How Can We Prevent or Manage Plant Disease Epidemics?

IN THIS CHAPTER:

➤ How do we choose the appropriate methods for disease management?
➤ How do we avoid pathogens?
➤ How do we exclude pathogens?
➤ How do we eradicate pathogens?
➤ How do we protect plants?
➤ How can we create integrated, sustainable disease management programs?

How do we choose the appropriate methods for disease management?

Decades ago, this chapter would have discussed disease control, with the implication that plant diseases can be completely eliminated. Over the years, approaches to reducing plant diseases have evolved into forms of disease management. Unlike disease control, disease management attempts to maintain disease levels below economic thresholds because complete elimination of diseases is unnecessary and may result in unacceptable costs, labor, and environmental impacts. There are many approaches to the management of plant diseases. As the disease triangle reminds us, the appropriate choices depend on the pathogen, the plant, and the environment in which they interact. We can sometimes optimize our choices by including the additional factor of time and how it impacts an epidemic.

As discussed in Chapter 10, most epidemics can be categorized as monocyclic or polycyclic. Although many epidemics fall in the spectrum between these two categories, they still help us to determine which management practices
DID YOU KNOW?

The rubber plant (Hevea brasiliensis) originated in Brazil. The first large plantation was established in Brazil at “Fordlandia” by the Ford Motor Company in 1927. By 1934, Ford had planted over 3,200 hectares (8,000 acres), but the rubber trees quickly began to die of South American leaf blight (SALB) caused by the polycyclic ascomycete Microcyclus ulei, which thrived in the wet tropical climate. Another 5,000-hectare (12,000-acre) plantation was established, but that too failed. Today, 90% of the world’s rubber comes from Southeast Asia to avoid SALB. The plants are protected by strict quarantines.

How do we avoid pathogens?

As discussed in Chapter 10, diseases have sometimes determined where crops are grown. Natural rubber originated in Brazil but is now grown mostly in Southeast Asia, because of South American leaf blight (Figure 11.1). Coffee originated in Ethiopia, but most coffee production is now in the Western Hemisphere because of coffee rust. In the United States, pears are mostly produced in drier regions instead of humid regions because of fire blight.

Certain diseases can be reduced or managed through choice of the planting site or the planting date in a local area. The goal, to reduce exposure of the plant to inoculum, is essentially a form of escape. For example, damping-off often can be avoided by planting seeds in well-drained soils and at temperatures that minimize germination time. Seeds planted in cold, poorly drained soils are more likely to be attacked by damping-off pathogens. White pine blister rust hazard zones have been established in the western forests of the United States. By choosing upper slopes and ridges for planting rather than humid valleys, disease is minimized, even though not all of the wild Ribes alternate hosts have been eliminated. In California, growers honor a “lettuce-free” period for 2 weeks each year to break the cycle of aphid vectors and infection by Lettuce mosaic virus (Figure 11.2).

To Avoid Damping-Off in Outdoor Soils

- Prepare soil to have a uniform grade without low spots where water can accumulate.
- Avoid areas of soil compaction or poor drainage.
- Provide for good air movement across the planting area.
- Avoid planting seeds when excessive rainfall is expected.
- Choose a planting time when soil temperatures favor germination of seeds and air temperatures favor rapid growth and development of the plant.
Home gardeners can try to avoid diseases when they establish their gardening areas. Open areas in full sun should be chosen for most flower and vegetable gardens. If soil is poorly drained, the construction of raised beds and the use of soil amendments will improve drainage and create a more favorable root environment. A soil sample should be sent to a local extension office or garden store to test for pH and soil nutrients. Sometimes lime or other amendments are necessary to optimize soil pH for plant growth and to avoid certain diseases. Fertilizers should be added as recommended by the soil test results. Finally, recommended planting times for seeds and transplants should be followed to encourage rapid establishment and to avoid damping-off pathogens and frost injury.

Unfortunately, it is not usually possible to completely avoid disease. Therefore, most disease management choices either reduce the amount or efficacy of inoculum (by exclusion and eradication) or protect the plant.

Pathogens can sometimes be avoided by choice of the planting site or the timing of planting.

How do we exclude pathogens?

Exclusion (management of plant disease by preventing the introduction of pathogens to crop production areas) is usually considered to include various legal restrictions on movement of plants and pathogens, such as quarantines, and methods used to ensure that seed and other propagative parts are pathogen-free at planting time.

Quarantines

From previous chapters, it should be clear that introduced pathogens have caused some of the most devastating plant diseases. Plants and pathogens moved around the world without restriction for many years. The years 1800 to 1850 were a particularly active time for exploration to find and import interesting new horticultural and agronomic species.

The word quarantine is derived from the Latin word for 40, which refers to the number of days that passengers were held on ships after arrival in foreign ports to make sure that they were not bringing diseases to the cities. Apparently, anyone who was ill would have recovered or died by the end of that period. Today, the word quarantine relative to plant diseases refers to any restriction in the movement of plants, plant materials, seeds and propagative parts, soil, machinery, or anything that might introduce dangerous pathogens into new areas.
The first U.S. plant quarantine law was passed in 1912 following the introduction of citrus canker, chestnut blight, and white pine blister rust. These diseases had devastating impacts on their host plants and caught the attention of legislators. Many other important pathogens of fruit, vegetable, and field crops have been introduced into the United States, and many have been spread from the United States to other parts of the world over the years.

Tourists are not allowed to bring any fresh plant materials, including flowers, fruits, seeds, and vegetables, into the United States (Figure 11.3). These materials are confiscated because it is not usually possible to identify the presence of plant pathogens or early infections from cursory visual inspections. Around the world, travelers may be questioned about visits to farms because boots may carry infested mud, or they may even find their airplane cabin sprayed with an insecticide before they are allowed to disembark from the plane.

Commercial plant producers are subject to different restrictions and must apply for permits to import plant materials. Some items are unrestricted, but most fall into the restricted category, which requires inspection, and sometimes chemical treatment, before release. The post-entry category requires that plants be kept in isolation for up to two years and be subject to additional inspections during that time since pathogens may not be obvious at the time of import. A few kinds of plant materials from certain areas are considered so dangerous that they are completely prohibited. Imported plant materials, including seed, must receive a phytosanitary certificate (see Figure 4.17) before they can be imported or exported across national boundaries, according to the regulations of the importing country.

Local quarantines are sometimes established by regional areas, such as states. For example, a number of agricultural pests and pathogens are present in Hawaii but not on the mainland of the United States and vice versa, so quarantine inspections may be required. In 2006, quarantines were in effect for citrus canker in Florida; the golden nematode on Long Island, New York; Plum pox virus in Pennsylvania; and witchweed in North and South Carolina. In addition to these official quarantines, seedlings and other plants may be subject to inspections before interstate shipment. A website at the end of this chapter lists the pests and pathogens that are under quarantine for various U.S. states.

One of the major limitations of quarantines is that they are based on political boundaries that may or may not correspond to biological boundaries. Quarantines are not useful where natural dispersal by air, vectors, or water is likely to occur. For example, most quarantines between the United States and Canada are for soilborne pathogens rather than for airborne pathogens. Airborne pathogens can sometimes

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Import of Plant Materials into the United States

Tourists
- No plant materials may be imported by tourists.

Commercial plant material import categories
- unrestricted
- restricted
- post-entry (must be maintained for continued inspection for up to two years)
- prohibited

Limitations to Successful Quarantines
- natural dispersal of pathogen or vector
- inability to see microscopic pathogens or early infections
- language differences among countries
- insufficient resources and/or technical training
- need for rapid testing and risk assessment to meet commercial import and export needs

"One of the unintended consequences of the globalization of trade has been an increase in the frequency of introductions and the number of exotic (alien, introduced, foreign, non-native, or non-indigenous) species intercepted at ports of entry."
move quickly over large areas. For example, in a single year (1978), the sugarcane rust fungus was naturally distributed from Africa to the Dominican Republic and on to Florida in the United States.

Another limitation to successful quarantines is the inability to easily determine whether plant materials carry pathogens. Many countries do not have sufficient resources or trained inspectors. Language differences and variable regulations impede successful quarantines, especially for land-locked countries that share their borders with several different countries. Quarantine enforcement for the United States, bounded only by Canada, Mexico, and two oceans, is less challenging in comparison.

The globalization of trade is an important threat to the successful enforcement of quarantines. Inspectors must quickly decide whether large shipments of fruits, vegetables, cereal crops, and wood products are carrying dangerous pests, pathogens, or vectors. Rapid detection methods such as DNA-based tests (e.g., PCR) and immunoassays have improved our ability to test materials quickly and accurately, but these methods are expensive and require that the inspectors know what pathogens might be present (see Appendix 3).

To remain competitive, growers who produce flowers, vegetables, fruits, and ornamentals must meet market demands, which means that they routinely import new cultivars. These growers want the new plant materials released for propagation as quickly as possible. The employees of the U.S. Animal and Plant Health Inspection Service (APHIS), state diagnostic laboratories, and comparable government agencies in other countries are under increasing pressure to monitor more (and different) plants and plant products every year. They must quickly conduct risk assessments for numerous pathogens, asking such questions as:

- Is the pathogen capable of causing serious damage?
- Is introduction by natural dispersal unlikely?
- Is the pathogen capable of becoming established anywhere in the country, including greenhouses?

In most cases, quarantines are only a delaying mechanism, which give plant pathologists time to devise management programs and develop resistant cultivars.

### Pathogen-Free Seed

Seedborne diseases are of particular concern because they introduce the pathogen along with the plant and can cause devastating losses (Figures 11.4 and 11.5). People were aware of this problem even before they understood its nature. For example, they soaked wheat and other cereal grains in copper, urine, and various concoctions to try to reduce problems with smut diseases. Some of these early investigations added

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**Quarantine Legislation and Organizations**

- **Plant Quarantine Act of 1912:** first U.S. legislation establishing plant quarantines
- **Animal and Plant Health Inspection Service (APHIS):** federal agency responsible for quarantines
- **Plant Protection and Quarantine (PPQ):** branch of APHIS that issues federal phytosanitary certificates for exporters
- **International Plant Protection Convention (IPPC):** sponsored by the Food and Agriculture Organization (FAO) of the United Nations in 1952 to provide member countries with phytosanitary export permits for eight regional organizations, including:
  - European and Mediterranean Plant Protection Organization (EPPO)
  - Intraafrican Phytosanitary Council (IAPSC)
  - North American Plant Protection Organization (NAPPO)

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**DID YOU KNOW?**

Black knot disease of plum and cherry is mainly a problem in North America, where it is indigenous. It is not yet found in European or Mediterranean countries. Currently, its pathogen, *Apiosporina morbosa*, is listed as an EPPO quarantine pathogen.

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**Plant Disease Lessons: Black knot**

Figure 11.4. A variety of fungal contaminants growing from infested seed placed on a nutrient medium.
Figure 11.5. Barley seed embryo infected by the loose smut pathogen (*Ustilago nuda*) (right) and an uninfected embryo (left).

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<thead>
<tr>
<th>Seedborne Pathogens</th>
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<td>nematodes</td>
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<td>uncommon</td>
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**To Produce Certified Pathogen-Free Seed**

- Grow mother plants in dry regions when possible.
- Isolate seed-production fields from commercial fields that may be a source of pathogens and/or vectors.
- Use careful water management to minimize leaf wetness.
- Remove infected or off-type plants during production.
- Test seed lots as required to meet certification standards for pathogens.

Evidence that led to the eventual acceptance of the germ theory of disease.

In the United States, seed production of many flower and vegetable crops is now centered in the drier western states, where plants can be grown in the near absence of seedborne fungal and bacterial pathogens. By starting with this pathogen-free seed, susceptible crops can be grown in humid climates.

**Certification** schemes determine what percentage of infested or infected seed would still allow a viable crop to be grown. Seed lots are then tested and certified as meeting these standards before seeds are sold. Certification is particularly important for many seedborne viruses because no effective seed treatments exist. Acceptable levels of seedborne pathogens vary, depending on the needs of the growers. In the United States, the threshold for *Lettuce mosaic virus* is 0 infected seeds in 30,000 tested, whereas in the Netherlands, it is 0 in 2,000 because disease pressure is lower there.

**Pathogen-Free Vegetative Propagation**

Propagative parts such as bulbs, corms, and tubers are likely to carry pathogens in their tissues or in soil attached to their outer layers. Modern plant production uses vegetative propagation for rapid multiplication of many plants, including fruit trees, flower crops, ornamentals, small fruits, potato, and sweet potato. The mother plant used to propagate numerous new plants should be free of systemic pathogens before propagation begins.

A method of culture **indexing** began in the flower industry to test mother plants for pathogens (see box “Meristem Culture and Certification for Vegetative Propagation”). In the early days, stem samples were placed in liquid media to look for bacterial growth or on solid nutrient media to test for fungal infection; various bioassays were used to test for viruses. Plants that tested clean would then be maintained under very strictly controlled conditions to prevent new infections. A small **mother block** of apparently pathogen-free plants was used to create **foundation** stock. These plants were generally still too expensive to use for production, so propagation from the foundation stock created various categories of **certified** stock that were eventually sold to producers.

Although this was an effective way to reduce a number of systemic pathogens, it was not cost effective for most kinds of vegetatively propagated plants. However, a new technology was developing at about the same time that indexing was created. As scientists became familiar with plant growth regulators, they discovered that tiny pieces of the apical meristem could be cut and used to propagate almost unlimited numbers of new plants.
Not only were the meristems generally free of pathogens, but it was economically feasible to propagate large numbers of pathogen-free plants using meristem culture (see Figures 5.13 and 5.14). The tiny plants are grown in pathogen-free laboratories on sterile growth media containing various plant growth regulators until they are ready to be transferred to a greenhouse (Figure 11.6). In some cases, plants are sent to production fields directly from the greenhouse. More often, they are grown for a year or more outdoors for additional propagation before they are finally used in commercial production. These plants must meet various established certification requirements; limits are set for pathogens that are likely to cause severe disease problems that usually cannot be managed by means other than exclusion.

Exclusion of the pathogen is useful for both monocyclic and polycyclic pathogens. When successful, no disease will occur. Some pathogens can be excluded, at least temporarily, by quarantines. Regulations must accommodate the import and export needs of international trade. The production of pathogen-free seed and propagative parts depends on research-based certification standards and the ability to produce affordable planting material. Indexing tests plants for a variety of systemic pathogens. Meristem culture revolutionized the production of affordable pathogen-free plants.

How do we eradicate pathogens?

It is quite common for new cultivars or other desirable plants to be infected by pathogens. In addition, soil, tools,
Methods of ERADICATION

Cultural practices
• crop rotation
• fallowing
• flooding
• host eradication
  • following failed quarantines
  • roguing of infected plants
  • destroying alternate or alternative hosts
• plowing or tillage
• sanitation

Heat
• burning
• steaming of soil, pots
• composting
• solarization
• hot-water treatments
• thermotherapy

Chemicals
• disinfectants
• herbicides for pathogen reservoirs
• insecticides for vectors
• seed treatments
• soil treatments (fumigants or nematicides)

Biological control
• hyperparasitism
• predation
• hypovirulence

and machinery may be infested with pathogens. Therefore, it often is necessary to eradicate (remove or destroy) pathogens before production of healthy plants can occur.

Eradication can be organized under a series of approaches, all of which attempt to reduce the amount or efficacy of primary inoculum. Eradication implies complete elimination, which is not usually feasible or necessary for endemic pathogens. Furthermore, one needs to consider the cost-benefit relationship since complete eradication is much more expensive than partial eradication of inoculum. Methods for eradication include a range of cultural practices, chemicals, and biological controls. The following methods are commonly used to eradicate pathogens.

Cultural Practices

CROP ROTATION

Rotation to a nonhost crop (Figure 11.7) forces pathogens to persist as survival structures and/or as saprophytes. Starvation of the pathogen is a key mechanism of crop rotation. There are several important economic or biological limitations to the use of crop rotation. Some pathogens are good soil inhabitants, so their populations do not decline rapidly even in the absence of a host plant. Other pathogens have a wide host range, limiting the choices for nonhost crops. Rotation is not an option for perennial agricultural systems such as golf courses, forest crops, nurseries, and small fruits. Specialized equipment used for planting and harvesting may limit crop choices available to a grower. Finally, crops vary in their value, so there is sometimes an economic incentive to produce a high value crop as often as possible.

CROP ROTATION AND DISEASE

4. The reason for Crop Rotation is not particularly to prevent loss of fertility. It is a Sanitary Measure.

Proper Rotation Frees the Soil From Specific Crop Diseases.

No matter how fertile the land, you cannot raise heavy seed if the mother seeds carry fungus diseases internally. Flux does this. Wheat does. Oats and barley do.

Nor can you raise Heavy Seed Wheat if Soil is Wheat-Sick.

Our old Wheat Lands are not “Worn Out” — They are Full of Diseased Wheat Roots and Stubble. ROTATE.

Bolley, N. D. A. C.

Figure 11.7. A poster by H. L. Bolley, from North Dakota in 1909, explaining that the benefits of rotation of wheat with other crops result from a reduction of soilborne pathogens.
FALLOWING
Leaving a field free of a crop as part of a rotation plan has been practiced historically and is practiced today in subsistence farming and dry-land agriculture. Fallowing is not an effective strategy for pathogens that can survive on weed hosts or for long periods of time in the soil. In many areas, fallowing is no longer economically feasible because a food, forage, fiber, or cash crop must be obtained from all fields each year.

FLOODING
Flooding soil creates anaerobic conditions that reduce pathogen populations. This ancient agricultural method is widely used in rice culture (Figure 11.8). It also is used before planting to reduce Panama wilt (Fusarium wilt) in banana and for nematode problems in certain crops.

HOST ERADICATION
There are several situations in which infected plants may be eradicated to remove sources of primary inoculum. For example, quarantines sometimes fail despite our best efforts. The first step to control an introduced pathogen is to try to eradicate the infected plants before the pathogen can spread, although that is not always successful. Citrus canker became a problem again in Florida in 1984 despite its apparent eradication decades earlier in the citrus-growing states of the United States. Quarantines followed in an attempt to prevent reintroduction, but these ultimately failed. With the current epidemic, authorities have attempted to eradicate all citrus trees within 580 m (1900 ft) of an infected specimen. They have had good cooperation from commercial growers, but some homeowners have resisted the regulations. When Plum pox virus (Figure 11.9) was discovered in orchards in Ontario, Canada, and in Pennsylvania in the 1990s despite quarantines, a buffer of 20 stone fruit trees was cut down around every infected tree, and roots were pulled out to prevent regrowth. Coffee rust was found several times in South America in the 1970s, and attempts were made to eradicate it. However, it is now well established in South America and most coffee-growing areas of the world.

Volunteer plants are those that grow from leftover seeds or propagative parts of the previous crop. They are sometimes sources of primary inoculum for the newly planted crop and should be removed. When current-season crop plants first emerge, it is a common practice to visually inspect them for symptoms of disease. Infected individuals are removed, so that they do not serve as a source of inoculum for neighboring plants, a practice called roguing. For example, certification
of potato plants grown for seed-potato production requires that the fields be inspected for virus symptoms and certain other diseases on several occasions during the growing season (Figure 11.10).

Alternate hosts of rust fungi can be eradicated to break the infection cycle. The barberry and Ribes eradication campaigns attempted to protect wheat from stem rust and white pines from blister rust, respectively. Junipers (red-crests) often are eradicated near apple orchards to reduce cedar-apple rust. It also is common to try to remove weeds and other alternative hosts that are sources of inoculum of viruses, fastidious bacteria, and some nematodes. For example, wild cherry trees near peach and cherry orchards can serve as sources of X disease phytoplasma inoculum and should be eradicated.

PLOWING (TILLAGE)

As discussed previously, plowing stubble and debris from previous crops into the moist soil environment speeds decay of plant debris and forces soil invaders into competition with soil inhabitants more quickly.

SANITATION

A variety of basic sanitary practices can eradicate pathogens. Cull piles of infected plant materials should not be left just outside greenhouses or at the edges of fields after harvest, where spores or pathogen-carrying vectors can easily travel to new healthy plantings (Figure 11.11). Cleaning up infested debris or fallen leaves is sometimes practical and effective. Infested tools, machinery, and boots should be cleaned before being moved to areas where a pathogen is not active or established (Figure 11.12). Sometimes a simple water rinse is sufficient, but in other cases disinfectants are applied to machinery, tools, and tires. Infected plant parts can sometimes be pruned away in the early stages of infection, especially in woody plants.
Many of the cultural practices used to eradicate pathogens are done before planting and are most effective for annual crops. In some cases, living host plants near the crop are removed because they are a source of inoculum. In other cases, practices such as tillage, crop rotation, and flooding help to reduce surviving populations of pathogens from previous crops. Sanitation may be done at the end of the growing season by cleaning up pathogen-infested debris or during the growing season by removing infected plants or plant parts.

**Heat**

As can be seen in Figure 11.13, relatively low temperatures can effectively eliminate many pathogens.

**BURNING OF STUBBLE AND DEBRIS**

This ancient practice reduces weeds, pests, and pathogens, especially those near the soil surface. These benefits also probably accompany traditional “slash and burn” agriculture. Grass seed production fields, peppermint fields, and hops yards all are burned using techniques that reduce pests and pathogens but do not kill these perennial plants (Figure 11.14). Infested debris that has been pruned or removed from fields is sometimes burned to prevent inoculum from spreading to nearby plants (Figure 11.15).

**STEAM HEAT**

Steam heat is commonly used to disinfest pots, soil, and other planting media used for potted plants in nurseries and greenhouses. Soil-free planting media usually have fewer pathogens than native soils, but it is easy for these products to become contaminated with pathogens, so they are usually pasteurized before use. Many purchased potting mixes have already been heat-treated before packaging. As discussed in Chapter 9, soil pasteurization is designed to heat soil to 60–70°C (140–160°F) to kill most pathogens but not the protective soil inhabitants. This also helps to retain good soil structure compared to soil sterilization with live steam. In some cases, steam heat is used for outdoor soils, but the time required, the inconvenience, and the expense usually limit this to flower beds or other small areas.

**COMPOSTING**

This is an effective method to reduce pathogens. Composted organic materials provide a favorable environment for the
growth of thermophilic (high-temperature-loving) organisms that sufficiently compete with the pathogens, which are generally adapted to ambient conditions. Effective composting requires adequate heating and frequent turning of the pile to expose all of the materials to moisture and microbial activity. Composted plant debris is a good source of nutrients and organic matter for soil amendments, but it is usually recommended that plant debris that is heavily infested with pathogens should be buried or destroyed rather than used for compost.

**SOLARIZATION**

The process of trapping solar radiation under clear plastic sheets to heat the soil and reduce pathogens, pests, and weeds is called **solarization** (Figure 11.16). This can be an effective way to reduce primary inoculum because many important pathogens are killed at relatively low temperatures. It is most effective for pathogens that are near the soil surface, but it does not control some heat-tolerant pathogens such as root-knot nematodes. Solarization should usually be done during the hottest part of the year, so it can be used during the summer in greenhouses that are used for plant production during the cooler months. Some additional limitations to the use of solarization are the relatively long time (several weeks) that the procedure requires, the need for access to uninterrupted and intense solar radiation, the storage or disposal of large amounts of plastic, and the cost.

**HOT-WATER TREATMENTS**

Hot water is sometimes used to kill pathogens in seeds and propagative parts. Of course, one must take care not to kill embryos or buds in the process of killing the pathogen. Hot water treatments for seeds have been used for bacterial and fungal pathogens. The production of seed in drier climates has greatly reduced the need for seed treatment for bacteria, and systemic fungicides have greatly reduced the use of hot water seed treatment for fungi. Hot water dips are occasionally used for nematodes such as *Ditylenchus* spp. in bulbs.

**THERMOTHERAPY OF PLANTS OR PLANT PARTS**

To eradicate viruses before propagation, long periods (6–10 weeks) of heat treatment (30–40°C/86–104°F) have been used to obtain virus-free meristems from virus-infected plants. Heat treatment has become a routine step in meristem culture, even for mother plants that have tested virus-free, because unknown systemic pathogens might be present. Thermotherapy is thought to be effective because the high temperatures reduce virus replication, and plasmodesmata
(cytoplasmic strands or channels through which viruses move from cell to cell) are not developed in meristems.

Heat is a very effective means of eradicating pathogens. High temperatures can be used to disinfect soil, tools, and pots. Lower temperatures must be used on living plant materials such as mother plants for meristem culture, propagative parts, and seeds, but, fortunately, many pathogens are quite sensitive to even moderate heat.

**Chemicals**

Various chemicals have been used in plant disease management. In some cases, they are used to eradicate the pathogen from soil, tools, machinery, seeds, or propagative parts. Other chemicals are applied to growing plants to protect them from infection or to eradicate very early infections. The use of chemicals as plant protectants is discussed in the Protection section of this chapter.

**DISINFESTANTS**

Alcohol, bleach (sodium hypochlorite), and quaternary ammonium are common disinfectants. They are used to clean storage areas for harvested fruits, vegetables, seed, and propagative parts for the next planting, as well as boots, greenhouse benches, tools, machinery, and vehicles (Figure 11.17). The concentration of the disinfectant and the exposure time needed to eradicate pathogens vary depending on the material to be disinfested.

**HERBICIDES**

Herbicides kill plants. They are occasionally used to kill parasitic plants, but it is difficult to kill the parasite without harming the host. Weed reservoirs of plant viruses, fastidious bacteria, and certain other pathogens may be reduced using herbicides. Herbicides may be used to eradicate alternate hosts of rust fungi (Figure 11.18).

**INSECTICIDES**

As discussed in previous chapters, the routine use of insecticides is not recommended to kill vectors of fastidious bacteria and viruses. In some cases, traps are used to monitor vectors to determine whether insecticide use is warranted. For example, in the United Kingdom, suction traps 12 m (36 ft) above the ground are used to monitor migrating aphid

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**Figure 11.17.** A cleaning unit with which a disinfectant is applied to fruit conveyor rollers for daily sanitation of the citrus packing line.

**Fig. 11.18.** Herbicide application to a Ribes bush, the alternate host of the white pine blister rust fungus, along a waterfall in Glacier National Park. The applicator is shown by the arrow.

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<th>Generic Terms for Pesticides</th>
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<tbody>
<tr>
<td>antibiotics (bacteria)</td>
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<tr>
<td>biocides (broadly toxic—used for some soil fumigants)</td>
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<tr>
<td>fungicides (fungi)</td>
</tr>
<tr>
<td>herbicides (plants)</td>
</tr>
<tr>
<td>insecticides (insects)</td>
</tr>
<tr>
<td>nematicides (nematodes)</td>
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<tr>
<td>rodenticides (rodents)</td>
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<table>
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<th>World Pesticide Use for Agriculture, 2000</th>
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<tbody>
<tr>
<td>44% herbicides</td>
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<tr>
<td>28% insecticides</td>
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<tr>
<td>19% fungicides</td>
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populations that may be carrying Barley yellow dwarf virus. The insects are tested by immunoassay to determine whether they are carrying the virus, and an insecticide is applied, if needed, to limit infections. Yellow sticky traps are commonly used in greenhouses to trap aphids and thrips, both of which can be vectors of harmful viruses (Figure 11.19).

**NEMATICIDES**

These chemicals are used to reduce certain nematode pathogens of high value crops. Most nematicides (e.g., aldicarb, fenamiphos, and oxamyl) target the nervous system, so they also kill soil insects, worms, and other beneficial organisms. Because of their toxicity, they must be used with care during application; their use is strictly regulated and may be banned in the near future.

**SEED TREATMENTS**

Some seeds are treated with surface fungicides to protect them from damping-off pathogens for a short time after planting. Chemical treatments with systemic fungicides are used to eradicate pathogens from seeds (Figure 11.20). Systemic fungicides are most commonly used for seeds of cereals that might be infected by various smut fungi (Figure 11.5). Copper and organic mercury compounds were used to treat seeds in the past, but they required soaking the seed in water or slurries and could be toxic to the seed embryos.

**SOIL FUMIGANTS**

Fumigants were developed to temporarily reduce the populations of a variety of plant pests and pathogens. These chemicals harm plants, so the chemical must have time to dissipate after application and before seeding or planting. Some soil fumigants are so volatile that fields must be sealed with plastic tarps to retain the chemical in the soil long enough for it to be effective (see Figure 4.20). A number of soil fumigants are classified as "biocides," which means that they reduce populations of fungi, nematodes, and weeds as well as many beneficial organisms. Some examples of soil fumigants are chloropicrin, dazomet, 1,3-dichloropropene, and methyl bromide. High cost limits the use of soil fumigation to high value crops or to perennial crops (e.g., golf putting greens, fruit trees, nursery crops, or strawberries) before plant reestablishment in soil with high pathogen populations. There are increasing concerns about applicator hazards and environmental problems, including destruction of the protective ozone layer (by methyl bromide) and groundwater contamination with toxic compounds. Some soil fumigants have been banned. The use of the remaining available compounds is strictly regulated.
Chemicals are used in a variety of ways to eradicate pathogens. Disinfectants are used for tools, pots, tires, and other inanimate objects that may carry pathogens. Herbicides are used to eradicate weed reservoirs of pathogens. Insecticides may be used to eradicate pathogen vectors. Nematicides eradicate plant-pathogenic nematodes but may affect other animals with a nervous system. Soil fumigation helps to eradicate most pathogens, weeds, and insect pests, but it is expensive and is restricted because of the toxicity of the chemicals used.

**Biological Control**

As discussed in Chapter 9, pathogens interact with numerous other microorganisms in their environment. Biological control is the deliberate exploitation of these microorganisms by people to reduce inoculum or protect plants. The concept of biological control grew out of careful observations of certain disease phenomena followed by investigations into their causes. For example, we now know that some standard agricultural practices such as crop rotation could be considered biological control because competition with and antagonism by soil microorganisms reduce pathogen populations.

Suppressive soils, in which various diseases were naturally at lower levels than expected, have been observed. Further investigations demonstrated that the suppression was due to biological factors in the soil, but it has not been possible to identify the exact causes and recreate these suppressive soils in other places.

In some cases, disease declines when a crop is grown in the same soil for several years. With repeated planting of the same crop, disease first increases and yields decline for several years as expected, but then, surprisingly, some diseases begin to decline. Take-all decline in wheat is the best known example of this, but it also has been observed for other diseases such as necrotic ring spot, summer patch, and take-all patch of turfgrass. These diseases are more common and more severe in newly established turfgrasses and tend to decline as the turfgrasses mature. Research into the nature of disease declines has improved our understanding of the role of rhizosphere populations of microorganisms and how they function in biological control.

The previous examples demonstrate that general populations of soil microbes can help reduce diseases. Green manures are crops that are plowed under to increase populations of antagonistic organisms, a form of general biological control. Composts, sometimes added as organic soil amendments, may reduce disease by introducing microbial populations.

**Modes of Action of Biological Control**

*For eradication of the pathogen*
- parasitism (hyperparasites)
- predation
- hypovirulence

*For protection of the plant (see page 283)*
- antibiosis
- competition
- cross-protection

**DID YOU KNOW?**

The first attempts at direct applications for biological control of plant pathogens were made by C. Hartley in 1921. He inoculated pots of autoclaved soil with 13 antagonistic fungi to try to reduce damping-off of pine seedlings.

**General Methods of Biological Control**

*Green manures*: living plants plowed into the soil to stimulate the growth of populations of biological control organisms

*Compost and other organic amendments*: introduction of microbial populations and organic matter that helps to support microbial populations
The successful use of compost depends on the organic base that is used and the types and numbers of microorganisms. Microbial colonization of compost occurs naturally after the thermophilic phase, and sometimes the colonizing populations do not suppress disease. Some commercial enterprises deliberately introduce specific organisms into composts to enhance their ability to suppress disease.

All of these general enhancements of natural microbial populations that reduce plant diseases have led to the hope that specific biological control agents could be isolated and applied in ways similar to fungicides and other chemicals. As with chemicals, biological controls may be used to protect plants from infection or to eradicate primary inoculum. **Antagonist** is a general term for an organism that interferes with plant pathogens. Antagonists may act in various ways but have several specific modes of action. Two of these, **parasitism** and **predation**, mostly reduce inoculum and are considered forms of eradication. **Hypovirulence** describes a phenomenon in which the pathogen’s ability to cause disease is weakened.

**PARASITISM**

Parasites of parasites are called **hyperparasites** (Figure 11.22A). They have been isolated from nematodes, nematode eggs, fungal survival structures, and mycelia. One of the most studied hyperparasitic fungi is *Trichoderma*, a common soil fungus. Many other fungal and bacterial hyperparasites have been isolated from plant pathogens. It is sometimes difficult to produce and effectively distribute inoculum of hyperparasites, which has limited the use of hyperparasites as commercial eradicants.

As with all parasites, it is important to know the host range of the organism. In some cases, a very narrow host range is a benefit because the hyperparasite is likely to infect only the pathogen and not beneficial organisms. Hyperparasites do not necessarily have to completely kill a pathogen to be effective. A fungal hyperparasite of a powdery mildew fungus was found to inhibit spore production and thus reduce the ability of the pathogen to spread (Figure 22A).

**PREDATION**

Various predaceous nematodes and other soil microfauna feed on plant-pathogenic nematodes and their eggs. Many nematode-trapping fungi have been isolated from soils. Commercial products utilizing predation for control of pathogens are still in the research and development stages.
HYPOVIRULENCE

This phenomenon is best known in chestnut blight (see Robert Frost’s prediction in Chapter 10) (Figure 11.23). A mycovirus, a virus that infects the pathogenic fungus, reduces the virulence, or disease-causing ability, of the pathogen. The hyphae of genetically compatible strains of the fungal pathogen may fuse (anastomose), and the mycovirus can then spread from the hypovirulent strain into the mycelium of the virulent strain, reducing its ability to cause disease. These hypovirulent strains are applied to active chestnut blight cankers to restrict their growth. This has been accomplished successfully in chestnut orchards in Europe, where there are relatively few genetic strains of the pathogen. The problem is more challenging in the forests of the Appalachian Mountains, the natural habitat of the American chestnut. The extensive geographical range and the numerous genetic strains of the pathogen have limited the successful use of hypovirulence so far. Mycoviruses have been found in other fungi, but practical uses have not yet been developed.

Careful observations of plant disease epidemics provided evidence that biological control of plant diseases might be possible. The effectiveness of crop rotation, suppressive soils, and disease declines were studied and found to have a biological basis. Green manure and compost amendments are used to generally increase populations of antagonists. Biological controls can be eradicative or protective. Hyperparasites and predators have been isolated and used to reduce pathogens and their inoculum. Hypovirulence has been used to stop the expansion of chestnut blight cankers and may be useful against some other pathogens.

How do we protect plants?

The previous sections described methods to avoid, exclude, or eradicate pathogens. These are useful for both monocylic and polycyclic pathogens. They are the primary methods used to manage monocylic pathogens, for which primary inoculum is most important. Although it is helpful to reduce the amount of primary (initial) inoculum, another option is to reduce its efficacy, i.e., to protect the plant from infection by primary inoculum even if it is there. For polycyclic pathogens, it also is necessary to protect plants from secondary inoculum for as long as the plants remain susceptible to infection. Luckily, there is a wide range of options to protect plants against infection. They can be grouped as cultural practices,

Figure 11.23. A chestnut tree in Michigan recovering from chestnut blight because of naturally occurring hypovirulent strains of the pathogen.

DID YOU KNOW?

The American chestnut might return a century after the terrible chestnut blight began with the introduction of the ascomycete Cryphonectria parasitica. By 1950, 3.5 billion trees, nearly 90% of the U.S. population of chestnuts, had died. The American chestnut was sometimes called the “redwood of the East” and was important as a source of decay-resistant lumber, tannins for the leather-tanning industry, and, of course, its delicious nuts. The nuts not only were important to people who collected them for food and income but also were an important food for bears, wild turkeys, and other animals of the forest. Several groups of scientists are working to bring back the chestnut in its natural range in the Appalachian Mountains of the eastern United States. Traditional plant breeding and genetic engineering are being used to create a variety of blight-resistant chestnut trees. Other scientists are trying to use the phenomenon of hypovirulence, which results when a pathogenic fungus is infected by a virus and weakened. As with all plant diseases, a combination of approaches is most likely to succeed.
Methods of PROTECTION

Cultural practices
- barriers and mulches
- plant nutrition
- modification of soil pH
- temperature management
  - cool plants
  - cold storage of plant products
- water management
  - improve soil drainage
  - minimize leaf wetness

Chemical protection
- for bacteria
  - antibiotics
  - copper-based chemicals
- for fungi
  - protectant/contact fungicides
  - systemic/penetrant fungicides

Biological control
- antibiosis
- competition
- cross-protection

Genetic resistance
- specific (R gene) resistance
- general resistance

chemicals, biological controls, and genetic resistance. Not all of these can be used on every kind of plant or for every kind of pathogen, but usually several them will be generally effective in reducing disease.

Cultural Practices

BARRIERS AND MULCHES

It is sometimes possible to create barriers that help to protect plants. In greenhouses, it is common to use very fine mesh screens that prevent access of insect vectors of fastidious bacteria or viruses. Outdoors, reflective or colored plastic mulches are sometimes used to repel aphids and other vectors. Unfortunately, as plants grow larger, they tend to cover the mulch and reduce its effectiveness, but mulches can delay infection substantially and thus increase yields. Organic and plastic mulches also can help to protect the “splash zone” parts of plants such as tomatoes and cucurbit fruits from soilborne pathogens such as oomycetes (Figures 11.24 and 11.25). Shredded bark and other organic mulches serve as physical barriers to foliar pathogens, including nematodes attempting to move upward from the soil and plant debris on the soil surface.

PLANT NUTRITION

As discussed previously, nutrient deficiencies can stress plants and make them more susceptible to diseases. The macronutrient nitrogen seems to have the most important impact on plant diseases by causing lush tissue when used in excess and senescent tissue when deficient. A combination of small applications of quick-release nitrogen fertilizers along with a base of slow-release nitrogen helps to prevent the extremes that can enhance diseases. Frequent small applications of fertilizer (“spoon-feeding”) often are recommended for green-

Figure 11.24. Tomatoes staked and growing on plastic mulch to aid drying of plant surfaces and to protect plants from soilborne pathogens that might splash up from the soil.
houses and golf courses. In some systems, fertilizers are applied in the irrigation water, a process called "fertigation."

SOIL pH

Recommendations for soil pH level are generally based on plant requirements and the effects on the availability of nutrients. Certain plants, such as ericaceous species (blueberry, rhododendron), grow best in acid soils. Soil pH is sometimes modified to reduce infection by certain soilborne pathogens. Some classic examples are raising pH to about 7.2 to reduce clubroot of brassicas (crucifers) and maintaining pH at 4.0–5.2 to reduce common scab of potatoes. Necrotic ring spot, summer patch, and take-all patch of some turfgrasses are reduced by lowering soil pH with the use of sulfur or certain forms of nitrogen fertilizer such as ammonium sulfate. Most soilborne pathogens are not affected by soil pH within the range appropriate for plant growth.

TEMPERATURE

Temperature is controlled in greenhouses with shade and ventilation by fans. For some plants, midday heat can be dissipated by brief applications of irrigation water, known as syringing when used on golf course putting greens. Cold is used to reduce pathogen activity in stored harvested crops, seed, and propagative parts.

WATER MANAGEMENT

Poorly drained soils increase root diseases by reducing the oxygen supply to roots and enhancing the activity of many pathogens, especially oomycetes (Figure 11.26). Improved drainage reduces problems associated with some pathogens.

Figure 11.25. Protection by a barrier. A, Use of organic mulch (a method called frijol tapado, "covered beans") as a barrier to the soilborne fungus that causes web blight of beans (Thanatephorus cucumeris). The mulch also reduces weed growth and conserves soil moisture. B, Web blight of beans where organic mulch was not used.

Figure 11.26. Damage to onions caused by Pythium in a field with poor drainage.
Although compacted, poorly drained soil is an important factor in many soilborne diseases, it also increases the humidity around the aboveground parts of plants and lengthens drying time.

Leaf wetness is a key factor for foliar infection by bacteria, fungi, and foliar nematodes. Leaf wetness can be reduced by several practices.

1. Fans. Fans move air, increase evaporation, and thereby reduce leaf wetness. They are often used in greenhouses and on some golf courses.

2. Plant spacing and form. Use of the recommended spacing of herbaceous plants helps to reduce competition among plants and helps plants dry quickly as they mature and the leaf canopy closes. On woody plants, thinning of canopies by pruning branches enhances air movement and drying.

3. Removal of dew. It is best to mow lawns after the turfgrass leaves are dry to avoid spreading pathogens. However, early morning mowing of golf course putting greens and fairways is usually a commercial necessity (Figure 11.27). On turfgrass with very short leaf blades, mowing can reduce foliar diseases by removing dew and nutrient-rich guttation fluid because the leaf blades dry quickly. On days when the greens and fairways are not mowed, hoses or poles may be dragged across the surface of the turfgrass to remove dew and reduce the length of time that the leaves remain wet.

4. Row orientation and air movement. At the time of planting, rows should be oriented to take advantage of prevailing air movement patterns, so leaves will dry quickly. Hedgerows along field crops and plantings on golf courses and in landscapes can impede air movement and allow retention of moisture on plants (Figure 11.28).

5. Shade. In outdoor plantings, areas may be in shade for parts of the morning or afternoon. Morning shade, in particular, increases the time that leaves remain wet from dew that forms overnight. Outdoor plants that are shaded for much of the day often have more foliar diseases, such as powdery mildew, because of the increased humidity in their environment.

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Methods of Reducing Leaf Wetness

- fans
- improve soil drainage
- plant spacing and form
- removal of dew
- row orientation
- shade reduction
- soil surface irrigation
- timing of irrigation
- weed control

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Figure 11.27. Removal of dew on turfgrass by early morning mowing.

Figure 11.28. Trees bordering this potato field may impede air movement and slow the drying of plants.
6. **Soil surface irrigation.** In greenhouses and some outdoor plantings, irrigating only the soil surface greatly reduces foliar diseases by minimizing periods of leaf wetness (Figure 11.29).

7. **Timing of irrigation.** Water should be applied in the early morning when the leaves are usually already wet with dew. Water also can be applied during the day when leaves have time to dry quickly, before infections can occur. Water conservation programs discourage midday watering because so much water is lost to evaporation. Watering in the late afternoon and early evening, or just as the leaves are drying in the morning, extends the period of leaf wetness and increases the potential for disease.

8. **Weed control.** Weeds can be a barrier to rapid drying of desirable plants.

To protect plants, cultural practices should favor plant growth and reduce opportunities for infection by pathogens. Physical barriers to pathogens and vectors such as greenhouse screens and mulches are sometimes effective. Temperature, soil pH, and plant nutrition affect both plants and pathogens. Because so many bacterial and fungal foliar pathogens require hours of leaf wetness for infection, many cultural practices focus on minimizing this time.

**Chemicals**

Chemicals that are used to reduce primary inoculum were discussed previously and include soil fumigants, nematicides, insecticides for vector populations, herbicides for pathogen reservoirs in weeds or management of parasitic plants, seed treatments, and various disinfectants. The most common chemicals used to protect plants are antibiotics and copper compounds for bacterial pathogens and fungicides for fungal pathogens. “Plant activators” are the newest crop protectants. They induce systemic acquired resistance (SAR) to a variety of pathogens (see Chapter 9, Section B).

**CHEMICALS FOR TREATMENT OF BACTERIAL DISEASES**

Because of their expense and the risk of bacteria developing resistance, antibiotics are not used very often for bacterial plant diseases. In fact, only 0.1% of the antibiotics used in the United States are used for plant diseases. The antibiotics tetracycline and oxytetracycline are sometimes applied to apples, pears, and some ornamentals to manage fire blight and other bacterial diseases. Tetracycline antibiotics may be

**Copper-Containing Sprays**

- strictly protective (no after-infection activity)
- effective for fungal and bacterial diseases
- must be reapplied every 5–10 days, depending on rainfall
- copper may build up in soil with repeated use

**Bordeaux mixture** (copper sulfate and lime) was the first effective foliar fungicide that could be sprayed on plants to prevent infection by fungi. It was named by Alexis Millardet, a professor at the University of Bordeaux, in France. A French farmer created the original mixture to leave a chemical residue on grape vines along the roadside to discourage pilfering of his grapes. Millardet noticed that the sprayed vines were not dying of the new downy mildew disease that was threatening the French wine industry.

**Plant Disease Lessons:**

**Grape downy mildew**

**DID YOU KNOW?**

During World War I in Germany, copper was confiscated from citizens by the German army for military uses such as shell casings. This led to a shortage of the copper sulfate necessary for Bordeaux mixture, the only effective foliar fungicide at the time. Subsequent late blight epidemics of potatoes caused by *Phytophthora infestans* led to starvation of many German people and weakened the morale of their soldiers at the fronts.
injected into trees infected with phytoplasmas or Xylella fastidiosa for remission of symptoms, but they do not cure the trees.

Copper-based fungicides are used to control the bacteria that cause citrus canker and foliar bacterial diseases such as bacterial spot of peppers and tomatoes. Copper formulations remain on the surface of the plant, so they are strictly protective, i.e., they offer no after-infection activity. They must be reapplied frequently to new tissue or when rain dilutes the application. Repeated applications can lead to a buildup of copper in the soil, which can cause toxicity in plants.

**Fungicides**

The earliest fungicides were inorganic compounds based on the toxic elements cadmium, copper, mercury, and sulfur. Cadmium and mercury fungicides are no longer available because of their toxicity and the hazards they posed to the environment. Copper- and sulfur-based fungicides are effective against a wide range of fungal diseases, but they are strictly protective, must be reapplied often, and may accumulate in the soil. Organic fungicides (carbon-based compounds) tend to be more specific in their mode of action, so accurate diagnosis of the problem to be treated is more important.

Every year, plant pathologists test fungicides, and many publish their results in the annual report *Fungicide and Nematicide Tests*. Extension specialists and crop consultants develop these results into recommendations. Fungicide recommendations change often, and the availability of fungicides varies from country to country and from state to state. Certain fungicides may be used on turf and ornamental plants only, and others are used on food crops only. Overuse of many of the organic fungicides available today can result in resistant fungal populations, so it is important to use fung-

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**DID YOU KNOW?**

Bananas are fourth among agricultural commodities, with world trade of $2.5 billion annually. Yet, 90% of all bananas grown are consumed by poor subsistence farmers in tropical Africa, America, and Asia (Figure 11.30). The fungal disease, black Sigatoka, is responsible for 15-20% of the costs of bananas in importing countries, because 38–50 fungicide sprays may be applied each year to manage this disease.

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Figure 11.30. Market in Malawi where several banana cultivars are for sale by traditional farmers.
cides as part of an overall resistance management plan. Thus, there is no simple answer to the common question: “What is the best fungicide for this disease?”

Fungicides are used to protect high value crops from polycyclic diseases. They also are used for diseases for which other means of control are not available (Figure 11.31). Most crops do not get routine applications of fungicides because we have cultivars with good genetic resistance or cultural practices that effectively manage the disease. Fungicides are not used for most root diseases because it is often too late for treatment to be effective when symptoms are noticed. It also is difficult to deliver fungicides to roots effectively.

Organic fungicides are toxic to fungi, but most of them are not particularly toxic to humans and other nontarget organisms. A few fungicides are toxic to fish or other organisms. Specific toxicity warnings are found on the fungicide label.

The relative acute toxicity of a substance is usually determined by calculating the dose that is lethal for 50% of a test population, often rats or mice. This is called the lethal dose 50 (LD<sub>50</sub>). It is stated as the amount of active ingredient (in milligrams) per kilogram of body weight. The LD<sub>50</sub> is chosen as the halfway point in a toxicity test because certain individuals in any population are very sensitive to the substance, and others may be quite resistant. LD<sub>50</sub> is a relative measure used to compare the toxicity of one compound to that of another. It is not a measure of exactly how much would be lethal to the applicator. LD<sub>50</sub> also is a measure of acute exposure, i.e., a single dose all at once, but not of the chronic (low-dose and repeated) exposures that most applicators face.

Most fungicides have a high LD<sub>50</sub>. This means that the lethal dose is quite large, and the product is not very toxic. This does not mean that there is no risk to the applicator, however, because chronic exposure or exposure to high concentrations of many chemicals can potentially cause other health problems, such as cancer. An LD<sub>50</sub> usually represents an oral dose, but some chemicals can be absorbed very well through the skin and lungs, so appropriate protective clothing, gloves, and respirators should always be used.

Nearly all of the fungicides used today are organic compounds that are eventually degraded by bacteria. Fungicides vary in their modes of action (i.e., how they work) and in what happens when they are applied to plant tissue. Factors that should be considered when choosing a fungicide are the following.

1. **Application**. Fungicides are most easily applied to aboveground plant parts. Most fungicides are formulated to be mixed in a water carrier and sprayed on aboveground parts of plants. A few fungicides are formulated as granules. It is difficult to apply fungicides to roots and other belowground parts. Only one kind of fungicide (phosphites such as fosetyl-Al), can
Limitations to the Use of Fungicides for Root Diseases
- Delivery to the root system is difficult.
- Nearly every fungicide must be watered in (only phosphites, e.g., fosetyl-Al, move downward after a foliar spray).
- It is usually difficult to know that a fungicide is needed until it is too late.

DID YOU KNOW?
Each year, the U.S. government tests domestic and imported fruits and vegetables for pesticides. In a typical year, over 14,000 samples were tested. Of these, more than 50% had no residues, and only 1.5% exceeded the tolerance. The total dietary intake of pesticide residues is <1% of the acceptable daily intake (ADI).

In the Annual Review of Phytopathology in 2000, Dr. Nancy Ragsdale examined the impact of the Food Quality Protection Act (FQPA) on the future of plant disease management. She wrote: "Public perception and political pressure were sufficient for the U.S. Congress to unanimously pass FQPA although scientific data indicating that our food supply was unsafe because of pesticide residues were lacking."

actually move downward in the plant following a foliar application. Therefore, root diseases almost always require that a fungicide be drenched in with large volumes of water. In addition, by the time aboveground symptoms of a root disease are noticed, considerable damage has already occurred, and it is probably too late to stop the pathogen with a fungicide.

2. Pesticide label and food safety. It is important to obey all pesticide label instructions because they constitute a legal document determined at the time of registration with the U.S. Environmental Protection Agency (EPA). The label includes dose, frequency of application, which plants may be treated, and other information. Labels for fungicides and other pesticides applied to food crops include a days to harvest time to minimize residues in food products. For example, if the label indicates five days to harvest, the crop may not be harvested sooner than five days after the last fungicide application. The days to harvest are calculated from toxicological studies of safe exposure levels for a pesticide (plus a safety factor) as well as the time it takes for a pesticide to attenuate after application (plus a safety factor). The goal of the calculation is to minimize residues at the time of harvest. A tolerance, or maximum legal residue, is established for all food-crop uses of pesticides. Any crop that has residues in excess of the tolerance can be confiscated and destroyed. Major food processors do their own testing, and representatives from the EPA can test any harvested crops for residues.

In 1996, the Food Quality Protection Act (FQPA) was passed by the U.S. Congress. One of its goals was to apply the science of food safety to the registration of pesticides. It considers all potential exposures to a particular pesticide, including uses in recreational areas and home pest control as well as food residue exposures. It also looks at pesticide exposure by chemical groups with the same mode of action and therefore the same health impacts on people. These are combined into what is called a risk cup of exposure. If the various uses of a specific chemical group exceed the risk cup allowed, then certain uses must be eliminated.

Chemical companies must then eliminate uses based on potential exposure and the economic value of the uses in product sales. For example, a number of fungicide registrations for lawn care have already been eliminated because the potential exposure is high near homes and the economic value of these uses to the companies is relatively low. All pesticide registrations are in review using the new FQPA guidelines, and the final impact of this new law remains to be determined.

3. Spills and care in application. Care should be taken to avoid spills or inappropriate disposal of concentrated amounts of fungicides and other pesticides in containers. Sprayers should be calibrated, spraying near surface and ground waters (e.g., wells and high-risk areas) should be
How Can We Prevent or Manage Plant Disease Epidemics?

CONTACT OR PROTECTANT FUNGICIDES

Fungicides are categorized by how they interact with plant tissue after application. Some remain on plant surfaces, where they function as a contact fungicide and are sometimes called "protecants." They tend to be effective against a broad range of fungi. They do not promote the development of resistant populations of fungi because their modes of action target multiple metabolic sites. In periods of rapid plant growth or rainy weather, they must be reapplied every 5–10 days. Complete plant coverage is necessary during application.

SYSTEMIC OR PENETRANT FUNGICIDES

These fungicides are absorbed (penetrate) into plant tissues. Because they kill or inhibit fungi without harming the plant, their modes of action tend to be quite specific, sometimes inhibiting a single enzyme system in a fungus. As a result, fungicide resistance is more likely to occur with repeated use. Systemic fungicides also are effective for a more-limited number of fungal diseases. Because they are absorbed, they

Avoided, and applications should not be made in high winds or before impending rainstorms.

In recent years, the contamination of groundwater by pesticides has become a concern (Figure 11.32). Groundwater is especially vulnerable to contamination (whether by septic tanks, buried gas tanks, or pesticide applications) in sandy soils with low organic matter, where groundwater is close to the surface, and where the climate is wet or irrigation is heavy. Pesticide characteristics also play a role in groundwater contamination. Chemicals are at a greater risk for movement into groundwater if they are soluble, do not adsorb well to organic matter, are applied to bare soil, or are injected or watered into soil.

Groundwater contamination has occurred in Cape Cod (in Massachusetts), Florida, Long Island (in New York), and some sandy river valleys in the eastern half of the United States. The most common pesticide contamination contaminants are preemergent herbicides, soil fumigants, and nematicides—all chemicals that are applied on or into bare soils. When fungicides are applied to growing plants, potential contaminants are more likely to be degraded by the increased microbial activity of the rhizosphere before they reach the groundwater. This is one reason that grass plantings, with their dense root system and organic thatch layer, help to prevent groundwater contamination. Grasses are sometimes planted between rows in perennial plantings to protect groundwater or at the edges of agricultural fields to help protect surface waters from run-off contamination.
do not wash off a plant and therefore require fewer applications. Despite the name “fungicide,” some chemicals are really fungistats, which inhibit growth but do not actually kill the fungus.

**Locally systemic fungicides** enter plant tissue but do not move far from the point of penetration. Other systemic fungicides, the **xylem-mobile systemics**, move upward in the xylem after they are absorbed and can move into new tissue as the plant grows. Only fosetyl-Al and other phosphites are **amphimobile** or **phloem-mobile systemics** and move upward, as well as downward into the roots after application.

Calibration of application equipment is very important when using systemic fungicides because **phytotoxicity** may occur if applications are too concentrated. Sometimes systemic fungicides are applied for **curative uses**, i.e., after infection has already occurred. Although systemic fungicides are absorbed into plant tissues and have some curative action, this is usually limited to the very early stages of infection, and the fungicides cannot be used to cure a severely diseased plant. Systemic fungicides cannot bring dead tissue or dead plants back to life. However, systemic fungicides make the use of environmentally based predictions of **infection periods** more effective and offer alternatives to routine calendar-based spraying.

**RESISTANCE MANAGEMENT**

Contact fungicides have multisite modes of action (i.e., multiple ways to attack fungal activities), so fungi are unlikely to become resistant to them. Some contact fungicides have been used for more than 40 years without resistance problems. Systemic fungicides usually have a single-site mode of action, so fungi are more likely to become resistant to them. Resistant strains or races of a pathogen are usually already present when a fungicide is first used. Continued use of the fungicide selects for survival of the resistant strains. Good stewardship of valuable fungicides reduces the chances that resistance of a pathogen to the fungicide will occur. Therefore, using fungicides only when needed and as part of an integrated program is recommended. There are some additional factors to consider in fungicide stewardship.

It is important to know what **active ingredient** or ingredients are in a fungicide because repeated use of the same active ingredient or the same **chemical group** of fungicides can lead to resistance. All commercial fungicides have brand or trade names that are used in commerce, but the chemical name of any active ingredient must also be listed on the label. Some active ingredients are sold under several different trade names, so applicators might believe that they are using different active ingredients when they are not.
It also is necessary to determine the chemical group or family to which each fungicide belongs because all chemicals in the group have the same mode of action. Even though an applicator might apply different active ingredients, the pathogens will react in the same way if the chemicals all have the same mode of action.

Whenever a new fungicide becomes available, it is important to ask for the name of the active ingredient and its mode of action. It is not necessary to memorize this information, but all applicators should have access to the trade names of the products they use, their active ingredients, and the chemical groups to which they belong. This information is available from chemical sales representatives, manufacturer websites, or university extension specialists.

How to prevent or delay the development of resistance is a matter of some controversy, but the repeated use of a single fungicide or fungicides from the same chemical group, i.e., with the same mode of action, will certainly lead to resistance more quickly. Some chemical groups are at a higher risk for resistance because a single gene in the pathogen confers resistance. Other chemical groups are less likely to result in resistance because several genes in the pathogen are involved in resistance.

Another factor that affects resistance management is how the fungicide-resistant strains of a pathogen interact with fungicide-sensitive pathogen strains. Sometimes, resistant strains of the pathogen are competitive and persist in the environment even after the fungicide group is no longer used. If the resistant strains are less competitive than the sensitive strains, withdrawing that chemical group from use for some time might allow the fungal population to return to having sensitivity to that chemical group.

Most scientists believe that it is best to try to prevent or delay resistance rather than to manage it after it occurs. They recommend that systemic fungicides from a chemical group with the same mode of action be mixed or alternated with a systemic fungicide with a different mode of action or with a contact fungicide that is not subject to resistance problems. Applications based on infection-period forecasts may reduce the number of fungicide applications used compared to the number required by calendar-based schedules. Fewer applications mean less selective pressure on the pathogen to become resistant to the fungicide.
"There is no beginning to love," Roger said. "It just creeps over you."
"Oh," said Hilma, "like brown rot on a plum tree in the dark winter months, and by the time you become aware of it, the leaves are out and it’s too late to spray."
—Bailey White, *Quite a Year for Plums* (Random House, New York, 1999)

Chemicals play an important role in the protection of plants against many foliar diseases. All pesticides should be used with care to avoid environmental contamination, phytotoxicity, residues in food, and applicator exposure. Plants are sometimes protected against bacterial infections with antibiotics or copper-containing compounds. Most fungicides used today are organic compounds with low mammalian toxicity (i.e., high LD₅₀) that are degraded by bacteria. Contact or protectant fungicides remain on the leaf surface, are effective for a wide range of fungal diseases, are not generally at risk for development of resistance, and must be reapplied after rain or plant growth. Systemic or penetrant fungicides may be absorbed locally, move upward in the xylem, or be amphiomobile in the phloem. They do not wash off, are effective against fewer diseases, and may have some after-infection activity. Because systemic fungicides have more specific modes of action, they are at risk for development of fungal resistance. Systemic fungicides should be rotated or mixed with systemic fungicides having a different mode of action or with a contact fungicide that is not subject to resistance problems. The development of resistance can be minimized by using fungicides only when needed and as part of a resistance management program.

A more complete discussion of fungicides, with animations of their movement in plant tissue, is on the CD-Rom.

**Biological Control**

As discussed earlier in this chapter, there is good evidence that natural biological control is at work in agroecosystems. The sporadic nature of disease suggests that pathogens are kept at bay unless conditions are particularly favorable for infection. With the use of fungicides that target only certain pathogens, we sometimes see an increase in a certain disease when a fungicide has been applied to control a different disease. This may be due to the impact of the fungicide on natural competitors and antagonists that usually inhibit the noncontrolled pathogen. Increased disease severity also has been observed following the introduction of pathogens into sterile potting media or in sand-based putting greens with little organic matter to support microbial activity. These observations have encouraged plant pathologists to try to isolate specific organisms that could be applied to plants to protect them against infections. The modes of action of biological

**Evidence of Natural Biological Control**
- the sporadic nature of disease
- effectiveness of crop rotation
- suppressive soils
- disease declines
- increase of a disease when a fungicide is applied for treatment of a different disease
- disease severity in sterile soils
control agents used to protect plants from infection include antibiosis, competition, and cross-protection.

**ANTIBIOSIS**

It is difficult to separate competition and antibiosis because many antagonists use both methods. However, some specific antibiotics are produced by antagonists of plant pathogens (Figures 11.22B and 11.33). Several fluorescent *Pseudomonas* bacteria found in the rhizosphere produce antibiotics and play a significant role in disease decline phenomena (Figure 11.34). A commercial biological control, Nogall, is derived from *Agrobacterium radiobacter* strain 1026, which produces *bacteriocins*—antibiotics that specifically inhibit the crown gall bacterium in many host plants. Studies have shown that competition at potential infection sites also plays a role in the success of this product.

**COMPETITION**

Microorganisms compete for food and space on plant surfaces. In many cases, timing is an important factor. In nature, it is often “first come, first served.” This can be exploited by applying competitive organisms on leaf and root surfaces to reduce infections by pathogens. A successful example is the use of a competitor to prevent a wood decay basidiomycete, *Heterobasidium annosum*, from colonizing freshly cut tree stumps during timber harvesting. This decay fungus can spread from stumps to neighboring, healthy trees through root contact. A competitive, saprophytic basidiomycete *Phlebia gigantea* (syn. *Peniophora gigantea*) was isolated from old stumps, and basidiospores were then applied to stumps immediately after cutting to prevent colonization by the wood decay fungus. The bacterium *Pseudomonas fluorescens* strain A506 is registered and sold commercially (as BlightBan A506) for protection of apple trees against fire blight. Its mode of action includes both antibiosis and competition.

**CROSS-PROTECTION**

The phenomenon of cross-protection was discussed in Chapter 9. Cross-protection uses mild virus strains to protect against infection by severe strains. This method has largely been replaced by the use of genetic engineering of viral coat-protein genes and other viral genes that protect plants from infection without the problems associated with infections by mild strains of viruses.

The successful use of a biological control agent for plant protection depends on the following factors.

**1. Source of the control.** Organisms isolated from plant surfaces are most likely to be successful because they are
Things to Consider Before Buying a Commercial Biological Control Product

1. Have independent researchers with no financial interest in the product published evaluations of the product?
2. Has the product ever been tested on the plants for which you wish to use it? For which diseases is it recommended?
3. Has the product been tested in your area?
4. If no independent data are available, look for this information:
   - Non-treated plots as controls for comparison with the treatments.
   - Replications of the treatments, not just a single area of application.
   - Statistical analysis of the data.
   - EPA registration. Some companies evade regulations for safety by claiming that the product makes plants less susceptible to disease.
5. Ask for a free sample to do your own evaluation: Try new products on a small area first where they are least likely to cause problems if they don’t work. Leave an untreated area for comparison.

adapted to the environment in which they must be effective. Such organisms are described as phylloplane-competent or rhizosphere-competent.

2. Proper application of specific isolates. It is unlikely that artificially high populations of applied agents will be maintained for very long. The natural microbial interactions will result in more balanced populations fairly quickly. The use of disease prediction systems might help by determining the specific times when protection is needed. At the very least, it is likely that repeated applications of biological control agents will be necessary to maintain the high populations necessary for efficacy. Even though there are many reports that certain species or genera of fungi and bacteria are likely to function as competitors and antagonists, isolates vary considerably in their impact on pathogens. Labels of biological control products should indicate which specific isolates are provided and not just list species or genus names of possible agents (Figures 11.35 and 11.36).

3. Formulations. Formulations must allow biological control organisms to be stored in a convenient form and become active quickly using a variety of water supplies, including chlorinated municipal water. Spores and freeze-dried fungal preparations are amenable to this kind of packaging. Some bacteria such as Bacillus species produce thick-walled endospores that have made them popular choices because they are easily stored in dry formulations. Pseudomonas bacteria, which do not produce endospores, may be formulated in liquid media that require refrigeration.

Figure 11.35. Biological control of Aphanomyces root rot of pea. Left, pea seeds coated with the bacterium Burkholderia ambifaria (Pseudomonas cepacia) strain AMMD. Right, pea seeds treated with the fungicide captan. All plants were inoculated with zoospores of the pathogen.

Figure 11.36. Begonias grown in the greenhouse and inoculated with Botrytis cinerea, the fungus causing gray mold, under conditions optimal for the development of disease. Treatments (with four replications) from left to right: untreated (Un), CaCl₂, chlorothalonil fungicide (Fung), and a biological control fungus Trichoderma hamatum T382 inoculated into the potting mix (T382).
4. **Safe handling.** Even though many people would like to use biological control products as an alternative to more toxic chemicals, it should be remembered that concentrated populations of microorganisms have their own potential risks. Inhaled spores of fungi can trigger allergic responses. Some soil bacteria might be secondary human pathogens and threaten the health of people with compromised immune systems. Safety instructions on labels should be followed.

5. **Reliable information.** Many biological control products are promoted on the basis of experiments in laboratories and greenhouses and only on certain kinds of plants. Evaluations by independent observers should be consulted to determine whether a product is successful in field conditions, in the environment in which it will be used, and on the plants to which it will be applied. Many biological controls are effective against specific diseases only. The Office of Pesticide Programs of the U.S. EPA maintains a website that lists biopesticide fact sheets that describe each agent, modes of action and applications, and risks to human health and the environment (Figure 11.37).

**The modes of action that are most useful in protecting plants using biological control agents are competition and antibiosis. Specific isolates of fungi and bacteria from plant surfaces are most likely to be successful, but repeated applications will probably be necessary. Research to develop products that will work reliably in field situations is ongoing.**

**Genetic Resistance**

**Genetic resistance,** discussed in Chapter 9, is usually available as specific (R gene, vertical) resistance that works against specific races (or strains) of a pathogen or as general (horizontal) resistance that usually is partially effective against all races of a pathogen (Figures 11.38–11.40). **Specific resistance** is commonly used for monocyclic pathogens. The probability

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**Some Organisms Found in Several Commercial Biological-Control Products Used to Protect Plants from Infection**

**Bacteria**
- *Bacillus subtilis*
- *Burkholderia cepacia* (syn. *Pseudomonas cepacia*)
- *Pseudomonas fluorescens*
- *Pseudomonas syringae*

**Fungus**
- *Trichoderma harzianum*

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**Figure 11.37.** Some examples of commercial biological control products (biopesticides).

**Figure 11.38.** Elm seedlings in the greenhouse prior to testing for resistance to Dutch elm disease.

**Figure 11.39.** Some apple cultivars that are resistant to apple scab.

**Figure 11.40.** Experimental plots with plants tolerant (left) and susceptible (right) to soybean rust.
Genetic Resistance for Monocyclic Pathogens

Specific (R gene) resistance is often effective when one strain or race of a pathogen dominates the population. This reduces primary inoculum because the resistance gene is effective against a single race of the pathogen.

To Prolong the Usefulness of the Specific Resistance Gene(s)

Use all appropriate cultural practices to reduce the population of the pathogen, e.g., clean up infested debris, rotate crops, minimize leaf wetness for foliar pathogens, and use general resistance.

Genetic Resistance for Polycyclic Pathogens

General resistance reduces the rate of the epidemic. It is effective against all races of a pathogen. Lesions are smaller, take longer to form, and produce less inoculum. This may or may not be sufficient to meet economic thresholds.

General resistance can be enhanced by good cultural practices that reduce the pathogen population and its opportunities to infect the plant.

Use of R-gene resistance for polycyclic pathogens
- geographic deployment
- temporal deployment
- gene pyramiding
- multlines or mixtures

DID YOU KNOW?
Seventy-five percent of crops grown in the United States are resistant cultivars. This rises to 95–98% when small grains and alfalfa are considered.

of selecting races of a pathogen that can overcome the resistance is reduced because the pathogen completes only one generation per season. Many monocyclic pathogens are soil-borne, so even if such races are selected, they are less likely to be quickly and widely distributed. Some R genes have remained effective for many years. Specific resistance can be considered a means of reducing primary inoculum because it is effective for specific races of the pathogen.

General resistance is a form of resistance that reduces the rate of an epidemic. Lesions are usually smaller, develop more slowly, and produce less secondary inoculum on plants with general resistance. This slows the rate of disease increase throughout the growing season and is therefore very useful for polycyclic pathogens. In seed catalogs, this type of resistance is often called “tolerance,” to warn people that the disease might still occur but it should be less severe on that cultivar. (Note from Chapter 9 that plant pathologists use the word tolerance differently.) General resistance is what allows plants to grow in the presence of a number of minor pathogens without significant economic impact. Environmental conditions and cultural practices affect how well or how poorly general resistance performs.

General resistance may not be sufficient to manage disease at a desirable level and is not easy to select quickly in breeding programs. Can specific (R gene) resistance be used for polycyclic pathogens without the danger of the “boom-and-bust” phenomenon? The methods discussed below have been developed to use R genes successfully against polycyclic pathogens. Many of these are used in cereal crops.

GEOGRAPHIC DEPLOYMENT
Although this requires good cooperation among seed suppliers and farmers, different R genes may be used in different regions. As spores arrive from different areas, they will meet new R genes and be unable to infect the plants.

TEMPORAL DEPLOYMENT
By monitoring the races of widespread, airborne pathogens, seed producers can provide different R genes in different years to help protect plants from the current year’s inoculum.

PYRAMIDING
In some cases, multiple R genes are crossed into a single cultivar. It is very unlikely that a pathogen would overcome all of the R genes. On the other hand, the possibility of selecting a “super-race” that could overcome all of the genes at once makes some scientists somewhat fearful that the usefulness of all of the R genes could be lost.
MULTILINES AND MIXTURES
Multilines and mixtures are alternatives to pyramiding. **Multilines** are a set of inbred cultivars that vary only in the R gene that they carry. These cultivars are physically mixed together and planted to create a plant population similar to what might be found in a natural ecosystem. Multilines have been used successfully for control of stripe rust in the U.S. Pacific Northwest. **Mixtures** of lines that are not so similar are sometimes used in a parallel way. Each plant has only a single R gene, but its close neighbors will have different R genes. If an infection occurs, secondary inoculum is less likely to land on a susceptible plant. Multilines and mixtures offer flexibility because breeders can add or subtract R genes each year based on pathogen monitoring from the previous season. Some argue that multilines and mixtures also are less likely to select for a “super-race” of a pathogen that could infect all of the plants because of a phenomenon called **stabilizing selection**. It is theorized that excess virulence genes actually decrease pathogen fitness, so a super-race would be at a competitive disadvantage compared to simpler races in fields of multilines or mixtures and would, therefore, be less likely to occur (Figure 11.41).

**Biotechnology**, including **genetic engineering**, offers new ways to create plants with genetic resistance. Currently, the most common genetically engineered plants are those with resistance to a nonselective herbicide or with insect resistance. Insect resistance is primarily conferred by genes from the insect-pathogenic bacterium *Bacillus thuringiensis* (*Bt* genes) that produce toxins that poison certain insects. Virus resistance from coat-protein genes and other viral genes is the most common disease resistance product at this time (Figure 11.42). Virus-resistant papaya, potato, squash, and

![Figure 11.41. Diagram of multilines of a cereal crop showing a mixture of six R genes planted out randomly.](image)

<table>
<thead>
<tr>
<th>Advantages of Genetic Resistance</th>
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<tr>
<td>- Introduced gene is inherited and permanent.</td>
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<tr>
<td>- No action is needed on the part of the grower.</td>
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<tr>
<td>- Resistance genes are likely to function in a new genetic background after crossing.</td>
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<tr>
<td>- Resistance does not harm the environment.</td>
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<tr>
<td>- Resistance is compatible with other disease management methods.</td>
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![Figure 11.42. Resistance to Plum pox virus in transgenic plum clone CS due to the insertion of the PPV coat protein gene into the plant genome.](image)
Biotechnology and Genetic Engineering

Limitations on producing genetic resistance

- Single genetic factors may be widely distributed in crop plants (genetic uniformity).
- Eukaryotic genes and systems are complex, compared to those of prokaryotes.
- Many characteristics are not governed by a single gene.
- Traditional plant breeding is a more efficient means of gene transfer.

Advantages for producing genetic resistance

- Introduced resistance genes may be available more quickly in a background of acceptable agronomic characteristics (multiple generations of backcrossing not needed).
- Resistance genes from genetically isolated organisms become available.
- Genes may be introduced into reproductively sterile plants.
- Resistance genes could be deployed as needed or in variable combinations more quickly.
- In the future, it may be possible to create synthetic resistance genes.

Genetic resistance is an important means of plant protection. Specific (R) gene resistance is used for monocyclic pathogens and in some specialized ways for polycyclic pathogens. It is a means of reducing primary inoculum. To avoid the "boom-and-bust" cycle, it is important to minimize the selective pressure on the pathogen to overcome specific resistance. General resistance is partial and reduces the rate of disease increase. It is used for many polycyclic pathogens and can be modified (strengthened or weakened) by environmental conditions and cultural practices. Biotechnology and genetic engineering offer new means of creating resistant plants.

How can we create integrated, sustainable disease management programs?

Constraints to plant production vary depending on the crop or plant-production system. All plants have an absolute genetic potential that could be reached if there were no limiting factors (Figure 11.43). This "absolute" level of productivity cannot be reached in commercial plant production. Ideal yields and optimal growth may be reduced by physical and chemical extremes in the environment, including extremes of temperature, soil pH, or rainfall. These vary from year to year and from area to area. The environment determines the "attainable" level of production. The "affordable" level of production is affected by the economics of plant production—the short-term costs to the grower and the long-term costs to the industry and eventually to society. Short-term costs include irrigation water, fertilizer inputs, and chemical and biological control applications. Long-term costs include environmental pollution, loss of
biodiversity, investments in new production and harvesting equipment, land rotation schemes, storage facilities, and water supplies. Once management decisions have been made, and the plants are growing, unexpected factors might reduce production even more. Hazards such as diseases, frost, drought, hail, or pests will determine the “actual” level of production in any given year.

Disease management strategies are an important part of any crop management plan. Management of a plant disease usually includes multiple methods. If the pathogen is monocyclic, the focus will be on reducing the amount or efficacy of the primary inoculum. If the pathogen is polycyclic, the relative amount of focus on reducing primary inoculum or on reducing the rate of disease increase depends on the specific disease, but usually methods that accomplish both are recommended.

It is not difficult to understand that relying on a single management method is risky, but it is not simply a matter of the potential success or failure of that single method. Many methods interact with each other synergistically. For example, a good cultural program of crop rotation, removal of infested debris, moisture management, and care in application of fertilizers reduces the pathogen population and reduces opportunities for infection. When resistance genes are used, the probability of selecting a pathogen strain that can overcome the resistance is reduced by the cultural program. Many agricultural crops are protected from diseases using only cultural practices and resistant cultivars. Home gardens often can be very productive without any pesticide use.

When fungicides are necessary, it is less likely that fungicide resistance problems will arise if the pathogen population is reduced and infection opportunities are minimized. Cultural practices can reduce the need for fungicides, especially when weather does not favor infection. Further reductions in fungicide use can be made when a good cultural program is combined with environmental monitoring of infection periods. Applications may be skipped entirely in dry weather, or the interval between sprays may be extended.

When we introduce biological controls and systemic acquired resistance (SAR) into management programs using plant resistance and pesticides, pathogens are less likely to overcome resistance genes in the plant or become resistant to pesticides. SAR is a protective biological reaction that is affected by the health of the plant and its ability to quickly produce defense compounds. Genetic resistance also relies on the defense reactions made by the plant when it is invaded. The cultural practices used to create an optimal environment for plant growth and development favor a rapid and effective biological defense response.

We do not have an unlimited supply of chemicals that can serve as plant protectants or an unlimited source of resistance genes in the gene pool of the world’s organisms. The

"Integrated pest management (IPM) is a site-specific, multitactic decision-making process for the management of a pest that is profitable for the grower, and promotes health and environmental quality."
—Tree Fruit IPM Working Group, Washington State Horticultural Association

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**DID YOU KNOW?**

Norman Borlaug won the Nobel Peace Prize in 1970 for his efforts in wheat breeding because the Nobel committee recognized the importance of food supply to political stability.
A measure of our world food security and the ability to meet the food demands of the world's population is the world grain stocks. The grain stocks are the amount of food grains stored around the world. In April 2004, world cereal grain stocks had fallen to their lowest level in 30 years, with only enough stored grain to supply the world for 59 days. Thus, the diseases that affect cereal crops become especially important when so little grain is in storage.

Only 12 species of plants contribute significantly to the world's food supply. Most of the calories consumed by people on our planet are provided by only three species: wheat, rice, and corn.

One-third of the world's food is grown on the 18% of the land that is irrigated.

In the past 40 years, 30% of the world's soils have become unproductive, which has contributed to malnourishment of 3 billion people.

It may take 500 years to make one inch of topsoil.

There has been more population growth since 1950 than during the preceding 400 million years. There were 1 billion people in 1800 and 4 billion in 1975. There are nearly 7 billion today.

stewardship of these valuable tools in the fight against plant diseases lies in the hands of those who use them. We have a responsibility to use them wisely and with minimal impact on the environment. Disease management programs that integrate cultural, chemical, genetic, and biological approaches are more likely to be successful and sustainable (Figures 11.44 and 11.45).

Putting it all together for sustainable crop management is a challenge, but a sound cultural program will be effective against a wide range of potential pathogens. This permits a grower to focus on more-threatening pathogens or on those that have specific management requirements. Some plant systems are more challenging than others. There are fewer options for perennial systems than for annual plantings. Modern technologies of environmental monitoring and rapid pathogen identification, using PCR and immunoassays, move growers from a “spray and pray” approach to one that is based on accurate diagnosis and environmentally sound
management choices. Finally, our developing understanding of the details of the ecological, physiological, and genetic interactions of plants and their pathogens will result in novel disease management approaches for the future.

Providing food, fiber, and pleasing landscapes to a rapidly increasing world population challenges all plant managers. Plant diseases are an important factor in this struggle. Diverse management practices are more likely to be successful and sustainable. Diversity in the plants on which we rely also will improve the sustainability of our food (Figure 11.46) and fiber supplies. The biodiversity of the world is concentrated in the tropics, where it is most threatened by growing populations and urban development. Our individual choices in the use of energy and other resources, the environmental regulations we are willing to obey, and the support we give to future research and diagnostic facilities for plant health will determine the world of the future.

REFERENCES
American Phytopathological Society. Plant Disease Compendium Series. APS, St. Paul, MN. More than 35 volumes, several available in Spanish, describing diseases of a wide variety of fruit, vegetable, and field crops and turf, flower, and landscape plants, with many color illustrations. A complete list of titles in this series is available at the APS website.
American Phytopathological Society. Plant Health Management Series. APS, St. Paul, MN. The four books in this series explain strategies to achieve healthy potato, wheat, citrus, and peanut crops—from seed to storage. The books address the use of integrated pest management techniques against weeds, diseases, and insects. A complete list of titles in this series is available at the APS website.

Fig. 11.46. A, Harvest of cassava (manioc) (Manihot esculenta) roots, an important crop in the tropics but not commonly consumed in temperate areas. B, African children harvesting cassava leaves. Crop diversity is important in providing a stable world food supply.

“Everyone says something must be done—but this time it looks like it might be us.”
—Will Rogers
Questions

General
1. What are the major approaches to plant disease management? Provide a brief definition for each.

2. Integrated pest management (IPM) is the mainstay of modern agriculture. How can IPM help maintain the effectiveness of disease resistance genes? How can IPM help reduce the chances of fungicide resistance problems? How can IPM help reduce the need for fungicides and make the needed application more efficacious?

3. Your town garden plots have a "no pesticide" policy, but the gardeners would like some guidance on disease management. What management practices would you recommend to minimize plant diseases in this situation? Begin with preparation of the plots and choice of seed, continue with in-season activities, and finish with harvest and preparation for winter. Be sure to include activities from the major categories of management: avoidance, exclusion, eradication, and protection. Consider diseases caused by all of the major pathogen groups.

Avoidance
1. Why is avoidance of the pathogen of little practical value for most diseases?

Exclusion
1. What are some limitations to the use of quarantines to exclude pathogens?

2. What are some advantages to producing pathogen-free plants through meristem culture? What are some potential disadvantages in terms of disease management?

Eradication
1. What means of eradication could be used to reduce pathogen populations on plants of interest to you? How are the options different for annual outdoor plants, perennial outdoor plantings, and greenhouse crops?

2. What uses of heat could be applied to reduce pathogen populations in plants of interest to you?

3. What are some advantages and disadvantages of crop rotation, soil fumigation, and solarization for the eradication of soil pathogens?


4. Briefly define the three modes of action of biological control that are used primarily as methods of eradication.

**Protection**

1. How can leaf wetness be minimized in plants that you wish to grow?

2. What are the common modes of action for biological control used for protection of plants? What are some major limitations to the commercialization of biological control agents for plant protection?

3. What pesticide application regulations minimize residues in foods at the time of harvest? What precautions should applicators take to minimize their exposure? How can you minimize the risk of groundwater contamination by pesticides that you apply?

4. What general kinds of fungicides are available for plant diseases? The words "systemic" and "curative" are sometimes used to describe certain fungicides. How do fungicides move in plants to which they are applied? Can they cure fungal diseases?

5. What information about a pesticide should you obtain from its label before using it? What information should you know about a new fungicide product in order to develop a resistance management plan?

6. If specific (R gene) resistance is available for a monocyclic pathogen, why do you still need to use cultural practices and other management activities?

7. General resistance is most effective for polycyclic pathogens, but it is not always available or sufficient to protect the plant. How can R genes be used for polycyclic pathogens?

8. What are some advantages of genetic engineering over traditional breeding for the production of disease-resistant plants?

9. Plant activators are chemicals that are applied to plants to trigger systemic acquired resistance (SAR). Is this chemical control, biological control, or genetic resistance? Should plant activators be allowed in organic crop production? Explain your answers.

**Challenge Questions**

**General**

1. You are the only plant pathologist on the first extraterrestrial colony. An epidemic is in progress on an indigenous crop. What do you need to know about the crop and the pathogen to develop a management plan for the disease?

2. What do you think are the five most important factors that will affect our ability to provide safe and abundant food and fiber to the world's population in the next 50 years?
Exclusion
1. You wish to establish quarantine regulations for the import of a new plant species. What information would you need to have about its pathogens and the diseases they cause in order to establish reasonable regulations?
2. What are some limitations (biological and political) to the successful enforcement of plant protection quarantines?
3. Choose a plant that is vegetatively propagated. What pathogens affecting this plant can be excluded through meristem culture?

Eradication
1. As the official “plant pathologist” for your family, which eradication methods do you recommend for your home gardens?

Protection
1. The continued registration of several fungicides is uncertain. Briefly, what is the role of fungicides in agriculture? What nonchemical alternatives exist? What would be the agricultural effects if all fungicides were banned?
2. Fungicide use is concentrated in the humid eastern half of the United States. Describe a plant production system in which:
   a. Cultural practices alone will produce an economically viable crop.
   b. Cultural practices must be supplemented with fungicides to produce an economically viable crop.
   (“Crop” may be interpreted broadly to include landscapes and turfgrass.) Explain why fungicides are needed or not needed in each case.

CD-Rom Resources
Illustrated Glossary

Special Topics
   Plant disease management
   What are fungicides?

Plant Disease Lessons
   Black Sigatoka of bananas and plantains
   Citrus canker
   Coffee rust
   Downy mildew of grape
   Fire blight of apple and pear
Late blight of potato and tomato
Soybean cyst nematode disease
Stem rust of wheat
White pine blister rust

**WORDS TO KNOW**

The CD-Rom provides links from the words in this list to definitions in the Illustrated Glossary.

alternate host
alternative host
amphimobile
antagonist
antibiosis
antibiotic
avoidance
bacteriocin
biological control
biotechnology
certification
compost
contact fungicide
crop rotation
cross-protection
days to harvest
disinfect
economic threshold
eradication
exclusion
fallow
fumigant
fungicide
general resistance
genetic engineering
green manure
hyperparasite
hypovirulence
indexing
infection period
initial inoculum
integrated pest
management (IPM)
LD₅₀
meristem
monocyclic
multiline
mycovirus
nematicide
phyloplane-competent
phytosanitary certificate
phytotoxicity
polycyclic
primary inoculum
protectant fungicide
protection
pyramiding
quarantine
rhizosphere-competent
rogue
sanitation
secondary inoculum
solarization
specific resistance
stabilizing selection
suppressive soil
systemic acquired resistance (SAR)
systemic fungicide
thermotherapy
tolerance
volunteer

**Exercises**

**Exercise 11.1.** Choose three diseases from the APSnet Education Center Plant Disease Lessons. At least one disease should be monocyclic and at least one should be polycyclic.

If the disease is monocyclic:

a. What is the primary inoculum?

b. What management practices are recommended? Do they reduce the amount or efficacy of primary inoculum?

c. Are any prediction or forecasting systems available?

d. Is a biological control recommended? If one is not available, what potential kinds might be useful?

If the disease is polycyclic:

a. What is the primary inoculum?

b. What is the secondary inoculum?

c. What management practices are recommended? Which are aimed at the primary inoculum and which help reduce the rate of the epidemic?

d. Is a biological control recommended? If one is not available, what potential kinds might be useful?

e. Is fungicide control recommended? What kinds of fungicides are effective? Is there a prediction system based on infection periods?
Internet Resources

APSnet Resources
Alternatives to methyl-bromide: A Florida perspective
Antibiotic use for plant disease management in the U.S.
Biological control of plant pathogens: Research, application and commercialization in the USA
Burkholderia cepacia: Friend or foe?
Cultivar mixtures
Management of apple scab: Simulation with Applescab
Management of potato late blight: Simulation with Lateblight
Population genetics of plant pathogens
Quin/L/Strobilurin fungicides: Benefits and risks
Risks of exotic forest pests and their impact on trade
Selection of fungicide resistance: Simulation with Resistan
Small grain cereal seed treatment
The future world food situation and the role of plant diseases
Transgenic virus resistant papaya: New hope for controlling Papaya ringspot virus in Hawaii
What are the nonindigenous plant pathogens that threaten U.S. crops and forests?

Recommended Websites
Database of Microbial Pesticides
NAPPO Phytosanitary Alert System
National Plant Board: Federal and State Quarantine Summaries
North American Plant Disease Forecast Center
Pew Institute Factsheet on Genetically Modified Crops in the U.S.
The Value of Fungicides in U.S. Farming Systems
Traditional Practices for Plant Disease Management in Traditional Farming Systems
US-EPA Biopesticides
US-EPA Pesticides and Food
World Health Organization—Food Safety

Internet Research

Internet Research Exercise 11.1. Choose the 10 most important diseases of a plant that you wish to grow or manage. Find information on the management of each disease. Answer these questions for each disease:
a. Is the disease monocyclic or polycyclic?
b. What management practices are recommended?
c. Which management practices focus on reducing the amount or efficacy of primary inoculum?
d. If the disease is polycyclic, what rate-reducing practices are recommended?
e. Is there a forecasting or prediction system?
f. What kinds of fungicides should you plan to use, and what is your fungicide resistance management plan?
g. Are any resistant cultivars recommended?
h. Are any biological controls available?

How could you integrate the management required for these 10 diseases into a crop/plant management plan? Do you see any management conflicts among the diseases? Are any of the management practices effective for more than one disease?

**Internet Research Exercise 11.2.** Go to the biopesticide websites listed on the CD-Rom. Choose a biocontrol product for a plant disease. Using the information on this website and others, try to find information about
a. the biological control organism and its mode(s) of action in this product
b. the disease(s) for which it is used
c. published research reports on its efficacy
d. any safety concerns

**Internet Research Exercise 11.3.** Go to the Spotted Wilt Eradication Action Team website and experiment with various options to minimize the risk of *Tomato spotted wilt virus* in peanuts.

a. Under which of these categories would you place each of the management activities?
   - Avoidance
   - Exclusion
   - Eradication
   - Protection

b. What are some limitations to achieving the minimal risk level for each category, i.e., why don’t growers simply choose the lowest-risk action for each category?

**Internet Research Exercise 11.4.** Go to the Plants, Pathogens, and People website and follow the links to Activities, Disease Management, and Dutch elm disease. In this exercise you will pose a hypothesis and design an experiment to answer the question: Can Dutch elm disease be managed by removing dead and infected trees?

**Internet Research Exercise 11.5.** Complete the exercise that accompanies the Resistant simulation of fungicide resistance in the APSnet Education Center.

**Internet Research Exercise 11.6.** In April 2000, *Reason* magazine interviewed Nobel Laureate Norman Borlaug about the future of agriculture and our ability to feed the world in the future. Using your knowledge of plant pathology, read the article and critique this interview with Dr. Borlaug.