (Fig. 7). Second, the average temperature for the resulting period makes up the ordinate value. The intersection of critical wetness periods and temperatures for cedar apple rust infection bound the timing window. The hatched area on the bottom and left edge of the window (Fig. 7) represents the minimum conditions necessary for light infection to occur 90% of the time, and the lower boundary of the speckled area represents the minimum conditions necessary for severe infection to occur 90% of the time.

The leading edges of the window also serve as triggers for deciding on a tactic for controlling cedar apple rust infection. If the coordinate of average temperature and total time elapsed since basidiospore formation falls to the left or below the window, no control measures are necessary. If the coordinate falls within the window, infection has occurred but the fungus can still be eradicated. If the coordinate falls to the right of the window, however, infection can no longer be eradicated. In many fungicides, the potential for eradicant activity increases as temperature decreases, which explains why the right side of the window is not symmetric with the left side.

Although available research data (2,5,6) define definite boundaries, the timing windows of decision aids should be flexible. Each window can be tailored to the decisionmaker's needs and capabilities. Dimensions can be made larger for the grower unwilling to risk the possibility of disease and smaller for the grower more willing to accept risk or do intensive disease monitoring or with quick response capabilities.

With the three graphic decision aids, the decisionmaker can conveniently determine the proper timing of fungicide sprays to control cedar apple rust. With minor modifications, any of the aids can be tailored to the individual farmer's needs.

Reflections on Decision Aids

The decision aids we have described may appear to circumvent many of the details addressed in the mechanistic

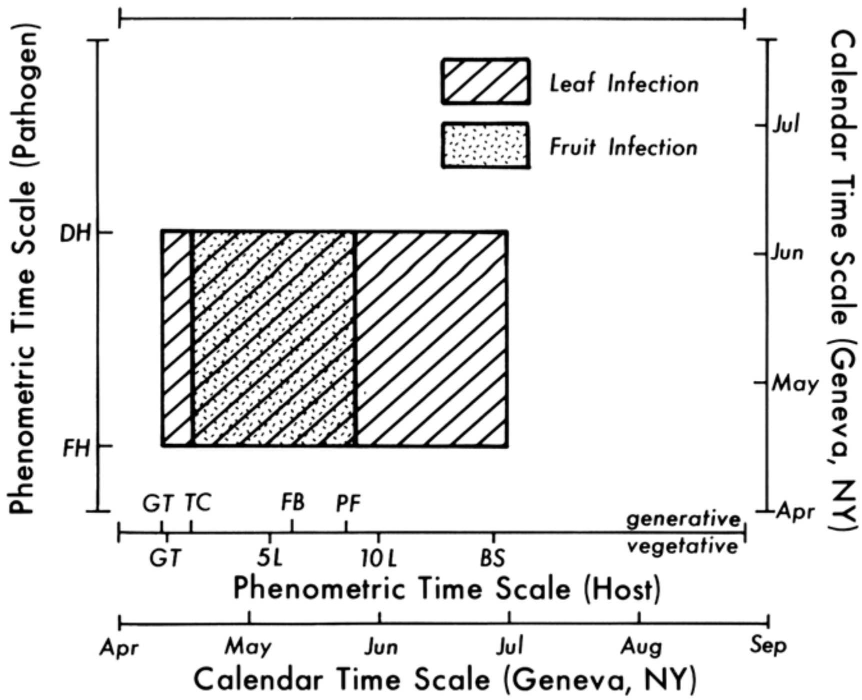

Fig. 5. Management window representing time and age bounds for cedar apple rust on apple. Phenometric key: BS = bud set, DH = dark horn, FB = full bloom, FH = first horn, GT = green tip, PF = petal fall, TC = tight cluster, 5L = 5 leaves, 10L = 10 leaves.

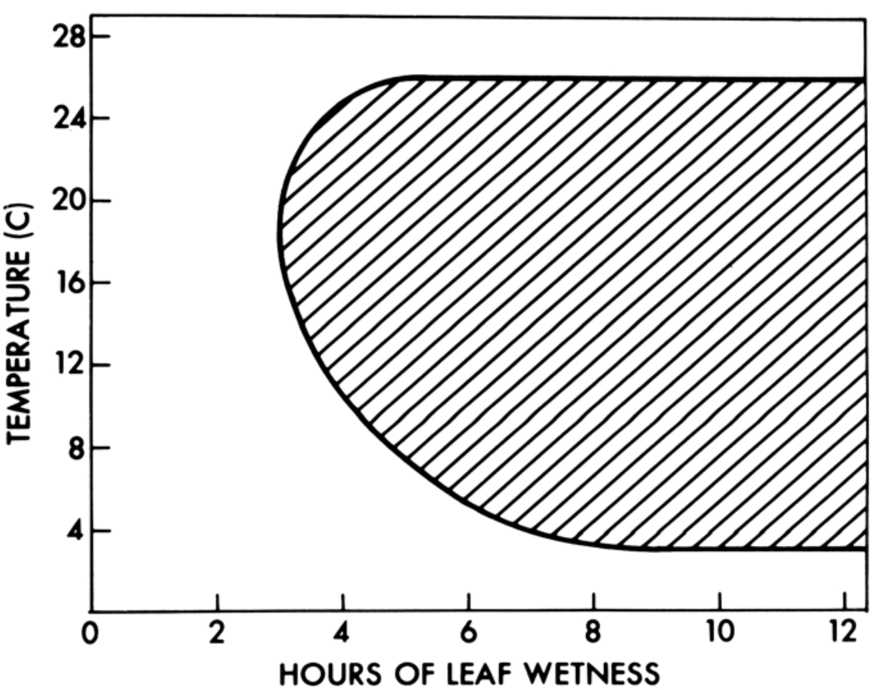

Fig. 6. *G. juniperi-virginianae* basidiospore formation occurs at the transition line between the clear and shaded areas of the diagram.

approaches used to describe biological processes. Yet the difference is primarily one of purpose rather than technique. Many sophisticated quantitative formulations of pest and plant development, such as simulation models, were never intended for use in production agriculture—they were designed to assist in research and teaching. We have attempted to show that simple techniques are available to aid farm management decisions.

Although decision aids can be readily expressed mathematically in computer-based delivery systems, we feel expressing them in easily understood graphs and decision rules is also desirable. The graphs and rules may be more cumbersome but tend to provide better comprehension and a measure of confidence in how decisions are made. Once confidence in an aid has been established, the faster computer-based system could be phased in and the manual method used as a backup or double check.

Our use of decision aids is by no means unique. Simple pest forecast schemes that have withstood the test of time include Mills's apple scab infection curves and Hyre's potato late blight forecast rules. Such successes prompt us to advocate the development of simple approaches in pest management programs. Developers of these early forecast schemes had a goal in mind and went through a logical process to gather and structure information, then developed relationships or decision rules that were easily incorporated into farming practices. This ability may be innate in some, but most of us must learn the process if we are to make sound decisions for practical control of pests. We hope we have provided an incentive for others to develop alternative or superior versions of the simple decision aids we have presented.

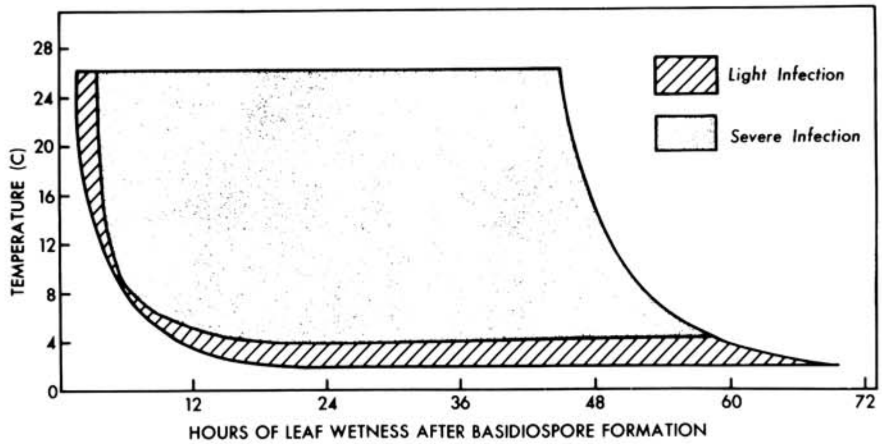

Fig. 7. Management window for light or severe infection of apple by *G. juniperi-virginianae* basidiospores.

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