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Managing Diseases in Greenhouse Crops

The commercial production of ornamental and vegetable crops in greenhouses has, until recently, followed traditional and largely empirical methods little changed since the turn of the century. Only 10 years ago, a yield of 6.4 kg (14 lb) of tomatoes (*Lycopersicon esculentum* Mill.) per plant was considered a fair production in Ontario; now yields of 15 kg (33 lb) can be attained. Mechanized hydroponic production of lettuce (*Lactuca sativa* L.) can yield over 62,500 heads per hectare per week (25,000 per acre) (10).

There has been a revolution in greenhouse production technology that demands critical reappraisal of the research and development approaches to phytopathology (7). At the same time, this revolution presents an exciting challenge and opportunity for the grower to control plant diseases relatively cheaply and without constant recourse to pesticides. The attitude that pesticides were universal panaceas has given way to the philosophy that pesticides are still useful but only in fully integrated programs of environmental and biological control, together with resistant germ plasm and disease escape mechanisms. In the 120-ha (300-acre) greenhouse industry around Leamington in southwestern Ontario, several vegetable growers have not used insecticides or fungicides for some years, except for the soil fumigant methyl bromide for nematode control. They have relied largely on resistant cultivars, biological control of insects, and manipulation of the environment for disease control.

Over the past 50 years, there has evolved a checklist of standard control measures routinely practiced in intensive greenhouse cropping (Table 1), but modern technology has given the grower some powerful management tools for production as well as for disease control. Precise environment and nutrition controls that optimize the partition of assimilates toward flowers and fruits are pushing plants to new limits of growth and productivity. This, however, is at the expense of roots, stems, and leaves—a chronic stress condition that is difficult to qualify and quantify. It is apparently conducive to diseases such as Penicillium stem rot of cucumbers, not common 10 years ago.

Managing the environment for insect and disease control has arrived relatively recently by the juxtaposition of computerized climate controls and a better understanding of the autecology of insects, fungi, and bacteria and the autecology of biocontrol organisms (4,9). These new developments, however, must still be integrated into a highly specialized crop husbandry that many still regard as a more of an art than a science.

Autecology of Pathogens and Biocontrol Organisms

Fungi have specific and often different optimum environmental requirements for sporulation, dispersal, spore germination, and infection. For example, consider the biology of the ubiquitous gray mold pathogen, *Botrytis cinerea* Pers.:Fr. (telemorph: *Botryotinia fuckeliana* (de Bary) Whetzel) (3). It is a necrotrophic pathogen whose inocula are enhanced from soilborne and debris-borne sclerotia and large saprophytic bases. It produces conidia at temperatures above 12 C (best at about 15 C) in subsaturated atmospheres, releases them by a hygroscopic mechanism in conditions of rapidly changing humidity, and generally infects plants, especially wounded plants, from conidia and occasionally ascospores in a film of water. Its conidia germinate best at 20 C, but germ tubes elongate fastest at 30 C.

Table 1. Examples of nonpesticide disease-control measures for greenhouse crops

Control	Disease	Crop
Disease-free seed	Lettuce mosaic virus	Lettuce
Disease-free mother plants	Bacterial rot	Geranium
Seed heat treatment	Bacterial canker	Tomato
Grafting on resistant rootstocks	Nematodes	Cucumber
Resistant cultivars	Powdery mildew	Rose
Soil sterilization	Fusarium wilt	Carnation
Solarization	Corky root rot	Tomato
Roguing	Bacterial canker	Tomato
Biological whitefly control	Beet pseudo yellows virus	Cucumber
Eradicating alternative hosts	Tobacco mosaic virus	Tomato
Bottom heat, air movement through seedling trays	Gray mold	Forest seedlings
	Rhizoctonia root rot	Poinsettia
Sanitation	Tobacco mosaic virus	Pepper
Allelopathy	Fusarium crown and root rot	Tomato
Hydroponic culture	Lettuce drop	Lettuce
Composted bark	Rhizoctonia, Pythium root rots	Poinsettia
UV-absorbing film	Gray mold	Tomato

The optimum temperature for infection depends partly on the defense reactions of the host. *B. cinerea* can behave as a snow mold in forest seedlings and it can infect potato tubers at 3 C, but infection mostly occurs between 15 and 25 C. However, this fungus often infects plants directly from a saprophytically based inoculum such as in a fallen petal adhering to a leaf or fruit surface. Its reliance on the appropriate sequence of environmental events for successful spore infection is then largely circumvented. It can also establish quiescent infections, which in tomato stems can last for up to 12 weeks before becoming aggressive. This behavior has profound implications in the design of prophylactic, disease-escape, and therapeutic control measures.

I have discussed gray mold biology at some length to illustrate the many different components of autecology and pathogenesis that must be considered in greenhouse management. Other groups of fungi, such as *Alternaria, Fusarium, Phytophthora, Pythium*, and *Verticillium* spp., and the downy mildews each has its own set of ecological requirements that demand a different rationale in the design of environmental control measures. The powdery mildews are generally regarded as dry-atmosphere diseases (Fig. 1) with high humidity requirements for infection (1), but opinions are divided as to the role of free water in promoting or inhibiting infection (1). Thus, there are reports that water sprays control powdery mildews and one report that water promotes pathogenesis by *Sphaerotheca fuliginea* (Schlecht.) Poll. This is an area demanding more critical research for important greenhouse pathogens as well as great caution in interpreting experiments in near-saturated atmospheres (8).

Bacteria are also important pathogens of greenhouse crops, often of cuttings such as geraniums and chrysanthemums or of pruned plants such as tomatoes and in situations where intensive plant handling and soil and water splash facilitate the transfer of inoculum. Bacterial diseases tend to be more serious in humid conditions; in succulent, soft plants; and in certain areas of the greenhouse where such adverse conditions as poor drainage and roof drips occur.

The epidemiology of virus diseases depends largely on the mode of transmission, whether on pruning knives or fingers or by insects. Thus, in order to devise rational management control measures, the autecology of the vector becomes a subject for in-depth study.

Understanding the autecology of phyllosphere biocontrol microorganisms is as important as understanding that of pathogens, if they are to be exploited rationally. The pycnidial hyperparasite of powdery mildew fungi, *Ampelomyces quisqualis* Ces., has sticky conidia that are splash-dispersed, as are the spores of

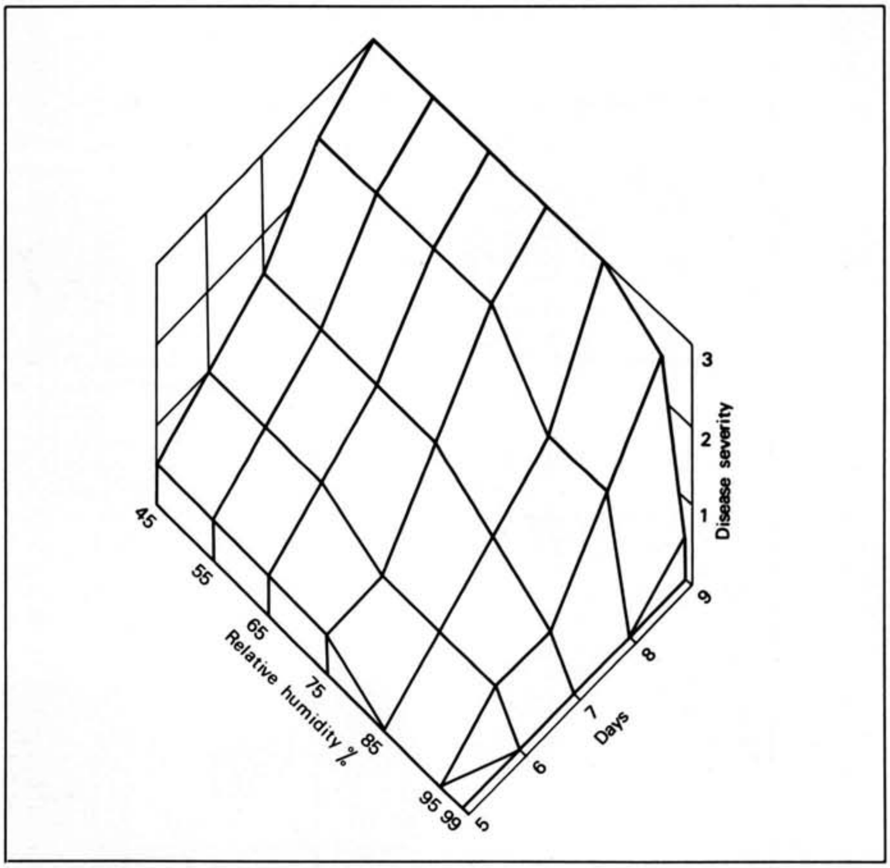

Fig. 1. The effect of relative humidity on the severity of powdery mildew (*Sphaerotheca fuliginea*) of cucumber. (Constructed from the data of K. Abiko and K. Kishi. 1979. Bull. Veg. Orna. Crops Res. Stn. Jpn. Ser. A. 5:167-176.) Disease severity scale: 0 = no mycelium or sporulation, 1 = scant mycelium and few conidia, 2 = abundant mycelium and sporulation, 3 = profuse mycelium and sporulation.

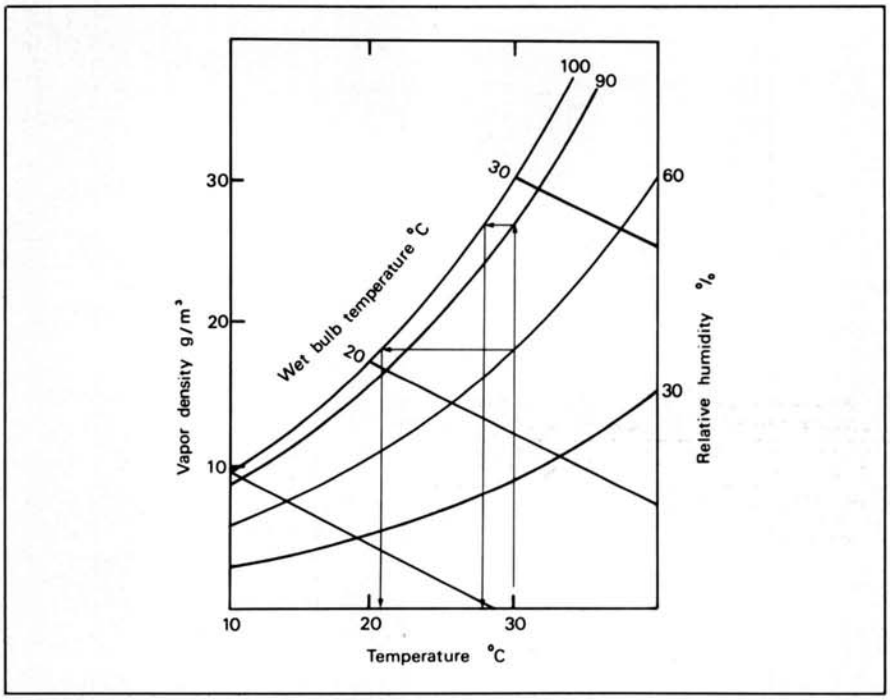

Fig. 2. The relationships among water vapor density, relative humidity, dew point, and wet and dry bulb temperatures. At a dry bulb temperature of 30 C and a relative humidity of 90%, the dew point is reached by a fall in temperature of only 1.8 C, whereas at 60% RH, a fall of 9.2 C is required to deposit dew (arrows). Computerized environmental controls can react to wet or dry bulb temperatures, or a humidity sensor, or incoming radiation in a preselected order of priority to maintain desirable temperatures and water vapor densities without the risk of dew.

Fig. 3. Planting cucumbers on ridges permits more rapid root-zone heating and better drainage to escape black root rot (*Phomopsis sclerotioides*) in a greenhouse with a history of the disease. Because this disease builds up slowly over the years, soil sterilization may not be necessary every year.

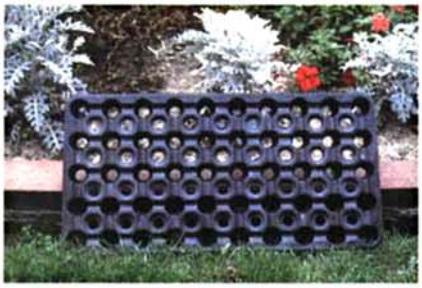

Fig. 4. When used on a slatted or expanded metal bench, a tray with ventilation holes between the seedling wells provides for upward air movement, which reduces the risk of lower stem diseases in seedlings and cuttings.

Fig. 5. These benches for rooting chrysanthemum cuttings have provision for through-the-bench upward air movement. Environmental controls include a ceiling shade cloth, supplementary lighting, and (right) an enclosed area for mist propagation.

the yeastlike antagonists, *Sporothrix* spp. They are both effective in controlling *S. fuliginea* on cucumber in high humidities. Biocontrol of powdery mildews, therefore, depends on maintaining high humidities and occasional water sprays to ensure splash dispersal of antagonist spores. A compromise is essential, however, because water films cannot be allowed to persist on plants long enough to invite water-dependent pathogens such as *B. cinerea.*

If a root pathogen regains early entry to a sterilized medium, the medium becomes highly disease-conducive because of the prior elimination of naturally occurring antagonists. Many antagonists, on the other hand, are retained in pasteurized and solarized media that thus generally remain suppressive to root pathogens (4). It is possible to infest sterile soils with selected, isolated antagonists, but general experience is that their effect is ephemeral. Enhancement of indigenous antagonist populations by means of amendments such as chitin or composted hardwood bark or peat seems more effective (2).

Fig. 6. The tangled, dense growth of western hemlock (*Tsuga heterophylla*) seedlings in nonventilated trays promotes the rapid development of gray mold (*Botrytis cinerea*). (Courtesy J. R. Sutherland)

Disease Escape

Notwithstanding a good general standard of within-greenhouse hygiene, long-distance transport of inocula by air, water, insects, or machinery sometimes negates elementary precautions (Table 1). Once conditions for infection are recognized and their environmental parameters are defined, however, infection can be prevented simply by avoiding those conditions. In the case of fungi such as *B. cinerea*, which are dependent on a water film for spore germination and infection, preventing temperatures from reaching the dew point (Fig. 2) is an effective mechanism of disease escape.

Primary disease escape, of course, is recognizing and eliminating inoculum sources, including contaminated or infected seed, diseased mother plants used for cuttings, weed reservoirs of viruses and insect vectors, trash piles, dirt on implements and headerhouse floors, and diseased mature crops in the same greenhouse as seedlings.

Diseases with a quiescent phase can be contained by recognizing and counteracting factors that trigger the onset of aggression. In the quiescent phase of gray mold in tomato stems, conidia of *B. cinerea* lie in clumps in xylem vessels of petiole stubs at deleafed nodes for up to 12 weeks before germinating (3). The aggressive stage of pathogenesis can be delayed by not overirrigating the groundbed and by supplying adequate soil nitrogen that seems to delay tissue senescence. Thus, although the plant may be infected, aggression can often be delayed by managing the crop so that yield is little affected.

A simple crop management practice can similarly often save plants with basal stem and root rots from total destruction. Several of these diseases, such as Pythium root rot and Fusarium crown and root rot of tomatoes, are diseases of cool and wet soils. A frequent plant

Table 2. Mechanisms of biological control successfully exploited in greenhouse crops[a]

Mechanism of biocontrol	Disease	Biocontrol agent	Crop
Allelopathy	Fusarium crown and root rot	Lettuce, dandelion residues	Tomato
Hyperparasitism	Powdery mildew, rust	*Ampelomyces quisqualis, Verticillium lecanii*	Cucumber, carnation
Antibiosis	Powdery mildew	*Tilletiopsis* sp., *Stephanoascus* spp.	Cucumber
	Fusarium wilt	Streptomycetes	Carnation
Suppressive soils	Fusarium wilt	Saprophytic *Fusarium* spp.	Carnation
Competitive saprophytic ability	Fusarium crown and root rot		Tomato
Soil amendments	Fusarium wilt, Rhizoctonia and Pythium root rots	Chitin, composted hardwood bark	Cucumber, poinsettia
Cross-protection	Fusarium wilt, crown and root rot	Nonpathogenic *Fusarium oxysporum*	Tomato
Passive exclusion	Gray mold	*Cladosporium* spp.	Tomato
Hypovirulence	Tobacco mosaic virus (TMV)	Attenuated TMV	Tomato

[a] From Jarvis (4).

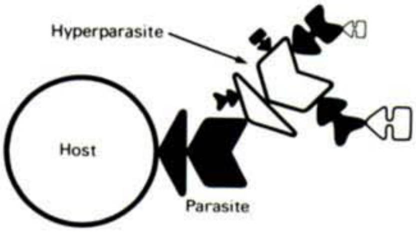

Fig. 7. The antagonist chain. To succeed, biological control must recognize that hyperparasites and antagonists controlling plant pathogens have their own hyperparasites and antagonists, as well as hostile environments.

response to root rots is the production of adventitious roots, and serious consequences of the disease can be escaped if the first few stem internodes are mounded over with a peaty soil mix. This mound is drained better and warms up faster than a groundbed, encouraging the formation of new roots that usually remain disease-free. Similarly, planting on ridges (Fig. 3) can afford some escape from debilitating but usually not killing diseases, such as black root rot (*Phomopsis sclerotioides* van Kesteren) of cucumber, that are slow to build up over a season or over years.

Altered greenhouse and bench design can improve air movement, which not only reduces the risk of diseases but also induces ethylene stress and hardier plants. Bottom heat, a traditional means of avoiding Pythium and Rhizoctonia root rots, is enhanced in seedling and cutting trays that provide for upward air movement between the young plants (Fig. 4). Through-the-bench air movement (Fig. 5) is perhaps the most neglected and simplest means of reducing seedling rots in such tangled plant masses as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Fig. 6).

Biological Control

Because of the precision with which the greenhouse environment can be controlled, the chances of success with biological controls is greater in greenhouse crops than in field crops. Several mechanisms of biological control have been successfully exploited in a wide variety of greenhouse crops (Table 2). There have also been some conspicuous failures to translate laboratory-observed antagonisms to crop production systems. In general, preliminary experimental work is done with two- or three-component systems in laboratory or greenhouse bench-top tests, including the parasite and its antagonist or hyperparasite and the host plant, which is usually in a nonproductive condition. We tend to forget that bicontrol agents have their own antagonists (Fig. 7) and that compromises inevitably have to be made when selecting between environmental conditions that are optimal for biocontrol activity and those that are optimal and economical for crop production.

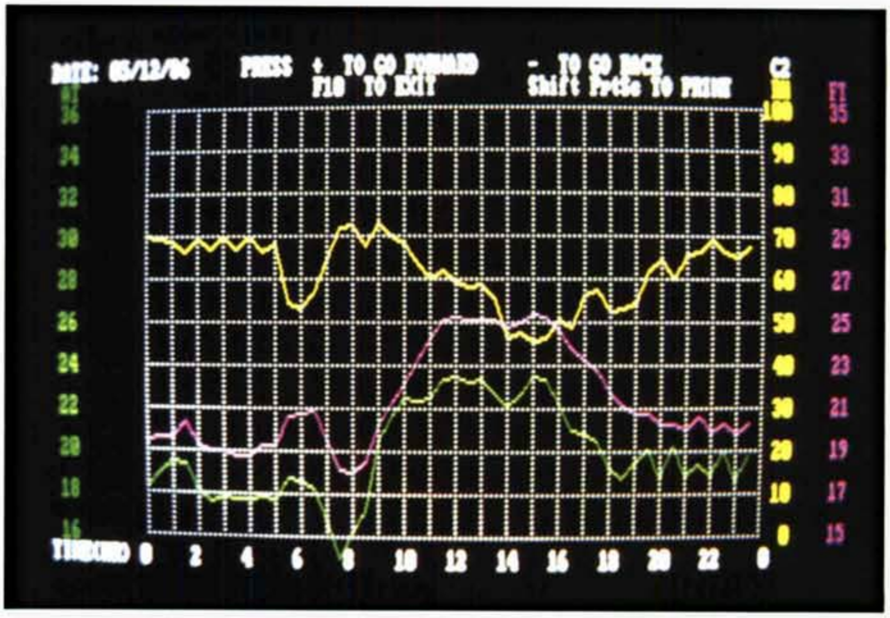

Fig. 8. Computers give the precision of environmental monitoring and control that permit accurate compromises to be made for maximum crop production without inviting infection by pathogens or triggering latent infections to become aggressive. Tomato fruit temperature (pink line) may not necessarily be the same as ambient air temperature (green line), an important point to consider when assessing the risk of dew deposition. The yellow line records relative humidity over the same 24-hour period. (Courtesy A. Ingratta)

Monitoring and Controlling the Environment

Monitoring the environment and controlling it to keep plants disease-free and pest-free has become a fundamental part of greenhouse management. Once the environmental parameters for the various activities of pathogens and biocontrol organisms are understood, those activities can be regulated by the relatively precise control growers can exercise over the environment. Precision is greatly enhanced by computer monitoring and controlling of temperature, energy input and conservation, light, shade, air movement and ventilation, water vapor density, relative humidity, dew point, crop nutrition, and carbon dioxide enrichment. Consideration must also be given to such external factors as site orientation, radiation, rain, wind velocity and direction, and cropping and marketing schedules. Of these factors, manipulating the interactions of temperatures and water vapor density is probably the most important in the control of diseases of leaves, flowers, and fruit. Rhizosphere moisture and temperature are the most important for root diseases. It is important in determining dew point to recognize that leaf or fruit and ambient air temperatures may not coincide (Fig. 8), so that dew points determined from aspirated wet and dry bulb sensors may not accurately reflect the deposition of water on plant surfaces.

Fig. 9. A microfine evaporating water mist is conducive to the environmental and biological control of cucumber powdery mildew (*Sphaerotheca fuliginea*) by cooling the crop, by raising the humidity without inviting water-dependent pathogens, and by encouraging antagonistic *Stephanoascus* and *Tilletiopsis* spp. and the hyperparasite *Ampelomyces quisqualis*.

In high humidities, guttation can occur from leaves and pruning wounds. A repeating cycle of guttation and drying can lead to a buildup of phytotoxic levels of salts; when wet, those areas are frequent infection points for necrotrophic pathogens. Dew deposition in the greenhouse is common on cool nights following warm, humid days, the more so at high humidities with a large day-night temperature difference (Fig. 2). Morgan (6), for example, has clearly demonstrated the importance of regulating day and night atmospheres in the control of lettuce downy mildew (*Bremia lactucae* Regel).

Some biocontrol organisms, on the other hand, may require short periods of free water (e.g., *A. quisqualis*) or periods of high relative humidity (e.g., *Stephanoascus* spp.). In such cases, an evaporative water fogging system (Fig. 9) provides the required relative humidity and also cools the air, improves convective air circulation, reduces water stress on the plants, and provides some radiation screening. The importance of compromise is highlighted by the necessity to restrict ventilation for efficient use of carbon dioxide; this can increase disease levels in modern, energy-efficient, well-sealed greenhouses.

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Dr. Jarvis received his B.Sc. degree from the University of Sheffield, U.K., and his Ph.D. degree from the University of London, U.K. He worked for many years in Scotland on diseases of small berry fruits and ornamental bulb crops, specializing in the gray mold diseases. He is now head of the Plant Pathology Department at the Harrow Research Station of Agriculture Canada and specializes in the biological and environmental control of diseases of greenhouse vegetables.

Decision Making

Given an adequate knowledge of the biology of pathogens and greenhouse crop plants, extension personnel and growers now have a comprehensive menu of control measures that must be integrated within a realistic economic environment. In many cases, pesticides can be eliminated or at least reduced in dose rate and frequency when used in combination with biological and environmental control and when applied with electrostatic and other improved spray technology. This reduces hazards to workers, leaves less unweathered residues on food, and reduces cosmetic blemishes on ornamentals.

Decisions must be made. Advisors and growers must decide whether purging humid air through the ventilators at sundown is more cost-effective than spraying pesticides. In some instances, greenhouse soils need not be sterilized by steam or fumigants every year just because it has always been so; some diseases are more severe in oversterile media, and others, such as cucumber black root rot and tomato corky root rot (*Pyrenochaeta lycopersici* Schneider & Gerlach), build up only slowly over the years. The several and disparate risks must be better assessed (5).

Improved monitoring systems to establish soilborne pathogen populations and their pathogenic and economic thresholds would enable the advisor and grower to make more rational management decisions. What are the economics of grafting cucumbers and tomatoes onto nematode-resistant rootstocks as against the cost of soil sterilization? Can the grower afford to let a greenhouse remain vacant in midsummer long enough to effect solarization? What is the payback time for the capital outlay of disease-controlling soilless systems and environment-managing hardware—and a computer to take out some of the guesswork in crop and environment management? Notwithstanding technological advances in management tools, growing a greenhouse crop is still as much an art as a science. The good grower will spot an aberrant plant among several thousand and have an intuitive feel for the well-being of the crop. The grower would like to have such feelings backed up by science. This is the role of better-integrated plant pathology.

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