Chapter 10

Disease Management for Wheat and Barley

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Abstract

Many pathogens can limit yield potential in the dryland cereal-based production region of the inland Pacific Northwest (PNW). The region's diverse biogeographical factors, including soil type, temperature, and precipitation, and production system variables, including crop genetics, tillage, residue management, rotation and other cropping practices, affect the incidence, risk, and severity of crop disease. This chapter provides an overview of several key wheat and barley pathogens, conditions or practices that favor disease, and integrated management practices. Climate change, with predicted shifts in temperature and precipitation patterns, will also influence crop disease dynamics in the region, but currently, only limited information is available.

Key Points

- Successful disease management relies on understanding pathogen distribution, environmental conditions, and cropping practices that favor disease incidence or severity, relative potential for economic crop damage to occur, and the appropriate use of integrated management strategies.

- The PAMS integrated management approach utilizes prevention, avoidance, monitoring, and suppression strategies. Genetic resistance or chemical controls are not available for many soilborne pathogens, and growers rely on cultural practices to favor plant health.
- Adoption of new technologies and cropping practices may have a greater impact on wheat and barley diseases than climate change in the near future. System-wide monitoring of crop response is an important tool to determine if changes in cropping practices or climate effects reduce the effectiveness of current management strategies.
- There is much uncertainty regarding the impact of climate change on disease incidence and severity in PNW cereal production. Climate change effects could accelerate, extend, or slow typical disease cycles, or favor the introduction of new diseases.

Introduction

Overview of Pathogens Affecting Inland PNW Cereal Production Regions

Historically, more than 30 wheat and barley diseases have decreased profitability in the dryland, wheat-based cropping region of the **inland PNW**. Small grain pathogens and plant parasitic nematodes reduce grain yield and quality by damaging roots, stems, leaves, or grain heads. Fungal pathogens cause the greatest economic damage to small grains globally and, in the inland PNW, are the second most challenging biotic factor after weeds. Foliar diseases, such as stripe rust, and several soilborne pathogens have the potential to cause severe crop losses.

For a disease to develop, three factors must be present: a virulent pathogen, a **susceptible** crop host, and environmental conditions favorable to development of the disease. Complex interactions among these factors determine the frequency and severity of a disease. Pathogen inoculum may be airborne, present in or on seed, in soil, in infected living host tissue or residue, or vectored from plant to plant, usually by insects. Pathogens are highly sensitive to changes in moisture and temperature. Foliar diseases are typically favored by high canopy humidity and free water, whereas root and stem diseases caused by soilborne fungal pathogens are often favored by cool, moist soils.

Variation in weather and climate, soil properties, and agronomic practices modify the host-pathogen environment, affecting pathogen distribution and population, and the potential risk of specific crop diseases. Cool season small grains are well-adapted to the region's Mediterranean-type climate and diverse biogeographical conditions. Typical warm, dry summers limit some foliar diseases that are more of a concern in other US wheat-growing regions, whereas cool, wet springs favor soilborne diseases, especially in high residue **conservation tillage** systems. Cool, wet conditions also favor stripe rust. For further information on the region's diversity and climate, see Chapter 1: Climate Considerations.

Foliar and head diseases

Diseases caused by fungal pathogens of small grains can lead to economic losses when unmanaged and conditions are favorable for development. Producers have successfully reduced the impact of many foliar wheat and barley diseases (e.g., smuts, stripe rust) using integrated genetic, cultural, and chemical management strategies. For example, over the past 50 years, the inoculum of smut pathogens, once widely distributed across the region, has been effectively reduced to very low levels due to the use of pathogen-free seed, **resistant** varieties, and fungicide seed treatments. These practices have reduced the incidence of common bunt, flag smut, loose smut, and dwarf bunt diseases. However, growers have become increasingly reliant on seed treatment for control as many of the current commercial wheat cultivars are susceptible to smut pathogens. Common bunt disease has emerged as a concern in organic production systems, highlighting a need for continued screening for resistant cultivars and for research on alternative seed treatments suitable for organic production (Matanguihan et al. 2011). Stripe rust damage, caused by the fungus *Puccinia striiformis*, can be managed by the integrated use of resistant varieties and fungicide when predicted to be severe. Stripe rust continues to be one of the most important foliar diseases of wheat and barley in the inland PNW and is discussed in detail later in this chapter.

Viral diseases

Historically, *Barley yellow dwarf virus* (BYDV) has been the most important viral pathogen of small grains in the PNW. Transmission of the virus is dependent on infected aphid vectors; therefore, the primary discussion of this disease is found in Chapter 11: Insect Management Strategies. The virus is widespread and has many hosts including barley, wheat, oats, corn, and grasses that can serve as inoculum reservoirs. Barley yellow dwarf (BYD) disease causes the greatest damage to winter wheat, barley, and oats; less damage occurs on spring-planted grains. BYDV-infected plants may also be more susceptible to root rot diseases. Although total field loss can occur, estimated average losses are less than 10%. Eliminating volunteer crop and grassy weed hosts and the **green bridge** effect reduces primary inoculum density. Control of aphid vectors, delayed fall planting, and use of cultivars with some resistance to BYDV can also limit economic impact.

Wheat streak mosaic virus, vectored by the wheat curl mite, is also discussed in Chapter 11: Insect Management Strategies. *Soilborne wheat mosaic virus* is a relatively recent discovery in the PNW. This pathogen, vectored by a soilborne fungus, is discussed later in this chapter.

Root-infecting fungal pathogens and nematodes

Root, crown, stem, and vascular diseases caused by root-infecting fungal pathogens and plant-parasitic nematodes significantly impact small grain production across the region and can be a barrier to producer adoption of **direct seeding**. The effects of soilborne diseases are most evident under dryland conditions because plants with damaged roots are less efficient at water and nutrient uptake than healthy plants, and predisposed to drought stress and nutrient deficiencies. Reduced tillage, increased residue levels, and cool, moist soils favor some soilborne pathogens and may increase the risk of disease.

This chapter focuses on many economically important soil and residue-borne pathogens and nematodes. In contrast to seed-transmitted, airborne, or insect-vectored pathogens, soil and residue-borne pathogens and nematodes have limited management options. Genetic resistance and chemical control options are often lacking and growers rely on cultural techniques to manipulate the crop environment to favor plant health and growth. Breeding efforts have produced commercial varieties with genetic resistance to some root-infecting diseases such as eyespot, snow molds, and Cephalosporium stripe; however, no locally adapted varieties are available with resistance to Pythium and Rhizoctonia root rots or take-all (Paulitz et al. 2009). Registered fungicide seed treatments are effective against many seed-transmitted pathogens but may provide only short-term suppression, or no control, of several soilborne pathogens, and most root-infecting pathogens cannot be controlled with foliar chemical applications. Nematicides are not registered for use. Crop rotation, or **fallow**, with at least one year out of wheat, barley, or other host crops can adequately reduce inoculum levels for some diseases, such as take-all, depending on the environment and how efficiently cereal residues break down; however, other diseases such as eyespot and Cephalosporium stripe require longer rotations. Long rotations may not be an economical or effective management tool for situations where multiple years away from wheat or barley are required, or for small grain pathogens with multiple hosts including legumes or oilseeds.

Effects of Climate Change on Cereal Pathogens and Disease

There are many unanswered questions about the potential effects of climate change on wheat and barley diseases in the PNW. Better understanding the conditions most favorable to pathogens and the development of disease will help growers adapt and minimize risk. Evolving cropping practices, technologies, and economic factors are likely to have a greater impact on our regional crop production systems than climate change, at least in the near future.

Complex interactions between crop host, pathogen, and environment make it challenging to predict the impact of climate change on the distribution of crop pathogens, the risk and severity of disease, and management guidelines. The main climate factors are variations in precipitation, temperature, and increased atmospheric carbon dioxide concentration. Any disease may become more important if climate tips the balance in favor of the pathogen. For example, *Pythium* would be favored by the predicted cooler, wetter early spring conditions.

Predicted decreases in late-spring and early-summer precipitation, in tandem with elevated temperatures, will make it more difficult for root-damaged crops to obtain water and nutrients during the warmer summer months, increasing economic risk. Milder winter temperatures may favor inoculum survival (e.g., stripe rust), whereas precipitation variability or earlier drought stress may predispose crops to disease or slow disease progress. Climate variability may also result in new pathogens or races of endemic pathogens emerging in the region.

Inadequate information has so far limited the opportunity to model regional climate impacts on wheat and barley diseases and potential crop losses in the inland PNW. In the future, data from recent baseline population surveys of fungi and nematodes across the region can be used to improve modeling, our understanding of pathogen response to changing environments, and management decisions. Effects are expected to be site-specific; yield response will depend on direct effects on pathogens, indirect effects caused by the host crop, and grower adaptation of management strategies.

PAMS Integrated Pest Management Strategies for Small Grain Pathogens

Producers seek to balance economic, crop health, and environmental constraints. Understanding production limits, setting affordable yield goals, and minimizing environmental and nutritional stresses on the crop support success. Targeted use of integrated genetic, cultural, chemical, and biological management tools to Prevent, Avoid, Monitor, and Suppress (**PAMS**) crop disease can eliminate or reduce the impact of many wheat and barley pathogens. Many useful management strategies have been identified and implemented in the inland PNW; using multiple strategies improves the odds for profitable management. The USDA-Natural Resources Conservation Service (NRCS 2010) adopted the PAMS approach to site-specific **integrated pest management** planning, an integral part of the Environmental Quality Incentives Program. This section presents a general overview of several PAMS integrated disease management practices; specific management options are presented later in the chapter for each of the pathogens discussed.

Prevention

Excluding a pathogen from a non-infested field is the first and most economical line of defense against crop disease. Many small grain pathogens are already widespread in dryland PNW fields, thus prevention is not applicable.

Field sanitation

Conscientious field and equipment hygiene reduces movement of soil or residue-borne pathogens from infested fields into clean fields.

Clean seed

Use of pathogen-free seed prevents the introduction of new seedborne diseases.

Avoidance

Avoidance is the use of cultural practices to avoid **pest** populations that already exist in a field to reduce the risk of disease.

Seed quality

Use of fresh, high-quality, pathogen-free seed promotes seedling establishment, vigor, and health.

Planting a non-host crop

Planting a non-host crop avoids infection and disease development, reducing inoculum of a specific pathogen.

Host crop resistance

Host crop resistance is the ability of a host crop (e.g., a cultivar) to inhibit growth and reproduction of a pathogen. Cultivars that suppress or prevent reproduction of a pathogen are classed as resistant; those that allow moderate to high rates of reproduction are susceptible. Tolerance is the ability to endure infection by a pathogen without serious damage or yield loss. Resistance may be race-specific (resistant to some but not all races of a pathogen) or race non-specific (resistant to all races). Planting a susceptible, **tolerant** variety can reduce yield loss of the current crop but does not limit reproduction or inoculum that can affect subsequent crops.

Use of resistant crops can be considered either an avoidance or suppression strategy, depending on the degree of resistance. Planting varieties with a high degree of resistance (i.e., no infection occurs) is an example of an avoidance strategy, whereas planting varieties that slow disease progress, if an infection occurs, is an example of a suppression strategy.

Monitoring

Identification and quantification

Effective disease management relies on accurate diagnosis and quantification of pathogens and timely application of control measures. It is helpful to identify pathogens to the level (i.e., genus, species, or race) that may affect management decisions. Root diseases are often difficult to diagnose based on aboveground symptoms. Sampling methods vary by pathogen.

Monitoring and recordkeeping

Understanding pathogen populations prior to planting can help determine risk and support crop choice and management decisions. Once visible symptoms caused by root-infecting pathogens appear in a crop, typically no actions are available to suppress disease development. However, tracking symptoms and severity by management unit during the current growing season informs subsequent management decisions.

Thresholds

Economic damage or action **thresholds** are based on population studies, forecast models, visual symptoms, field history, and yield correlation. Action guidelines are available for only a few cereal pathogens in the PNW (e.g., stripe rust, eyespot) where foliar fungicides can suppress damage. Correlation of pathogen population densities and predicted yield loss (e.g., the take-all pathogen) are needed to support pre-plant management decisions such as crop selection. Crop damage by parasitic nematodes is expected when pre-plant populations reach defined levels. However, precise yield loss is difficult to correlate with populations for most root-infecting pathogens because of complex environmental interactions across the region.

Forecasting models

Forecasting models are available for stripe rust.

Suppression

Growers can reduce or eliminate pathogen populations, disease severity, or crop damage using cultural, mechanical, chemical, or biological suppression practices.

Cultural

Green bridge control

Eliminating volunteer host crops and weeds is a first-defense management tool for reducing inoculum density. Timing cultivation or herbicide application with a sufficient period between application and planting to prevent the pathogen from bridging to the crop is important.

Host crop resistance

Planting crop varieties with varying degrees of resistance can prevent infection, slow disease progress if infection occurs, and reduce inoculum, limiting in-crop damage and risk to subsequent host crops. (See the Avoidance section.)

Rotation

Inoculum density of most root-infecting pathogens increases or decreases with the frequency of host crops in rotation. Using rotation to suppress disease is most effective when alternate, non-host crops are available, precipitation is not limiting, and conditions promote rapid residue decomposition. Clean fallow can adequately reduce some wheat disease inoculum (e.g., take-all) but may not meet conservation goals.

Planting dates

Planting dates influence crop growth and development, and severity of many cereal diseases. It is difficult to create precise planting date guidelines due to the diverse conditions across the inland PNW. Optimal planting dates should be site-specific to account for variation in landscape position, moisture, and temperature. In general, early fall planting favors pathogens causing stripe rust and BYD as well as several soilborne diseases including take-all, eyespot, Fusarium crown rot, and Cephalosporium stripe. Later fall planting favors Pythium root rot, Rhizoctonia root rot, and snow molds. Late planting tradeoffs include decreased grain yields and increased potential for soil erosion following fallow.

Nutrient management

Adequate nutrition optimizes crop health and profitability. Fertilizer rates should be based on site-specific yield potential (see Chapter 6: Soil Fertility Management). Placing fertilizer with the seed or deep-banding nitrogen (N), phosphorus (P), and sulfur (S) below the seed at the time of planting can offset the yield-limiting effects of Pythium and Rhizoctonia root rots and take-all; nutrients placed adjacent to roots help seedlings overcome early nutrient deficiencies caused by root pruning.

Mechanical

Conservation tillage and residue management

Crop choice, available moisture, temperature, and tillage affect biomass and production, residue decomposition, and pathogen survival. Greater surface residue creates cooler, moister soils at planting that can favor seed and root-infecting pathogens including Pythium root rot, Rhizoctonia root rot, and take-all. Cephalosporium stripe and Fusarium crown rot have had variable responses to tillage systems, whereas eyespot can be reduced under conservation tillage. Stripe rust and BYD are typically unaffected by tillage. Annual cropping regions have larger biomass and grain yield potentials compared to grain-fallow systems. However, greater precipitation supports faster residue decomposition. Adapting equipment to spread chaff evenly and using high-disturbance openers can reduce risk of infection by residue-borne pathogens. For more information on residue management, see Chapter 4: Crop Residue Management.

Chemical suppression

Foliar fungicides

Foliar fungicides, in combination with other management strategies such as planting resistant cultivars, are effective for a few cereal diseases such as stripe rust and eyespot.

Seed treatment

Planting pathogen-free seed helps eliminate the need for chemical treatment of seedborne diseases. However, where soil or residue-borne fungal pathogens are present, seed treatment is a relatively low-cost suppression strategy and is particularly effective for pathogens with short disease infection periods (e.g., smuts). Fungicide treatments (metalaxyl, mefenoxam) in tandem with careful planting practices, such as monitoring root zone moisture at planting, can protect seedlings from damping off and rot caused by *Pythium* species. Root pathogens with the ability to infect plants over a longer time period have shown less response to seed treatments. Some fungicide seed treatments including difenoconazole, tebuconazole, or triadimenol (not registered in Washington) can temporarily suppress root diseases caused by *Fusarium* spp. and take-all disease. Newer chemistries (tebuconazole, sedaxane, pyraclostrobin, penflufen) have improved short-term suppression of some root diseases such as Rhizoctonia root rot. Systemic fungicides are effective for a longer time period than contact fungicides. Although helpful in controlling some diseases, systemics are less helpful in controlling root rots because the active materials move upward through the seedling rather than downward into the roots. There are no seed treatments available for bacterial or viral diseases. Systemic insecticide seed treatments can help control aphid vectors of BYDV.

Biological

Suppressive soils

Suppressive soils are defined as “soils in which the pathogen does not establish or persist, establishes but causes little damage, or establishes and causes disease for a while but thereafter the disease is less important even though the pathogen may persist in the soil” (Weller et al. 2007). Take-all decline and Rhizoctonia bare patch suppression are examples of natural, microbial-based mechanisms of defense against root-infecting pathogens. In many areas of the US, growers have been able to maintain long-term suppression of take-all in continuous wheat production, especially under irrigation. Periods of fallow or rotation away from continuous cereals reduces suppressiveness of take-all decline. It takes several years for soils to develop suppressiveness to *Rhizoctonia* (Schillinger et al. 2014), thus it is not a practical management strategy.

Microbiological control

Currently no effective commercial biological controls are available for field use.

Selected Pathogens of Inland PNW Dryland Cereal Production Systems: Research and Management Implications

Recent studies have improved our understanding of the regional distribution of wheat and barley pathogens and agro-climatic and crop production factors that influence the risk of disease and affect management decisions. This chapter summarizes several key dryland diseases and management strategies, particularly those that may be impacted by **conservation cropping** practices or have limited control options. Table 10-1 illustrates

Table 10-1. Cropping system practices that can impact (+) disease management in the PNW or that have no effect or are not available (–).

	Cultural practices	Variety selection	Chemical control	
			Foliar	Seed
Stripe rust	+	+	+	–
Eyespot	+	+	+	–
Cephalosporium stripe	+	+	–	–
Rhizoctonia root rot	+	–	–	–/+
Fusarium crown rot	+	–/+	–	–/+
Pythium root rot	+	–	–	+
Snow molds	+	+	–	–
Barley yellow dwarf	+	–	–	+
Take-all	+	–	–	–
Cereal cyst nematode	+	+	–	–
Root-lesion nematode	+	+	–	–

Note: Gray boxes indicate greatest impact. Adapted from Murray 2016.

Table 10-2. Cultural management practices that impact disease incidence.

	Seeding date		Tillage		Green bridge	Fertility	Soil pH	Crop rotation
	Winter	Spring	MinTill	NoTill				
Stripe rust	↓L	↓E	–	–	+	+	–	–
Eyespot	↓L	–	↓	↓	–	–	–	–
Cephalosporium stripe	↓L	–	–/+	↑	–	+	+	+
Rhizoctonia root rot	+/–E	+/–L	–/+	↑	+	–/+	–	–
Fusarium crown rot	↓L	–	–	↑↓	–	+	–	–/+
Pythium root rot	↓E	↓L	–	↑	+	–/+	–	–
Snow molds	↓E	↓L	–	–	–	–	–	–
Barley yellow dwarf	↓L	↓E	–	–	+	+	–	–
Take-all	↓L	–	–	–	+	+	+	+
Cereal cyst nematode	–	–	–	–	+	–	–	+
Root-lesion nematode	–	–	–	–	+	–	–	–/+

Note: (↑) Practice can favor pathogen; (↓) Practice can reduce risk; E = early and L = late; (+) Practices can impact management; (-) Practices do not impact management or are unavailable; Tillage impact is relative to conventional tillage. Gray boxes indicate greatest impact.
Adapted from Murray 2016.

general management components (cultural practices, variety selection, or chemical control) that impact management, have no effect on management, or are not available. Table 10-2 summarizes specific cultural practices that may favor or reduce disease.

It is beyond the scope of the chapter to address all small grain cereal and broadleaf rotation crop diseases that occur in the dryland PNW. Excellent resources are available for additional detail on multiple wheat and barley diseases and their management, including the Compendium of Wheat Diseases and Pests (Bockus et al. 2010), the Compendium of Barley Diseases (Mathre 1997), and Diseases of Small Grain Cereal Crops: A Colour Handbook (Murray et al. 2009b). Readers should refer to the PNW Plant Disease Management Handbook especially for chemical suppression information. Additional local resources are listed in the Resources and Further Reading section.

Stripe Rust

Background, causal agents, and distribution

Rusts are the most serious foliar diseases of small grains in the PNW. Stripe rust occurs on wheat, barley, rye, and various cultivated and wild grasses. Stripe rust is caused by the *Puccinia striiformis* species that is divided into different special forms (*formae speciales*) based on specialization to different cereal crops. For example, wheat stripe rust is mostly caused by *P. striiformis* f. sp. *tritici* and barley stripe rust is mostly caused by *P. striiformis* f. sp. *hordei*. The forms of wheat stripe rust and barley stripe rust can infect some barley and some wheat varieties, respectively, but do not cause severe diseases on the other crop. Therefore, stripe rust that develops in wheat fields generally does not impact barley crops and vice versa. Many grass species are highly susceptible to both the wheat and barley stripe rust forms and, when infected, can provide an inoculum reservoir (Table 10-3).

Barley stripe rust is a relatively new disease in the US. The disease reached the inland PNW by 1995 causing localized severe damage in the late 1990s. From 2001 to 2009, researchers observed up to 40% yield losses in experimental and commercial fields on susceptible varieties in eastern Washington. Yield losses on commercial barley varieties ranged from 0%

Table 10-3. Stripe rust characteristics and management options for dryland cereal producers.

<table>
<tr><th colspan="2">Stripe rust</th></tr>
<tr><td>Background
Causal agents: Puccinia striiformis
Source: wind dispersal of inoculum
Wide distribution across region
Hosts: wheat, barley, grasses
High risk: wet fall, warm winter; warm, wet early spring; cool, wet late-spring and summer. Barley has lower risk than winter and spring wheat.</td><td>Economic impact
Potential losses of 0–45% on commercial wheat varieties with varying degrees of resistance; potential losses up to 90% on highly susceptible-check varieties
Management options
Host resistance
Fungicides
Eliminate green bridge
Avoid early-fall planting</td></tr>
<tr><td>Key diagnostics
Irregular patches with yellow-orange rust pustules on seedling leaves; stripes with pustules on leaves, leaf sheath, and glumes on adult plants
Presence of yellow-orange spore powder distinguishes stripe rust from Cephalosporium stripe, physiological leaf spot, and BYD
Resistant varieties may have white necrotic stripes with or without rust pustules on mature leaves</td><td>Ongoing research
Forecasting
Monitoring occurrence, severity, and distribution
Identifying pathogen races and distribution, virulence, and frequency
Developing new resistant varieties
Fungicide testing and variety response</td></tr>
</table>

to 26% during that period, with average annual losses of 12% and 11% measured in 2002 and 2005, respectively. In general, stripe rust epidemics on barley are not as widespread and damaging as stripe rust epidemics on wheat because mainly spring barley is grown while both winter and spring wheat are grown. Also, barley-growing regions are scattered while wheat-growing regions are more contiguous; plus, barley matures faster. Thus, the barley stripe rust pathogen has a much shorter season to infect and develop on barley, and the much longer period between barley crops reduces pathogen survival.

Key diagnostic features

Stripe rust is more easily recognized when the disease is fully developed, but it is important to identify the disease as early as possible to implement appropriate controls. Infection can occur throughout the growing season. Once the pathogen infects plants, it takes one week to several months to show symptoms, depending upon temperatures. Symptoms first appear as chlorotic patches on leaves. These symptoms are hard to recognize as stripe rust as they appear similar to infections by other pathogens, abiotic stress, or chemical injuries. Recognizable signs are tiny yellow-orange uredinia (pustules), which are clustered in patches (not stripes) on seedling leaves, and form stripes between leaf veins in adult plant stages, usually starting at stem elongation (Figure 10-1). Stripe rust can be confused with Cephalosporium stripe, physiological leaf spot, BYD, or even cereal leaf beetles, especially from a distance, but it is easily distinguished from these by the rust spore powders. Pustules contain powdery urediniospores which may be rubbed off on fingers. Pustules

Figure 10-1. Stripe rust pustules in a commercial winter wheat field near Lamont, Washington, on November 8, 2016. (Photo by Xianming Chen.)

also occur on leaf sheaths, glumes, developing grains, and awns when the disease is severe. In the late plant growth stage, black telia form; at this stage no more infectious urediniospores are produced. Compared to a susceptible check variety, resistant varieties have different responses to stripe rust infection, ranging from no symptoms or rust signs, to various sizes or lengths of necrotic patches (on seedlings) or stripes (on adult plant leaves) without or with rust pustules, to a relatively low number of rust pustules.

Disease cycle and conditions that favor the pathogen

The three most important environmental factors governing the risk of stripe rust include temperature, moisture, and wind. The stripe rust pathogen prefers cool environments and causes more damage when the fall is wet; winter is warm; early spring is warm and wet; and later spring and summer are cool and wet. Urediniospores need a minimum of 3 hours of a dew period to germinate and penetrate plants; extended dew periods favor greater infection rates. During wet autumn conditions, urediniospores in the air, either produced in the region or blown by wind from other regions, can infect emerged wheat plants. The wetter the weather and the larger the plants, the more infection will occur. Urediniospore germination and infection can occur when temperatures are from just above 33°F to about 73°F, and best when temperatures are between 45°F and 54°F. Once the fungus grows into plant tissue, moisture is not an affective factor until producing new spores (sporulation). The period from infection to sporulation is called the latent period, and temperature is the most important factor during this time. In the PNW, stripe rust fungus lives as mycelium in the plant tissue during the winter time. The fungus can survive when temperatures are above 23°F; colder temperatures reduce survival. In general, if temperatures are below 14°F for about three days, the fungus will die. Snow cover, especially during cold spells, helps the rust fungus survive. Wind-kill can eliminate rust fungus as it kills wheat leaves. Winter hardy varieties can help rust fungus survive in plant tissue when temperatures are above 14°F (Ma et al. 2015). The latent period can take from two weeks when temperatures are optimal (59–75°F) for growth and sporulation to more than five months when temperatures are below 40°F. The warmer the winter is, the more rust survival. In the PNW, stripe rust fungus can occasionally produce spores during winter time. Because winter weather conditions, mainly temperatures and snow cover, determine the level of stripe rust survival, epidemics can be predicted for the PNW using forecast models based on historical weather and yield loss data (Sharma-Poudyal and Chen 2011).

With daily average temperatures in early spring constantly above 40°F, stripe rust will start to sporulate, and new spores will infect wheat plants. Warm, wet conditions speed up sporulation and increase new infections. Late-spring and summer high temperatures and dry conditions are not favorable for infection. Cool, wet conditions increase infection rates, prolong the crop growth season and rust season, resulting in more yield losses. Also, this will shorten the period from crop maturity to the emergence of the fall-planted wheat crops, increasing the chance for infection of the fall-planted crops. During late summer, the stripe rust fungus survives on spring wheat crops and volunteer plants. The major limiting factor is temperature. In general, when temperatures are above 74°F, no infection will occur, although the fungus can survive as mycelium in plant tissue for two to three weeks or as airborne urediniospores for up to a month. Cool, wet conditions help the rust survive summer temperatures by continually infecting plants. Generally, when daily high temperatures are above 95°F for a few days, stripe rust fungus will die even in plant tissue. The big difference between daily maximum and minimum temperatures during summer in the PNW allows stripe rust fungus to survive relatively well compared to many other regions in the US and the world. This is another reason why stripe rust is a more frequent disease in the PNW, in addition to the relatively mild winter and growth of both winter and spring wheat crops. Urediniospores survive well under cool and dry conditions, and they can infect fall-planted wheat crops when dew occurs on leaves, potentially leading to another cycle of rust fungus survival and development.

Potential effects of climate change

Changes in temperature and precipitation patterns, particularly during the growing season, and, to a lesser extent, mean annual changes, can affect stripe rust incidence. To some extent, the fungus is capable of adapting to climate change and continuing to survive and reproduce. Hotter, drier summers would limit epidemics that might occur later in the growing season; however, milder winters would enhance rust survival and lead to earlier infections. Also, less snow cover could result in increased wheat susceptibility to winter-kill, reducing inoculum. The need to continue to develop and grow stripe rust-resistant varieties will remain a priority regardless of direction of climate change.

Stripe rust management strategies

Prevention

The stripe rust pathogen is in the region and cannot be kept away. However, it is always a good idea to prevent transport of exotic races or strains of the pathogen from other regions. Clothing and footwear should be changed after visiting a field with stripe rust.

Avoidance

The best approach to prevent stripe rust is to grow varieties with a high level of resistance (varieties with a stripe rust rating of 1 or 2 in the most recent Buyer's Guide). However, appropriate late planting of winter wheat may avoid stripe rust infection in the fall. Similarly, later planting of spring wheat may shorten rust season as the normally hot and dry weather conditions are not favorable for stripe rust. However, spring wheat planted too late can suffer serious yield reduction as hot and dry weather conditions are not good for grain filling.

Monitoring

Good monitoring allows for timely fungicide application and avoids unnecessary use of fungicide. Fungicide application is more effective when disease is in the very early stage. The general recommendation is to apply a fungicide before stripe rust reaches 5%, at least no later than 10% incidence (percentage of leaves or plants with rust). Application is generally not recommended if (1) no rust can be found in the field, unless the field is planted with moderately susceptible or susceptible varieties (stripe rust ratings of 5 to 9), (2) stripe rust has been occurring in nearby areas, and (3) weather has been and will be favorable for disease. As fungicides vary in efficacy and duration of effectiveness (20 to 40 days depending upon chemicals), growers should begin checking fields about 2 to 5 weeks after application to determine if another application is needed. Varieties with race-specific resistance may become susceptible if new virulent races occur in the region. Monitoring fields planted with varieties having this type of resistance can prevent unexpected damage. Annual forecast data alert growers to the potential severity of stripe rust.

Suppression

Resistance

Planting resistant cultivars is the most effective control. Most wheat varieties grown in the PNW have some level of resistance, but not all have adequate levels of resistance when stripe rust is severe. Growing these varieties reduces rust damage. For example, under the extremely severe stripe rust epidemic in 2011, the susceptible check variety (not commercially grown) had more than 90% yield loss, while commercial variety losses ranged from 0% to 43% at an average of 21% yield loss without fungicide application. The commercial winter wheat varieties with various levels of resistance suppressed potential yield losses of over 90% to 21% (Chen 2014). Similarly, commercially grown spring wheat varieties were able to reduce potential yield loss from 45% to 15% on average. Several barley varieties also have some degree of resistance. An example of a stripe rust-resistant hard red winter wheat compared to a susceptible club wheat is shown in Figure 10-2.

Figure 10-2. Stripe rust damage on a susceptible club wheat (right) compared to a resistant hard red winter wheat, cv. 'Farnum' (left). (Photo by Xianming Chen.)

Chemical

When a variety does not have adequate resistance, fungicide should be used to suppress the disease and reduce yield loss. Several triazole (Group 3), succinate dehydrogenase inhibitor (SDHI) (Group 7), and strobilurin (Group 11) fungicides are labeled for control of stripe rust and information can be found in the PNW Disease Management Handbook. Check the labels for their rates, total amount that can be used in a growing season, and the latest stage by which they can be used. In the PNW, usually either one or two applications at the time of herbicide application (early application) and/or at the flag leaf to flowering stage (late application) are needed depending upon how early stripe rust starts and how fast the disease develops. If stripe rust starts early, early application is needed in fields grown with moderately susceptible or susceptible varieties (ratings 5–9) to reduce over-wintered rust and prevent new infection in the early growing season. Early application is easy to do as it is usually through ground application and adds no additional application cost because of mixing with herbicide. Often, this early application is not necessary if the disease starts developing after the herbicide application time. It is more important to use fungicide to protect crops for the grain-filling period. It is critical to make a decision for applying or not applying fungicides before flowering stage based on variety susceptibility, yield potential, disease pressure, and weather conditions, as most labeled chemicals cannot be used after flowering.

For more information on stripe rust, go to the USDA-ARS and Washington State University stripe rust website at ***http://striperust.wsu.edu/***.

Rhizoctonia Root Rot and Bare Patch

Background, causal agents, and distribution

Rhizoctonia is a soilborne parasitic fungus that can attack root systems of wheat and barley, pruning and rotting the roots and inhibiting their ability to take up water and nutrients. As a result, plants are stunted and show decreased yields. This disease was first documented in Australia in the 1930s and discovered in the PNW in the mid-1980s.

Most *Rhizoctonia* species have a wide host range and will attack cereal crops and volunteers, broadleaf rotation crops, and grassy weeds (Table 10-4).

Table 10-4. Rhizoctonia root rot characteristics and management options for dryland cereal producers.

Rhizoctonia root rot and bare patch	
Background • Causal agents: *Rhizoctonia solani* AG-8; *R. oryzae* • Source: infested soil, residue • Wide distribution • Wide host range: cereals, grasses, rotation crops • High risk: cool, wet, spring conditions	**Economic impact** • 10–20% potential grain yield loss **Management options** • Eliminate green bridge • Starter fertilizer placed below or with seed • Residue management (higher disturbance seed openers in no-till systems; fallow)
Key diagnostics • Chronic: field areas of uneven plant height • Acute: field patches with extreme stunting • Sunken brown lesions on girdled or severed roots (spear points)	**Ongoing research** • Distribution and impact surveys • Resistance screening • Suppressive soils, biocontrol • Fungicide efficacy (sedaxane)

Adapted from Schroeder 2014.

The most virulent *Rhizoctonia* causing root rot and bare patch of wheat and barley is *R. solani* AG-8; others can cause more mild symptoms. The species *R. solani* contains numerous groups, called anastomosis groups (AGs). Although very virulent on wheat, AG-8 can also attack roots of other rotation crops such as pea, lentil, and canola. Other groups of *R. solani* have been isolated from roots, including AGs 2-1, 4, 5, 9, and 10. Many of these have been tested in Washington State, but do not appear to cause major diseases on wheat, although they are pathogenic on other broadleaf crops such as pea and canola and may colonize wheat roots. According to recent surveys, AG-8 seems to be found in the PNW but not in the other wheat-growing areas of the US, including the upper and lower Midwest.

Another pathogen is *R. oryzae*. This pathogen is more severe as a seed and seedling rotter and can reduce plant stand under high inoculum conditions, as well as cause root rot. It forms very distinct microsclerotia on the roots that are pink-orange in color. One other group that has been isolated from wheat and barley are the binucleate *Rhizoctonia* species, also known as *Ceratobasidium*. There are many subgroups, but most have not been shown to be pathogenic on wheat, except for *R. cerealis*, which causes sharp eyespot on the lower stems of wheat.

Key diagnostic features

Soilborne pathogens are often difficult to diagnosis based on aboveground symptoms. However, *Rhizoctonia* does cause some distinct symptoms. Bare patch, the most acute form of the disease, is easily recognized by large patches in the field of severely stunted wheat or barley. These patches are irregular to circular, extending up to 10–20 feet in diameter (Figure 10-3). The plants in the patch are stunted, have delayed maturity, and may be yellow or purple in color from nutrient deficiency. The patches appear about one month after emergence when the plants in the healthy area continue to grow but the plants in the patches stop growing. Symptoms are more distinct on spring-planted wheat since the pathogen is more active under the cooler, wet conditions of spring.

Figure 10-3. Irregular patches in wheat field caused by *Rhizoctonia solani* AG-8. (Photo by Timothy Paulitz.)

In the more chronic disease phase, instead of patches, the stand will be of uneven height, with tall plants next to smaller stunted plants, giving the field a wavy appearance. In areas of stunted plants, the plant cover is reduced, more ground is visible, and weeds may be more of a problem.

The pathogen attacks the seminal and crown roots of seedlings. This causes a characteristic spear-tipping or tapered tips of roots, where the growing tip of the root is killed. The pathogen causes a brown rot/lesion on the root. In other parts of the root, the outer layer (cortex) is killed, leaving the stele or central vascular system intact. This area is usually brown in color and gives the roots a pinched appearance.

Under severe conditions, the entire seedling can be killed, usually when the plants are young, since young plants are more susceptible than older plants. These seedlings rot fairly quickly and are often difficult to see. Overall, barley is more susceptible than wheat, and shows more symptoms. In terms of economic loss, soilborne pathogens have been documented to cause 3–12% yield loss in wheat; with bare patch, the yield is essentially zero in the patches, and up to 10–20% of the field can be covered by patches in severe situations (Cook et al. 2002).

Disease cycle and conditions that favor the pathogen

Unlike many fungi, *Rhizoctonia* does not produce spores. Thus, it survives primarily as thick-walled hyphae in decaying roots, or as a multicellular structure composed of thick cells called a sclerotium. This inoculum can survive for one to two years in dry or frozen soils. When the root grows adjacent to an infected root or sclerotium in the spring, the fungus is stimulated to germinate, and forms a network of mycelium. These strands attach to the root, penetrate the root, produce enzymes that kill the root, and proceed to grow up and down the root system. Once the root is killed, the fungus can continue to grow on the dead roots as a saprophyte. *Rhizoctonia* distribution is affected by several environmental factors. It is favored by moist soil in the spring, and cool temperatures (50–60°F). The fungus can grow a considerable distance from the inoculum source and makes a network that spreads through the soil, causing patches. This disease is favored by reduced tillage, or direct seeding, but also occurs with **conventional tillage** (Schroeder and Paulitz 2008). Studies have documented that about 2 years after conversion from conventional to

no-till, the disease can become more severe and cause bare patches. However, after no-till has been continued for 7–10 years, the disease then declines which may be a result of natural suppression mediated by natural microflora in the soil. There is some evidence that the pathogen is favored by more sandy soils, possibly due to larger pore sizes and ease of hyphal spread. In eastern Washington, studies have shown the highest incidence of AG-8, and also the appearance of bare patches, is found in the **lower precipitation** zones of the wheat-summer fallow areas of Ritzville, Lind, and Connell, as well as the Dayton-Walla Walla area. *R. oryzae* is more evenly distributed across eastern Washington (Okubara et al. 2014). Finally, sulfonylurea (SU) and imidazolinone (IMI) herbicides may predispose cereals to infection by *Rhizoctonia*.

Potential effects of climate change

The potential effect of climate change on Rhizoctonia root rot is unknown at this time.

Rhizoctonia management strategies

Prevention

The pathogen is already widely distributed, and is not seed transmitted. However, use of fresh, certified seed contributes to overall seedling vigor and health.

Avoidance

There are no resistant wheat or barley varieties at the present time and crop rotation is not effective.

Monitoring

Tracking symptoms by management units during the current growing season is critical to making informed management decisions for the following growing season. There are no effective control actions to suppress the disease once symptoms appear in a crop. Sampling for positive identification of *R. solani* or *R. oryzae* aids decision-making. Historically, quantification of most of the soilborne pathogens has been very difficult. However, recently developed molecular methods of quantification (real-time PCR) and identification are now available and the technology has been transferred to commercial labs (e.g., Western Labs in Parma, Idaho). Bare patch can be monitored visually; remote sensing may be a useful tool for monitoring.

Suppression

Resistance

There is no resistance in any commercially available varieties. However, recent research has identified promising germplasm derived from synthetic wheats, selected in the field under high inoculum conditions (Mahoney et al. 2016).

Cultural practices

Cultural practices are the primary pathway for managing this disease. The most important strategy is green bridge management and appropriate herbicide timing. *Rhizoctonia* can also attack the roots of volunteer crop and grassy weeds in the fall and spring. When these plants are killed by herbicides such as glyphosate (Roundup), the herbicide shuts down the defense pathways in the plant. Thus, *Rhizoctonia* can act as a saprophyte and quickly colonize the dying weed in high levels. If the new crop is planted soon after spraying out, *Rhizoctonia* can bridge or spread from these dying roots to the new crop, causing extensive damage. However, if there is a suitable interval between spraying of weeds and planting, disease is reduced because natural microbial activity will reduce the *Rhizoctonia* inoculum. Research has shown the ideal interval to be about two to three weeks. Tillage may reduce the disease, possibly because of breaking up hyphal networks, but this has other disadvantages such as increased soil erosion, decreased organic matter and **soil health**, and increased fuel inputs. In no-till systems, high-disturbance seed openers such as chisel openers, as opposed to low-disturbance disk openers, may reduce disease. Fallow has been shown to reduce inoculum, but after one year, disease can still occur, although reduced. Rotation has not been shown to be effective because many of the groups also attack broadleaf crops. Application of a starter fertilizer in the seed row has been documented to reduce damage to the seedlings and increase yield by placing the nutrients adjacent to seedling roots and by overcoming early nutrient deficiencies caused by root pruning.

Chemical

Several classes of seed treatments have been shown to improve seedling health at early stages. These include triazoles, fludioxonil, strobilurins, penflufen, and sedaxane, an SDHI. Under high inoculum levels, they can improve plant height, number of roots, etc. However, these chemicals are not systemic in the plant and cannot protect roots of older plants. In most cases, yield will not be increased significantly.

For more information on Rhizoctonia root rot, see Smiley et al. (2012) and Schroeder (2014).

Take-All Disease

Background, causal agents, and distribution

This disease is called take-all because it takes a major proportion of the yield under severe conditions. It attacks the roots, lower crown, and lower stem of wheat plants. It is found worldwide in wheat production areas with higher precipitation or irrigation and neutral-alkaline soils in temperate areas, where wheat is sown in the autumn. It is caused by the pathogen *Gaeumannomyces graminis* var. *tritici* (Ggt). Low populations are found across the dryland PNW region. Cereal hosts include wheat, barley, triticale, and, to a lesser extent, rye. Another subspecies, *G. graminis* var. *avenae* attacks oats, and *G. graminis* var. *graminis* attacks other grasses such as turfgrass and rice. Weed hosts of Ggt include brome grasses, wheatgrass, and quackgrass. However, Ggt populations do not cause disease on broadleaf rotation crops such as pea, lentil, and chickpea (Table 10-5).

The main diagnostic feature is black discoloration of roots, crowns, and lower stems caused by external mycelial growth on the surface of the root or stem. This is seen even after the roots are washed free of soil. In some cases, adhering soil can also cause blackening of the root, but this is not take-all. Black discoloration may also be seen on the subcrown internode and seminal and crown roots. Under severe conditions, the blackening can extend up to the first internode. Crown discoloration can also be seen in other diseases, but the symptoms are distinct. With Fusarium crown rot, the discoloration is brown in color, not black. In

Table 10-5. Take-all characteristics and management options for dryland cereal producers.

Take-all disease	
Background • Causal agents: *Gaeumannomyces graminis* var. *tritici* • Source: decaying roots and host residue in soil • Wide distribution: low levels found in most dryland wheat • Host range: wheat, barley, triticale, rye, grasses • High risk: winter wheat, wheat after wheat, irrigation, neutral-alkaline soils (pH > 6), infertile soils especially where Mn is deficient	**Economic impact** • 30% average annual losses **Management options** • Eliminate green bridge • Rotation with 1–2 years of a non-host broadleaf • Accelerate residue decomposition
Key diagnostics • Black discoloration of roots and lower stem • Dark runner hyphae on roots • Whiteheads • Plants easy to pull or breakage	**Ongoing research** • Screening for resistance (currently no resistant varieties)

common root rot, the discoloration is dark brown to black, but is seen more on the subcrown internode rather than the lowest internode. With eyespot or sharp eyespot, the discoloration is in a distinct, elongated, eye-shaped lesion with distinct margins. The other distinct symptom is whiteheads, seen after heading, when normal wheat heads should still be green. Whiteheads turn prematurely, and the grain is smaller in size. This is because severe infections in the lower stem cut off the flow of water and nutrients during grain filling. But other diseases or pathogens can cause whiteheads, including Fusarium crown rot, Cephalosporium stripe, and cereal cyst nematode.

Disease cycle and conditions that favor the pathogen

Disease is most severe when wheat is grown continuously for 2 or 3 years without rotation to a non-host such as a legume. It is also most severe under high precipitation conditions or irrigation including areas west of the Cascade Mountains. It is mostly a disease of winter wheat, grown in soil with **pH** > 6. It is also most severe in soils deficient in N, P, and especially manganese (Mn). The pathogen survives in infected roots, and colonizes the roots as runner hyphae on the outer parts of roots. Unlike other soilborne pathogens, it does not form a resistant spore that survives in the soil. This is why just one year of rotation to a non-host can reduce the disease. It can form a sexual spore called an ascospore over the winter on fruiting bodies on infected roots and leaf sheaths, but this is probably not important in the epidemiology of the pathogen in the PNW. The disease spreads by runner hyphae from infected roots to new roots.

Potential effects of climate change

If spring and summer precipitation becomes more frequent and total spring and summer precipitation increases, the incidence and severity of take-all could increase. However, the frequency of wheat in the crop rotation and soil pH will likely have a stronger influence than changes in climate.

Take-all management strategies

Prevention

Not feasible since the pathogen is already widely distributed across the dryland PNW and is not seed transmitted.

Avoidance

There is no resistance in any commercially available varieties. Crop rotation with a non-host such as a legume, other broadleaf crop, or fallow is a means of avoidance.

Monitoring

Monitoring field symptoms during the current growing season is critical to making informed management decisions for the following growing season. There are no effective control actions to suppress the disease once symptoms appear in a crop. The disease can easily be identified by looking at black discolored crowns and whiteheads, but by then the damage is done.

Suppression

Resistance

There is no resistance in any commercially available varieties.

Other cultural practices

Rotation with a broadleaf non-host, such as a legume, or cereal, such as oat or corn, can be effective; a 1 to 2-year break is sufficient to reduce inoculum. Eliminating the green bridge is important because the take-all pathogen can survive on volunteers and grassy weeds. Residue management to accelerate breakdown of residues can reduce disease. Optimum fertility and soil pH suppresses the disease; avoid N, P, or Mn deficiencies, and avoid liming if soil pH > 6.

Chemical

Some seed treatments have been shown to be effective in Europe and Australia, but none are registered in the US. The most commonly used seed treatments have no effect on take-all.

For more information on take-all disease, see Cook (2003).

Pythium Root Rot

Background, causal agents, and distribution

Pythium is a soilborne, parasitic, fungus-like organism that can attack the seeds and root systems of wheat and barley, pruning and rotting the roots and inhibiting their ability to take up water and nutrients. As a result, plants are stunted and show decreased yields. Once classified with fungi, these organisms have been separated out based on several key differences, but plant pathologists still consider their behavior in soil to be like fungi. This pathogen is widespread across all dryland cereal production areas (Table 10-6).

Key diagnostic features

Soilborne pathogens are often difficult to diagnose based on aboveground symptoms. In fact, *Pythium* is often called "the common cold of wheat,"

Table 10-6. Pythium root rot characteristics and management options for dryland cereal producers.

Pythium root rot	
Background • Causal agents: numerous *Pythium* species, but *P. ultimum* and *P. irregulare* group I and IV are most virulent • Source: infested soil, decaying roots • Wide distribution • Wide host range: cereals, grasses, rotation crops • Highest risk: cool, wet, spring conditions; lower, poorly drained areas of the field	**Economic impact** • 15–20% potential yield loss **Management options** • Seed treatment • Eliminate green bridge • Starter fertilizer below or with seed • Residue management to reduce load in no-till systems (use of chaff spreaders, straw choppers, or mowers)
Key diagnostics • Stunted plants, yellowing, reduced tillering • Reduced root system • Delayed heading and poor grain fill	**Ongoing research** • Distribution of species across eastern Washington

because it is ubiquitous and the symptoms are so non-descript. The impacts of *Pythium* were not known until the early 1980s when R.J. Cook did landmark experiments with the new fungicide metalaxyl, which was specific for Oomycetes. When plots treated with a soil drench were compared side-by-side with non-treated plots, the effect was dramatic: greener tissue, more canopy, greater plant height, and better yield. *Pythium* causes stunting and yellowing of seedlings, which is often seen in wetter, lower parts of the field. Unlike *Rhizoctonia*, it is hard to see *Pythium* symptoms on the roots because infected roots are quickly rotted away. However, overall, the root biomass is less, and there are fewer lateral roots (Figure 10-4). Root hairs are reduced, but this can only be seen under a microscope. The first leaf is often reduced in length because of early infection while still in the embryo stage. One of the best diagnostic features is the observation of resting spores, called oospores, inside rotted roots, but this also requires a microscope. However, researchers at the USDA-ARS have developed molecular methods of detecting and quantifying *Pythium* in the soil. These tests can be performed by commercial labs (e.g., Western Labs in Parma, Idaho).

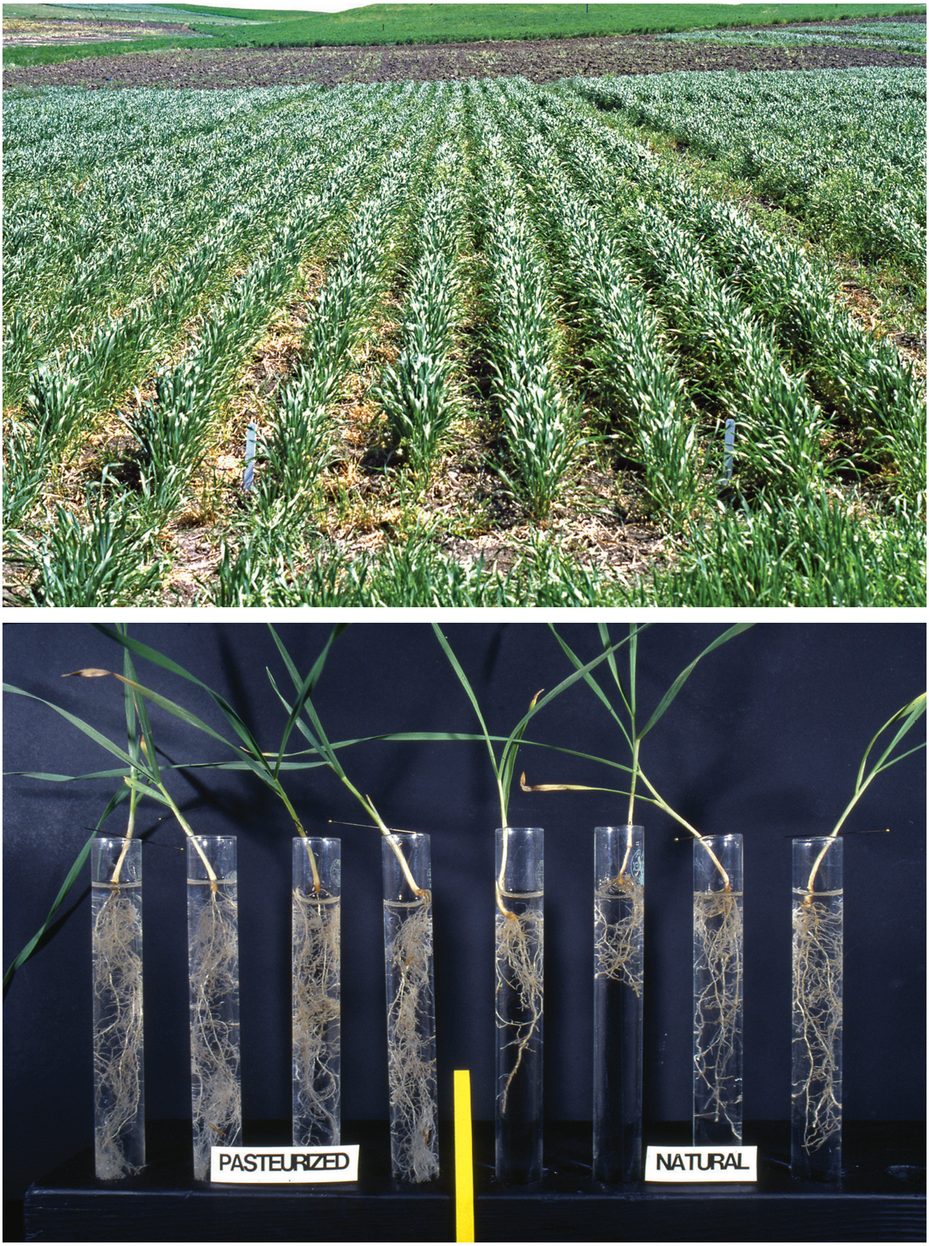

Figure 10-4. Top: *Pythium* symptoms on untreated wheat (rows on the left) and metalaxyl-treated wheat (4 rows on the right). Bottom: Wheat grown in pasteurized soil shows healthy root growth (left) compared to roots grown in natural soil (right). (Photos by R. James Cook.)

Disease cycle and conditions that favor the pathogen

Moist soil and cool temperatures (50–60°F) in the spring favor *Pythium* for several reasons. First, many species produce motile swimming spores, called zoospores, that are attracted to roots and seeds and can initiate infections. These require free water in the soil to move, so they are only active in wet soils. However, many of the species in the dryland areas of the PNW do not produce zoospores. Also, cool conditions delay the emergence of seeds and seedlings, giving more time for the pathogen to attack succulent juvenile tissue. *Pythium* species are considered pioneer pathogens because they can grow to the seed or seedling and infect it in a matter of hours as well as rot the root ahead of other pathogens. The slower the emergence (due to cool temperatures), the more damage. However, *Pythium* can still continue to attack the growing roots as long as soil moisture is adequate. Once the root is infected, the pathogen will destroy the root and root hairs. Then, in a matter of days, it will reproduce by producing sporangia, which can produce more zoospores, or produce oospores, which are the thick-walled, resistant survival structures. These can survive in the soil under hot, dry, or cold conditions for many years before germinating to infect roots. This disease can be favored by direct seeding conditions because the heavy residue in the spring will keep the soils wetter and retards the heating of the soil from solar radiation.

Potential effects of climate change

Pythium would be favored by cool, wetter conditions in the spring.

Pythium management strategies

Prevention

Prevention is not feasible. The pathogen is already widely distributed, and is not seed transmitted. However, use of fresh, certified seed contributes to overall seedling vigor and health. This is especially important with *Pythium* because older seed takes longer to emerge and gives more time for *Pythium* to attack.

Avoidance

There are no resistant wheat or barley varieties at the present time, and crop rotation is not effective.

Monitoring

Monitoring field symptoms during the current growing season is critical to making informed management decisions for the following growing season. There are no effective control actions to suppress the disease once symptoms appear in a crop. Sampling for positive identification of *Pythium* can aid management in decisions. Historically, quantification of most of the soilborne pathogens has been very difficult. However, recently developed molecular methods of quantification (real-time quantitative PCR) are now available and the technology has been transferred to Western Labs in Parma, Idaho.

Suppression

Chemical

Most commercially available cereal seed treatments contain metalaxyl or mefenoxam. This chemical is very effective against *Pythium* to protect the seed and young seedling. It is especially important to treat seeds such as pea, chickpea, or lentil, which may not emerge without protection. However, these chemicals are not systemic in the plant, and cannot protect roots of older plants. In most cases, yield of cereals will not be increased significantly. Recently, *Pythium* species from chickpea have been identified with resistance to mefenoxam, but the impact on cereal crops is not known.

Resistance

There is no resistance in any commercially available varieties.

Other cultural practices

One of the most important strategies is elimination of the green bridge using appropriate herbicide timing, which can also be effective against other soilborne pathogens such as *Rhizoctonia*. *Pythium* can attack the roots of volunteer crops and grassy weeds in the fall and spring. When these plants are killed by herbicides such as glyphosate, the herbicide shuts down the defense pathways in the plant, enabling *Pythium* to more readily attack the roots, greatly increasing in population. If the new crop is planted soon after herbicide application, *Pythium* can attack new seedlings that contact these dying roots, causing extensive damage. However, if there is a suitable interval between spraying of weeds and planting, disease is reduced because natural microbial activity will reduce the inoculum. Research has shown the ideal interval for *Rhizoctonia* to be about 2–3 weeks, and this may also apply to *Pythium*. Residue management such as chaff spreaders, straw choppers, mowers, or harrows may reduce the residue in the spring under no-till conditions, allowing soil to warm and dry faster to reduce *Pythium* damage. Rotation has not been shown to be effective because many of the groups also attack broadleaf crops. Fallow may not be effective for all species because of the long survival period of oospores. Application of a starter fertilizer in the seed row has been documented to reduce damage to the seedlings and increase yield by placing the nutrients adjacent to seedling roots and by overcoming early nutrient deficiencies caused by root pruning.

For more information on Pythium root rot, see Smiley et al. (2012).

Fusarium Crown Rot

Background, causal agents, and distribution

This disease is known by a variety of names: Fusarium crown rot, dryland foot rot, and Fusarium root rot. A number of *Fusarium* spp. can colonize the roots, lower stem (crown), and leaf sheaths of wheat and barley, but the most virulent and important are *Fusarium culmorum* and *F. pseudograminearum*. This disease is distinguished from another crown disease, called common root and foot rot, caused by the pathogen *Bipolaris sorokiniana*, which is present in dryland wheat but has not been a major problem like *Fusarium*. To make things even more confusing, the eyespot disease caused by *Oculimacula yallundae* and *O. acuformis* is also commonly referred to as foot rot or strawbreaker foot rot. In dryland areas with little summer precipitation, *Fusarium* pathogens are mainly confined to the lower stem, but in areas with precipitation at flowering or in irrigated areas, these pathogens may also infect heads causing head blight, along with another species, *F. graminearum*.

Fusarium is a parasitic fungus; both species are pathogens of cereals and grasses, including grassy weeds. Cereal hosts include wheat, barley, oats, and rye. Weed hosts include wheatgrass, downy brome, and fescue.

Table 10-7. Fusarium crown rot characteristics and management options for dryland cereal producers.

Fusarium crown rot	
Background • Causal agents: *Fusarium pseudograminearum*; *F. culmorum* • Source: infested soil, residue, chlamydospores in soil • Wide distribution, in 95% of PNW fields • Host range: cereals, grasses, not broadleaf crops • High risk: drought, water stress, excess N fertilizer, highly susceptible varieties	**Economic impact** • 10% average yield loss, but as high as 30% **Management options** • N management: do not over fertilize: excess N can lead to drought stress • Avoid early planting of winter wheat • Avoid highly susceptible varieties • Residue management
Key diagnostics • Brown discoloration of lower stem, subcrown internode • Whiteheads	**Ongoing research** • Resistance/tolerance breeding

However, they do not cause disease on broadleaf rotation crops such as pea, lentil, and chickpea (Table 10-7).

Key diagnostic features

The key diagnostic feature of both *F. culmorum* and *F. pseudograminearum* is the chocolate brown discoloration that is found on the lower stem and internodes of a mature wheat plant. In the early part of the growing season, the outer leaf sheaths are also brown and the infection can extend into the main culm. Brown discoloration can also be seen on the subcrown internode and seminal and crown roots. Crown discoloration can also be seen in other diseases, but the symptoms are distinct. In take-all, the discoloration is black in color, not brown. In common root rot, the discoloration is dark brown to black, especially on the subcrown internode. With eyespot or sharp eyespot, the discoloration is in a distinct, elongated, eye-shaped lesion with distinct margins. The discoloration caused by *Fusarium* is more diffuse, present on the entire culm. The other distinct symptom is whiteheads, seen after heading, when normal wheat heads should still be green (Figure 10-5). Heads turn white prematurely and the grain is smaller in size. This is because severe infections in

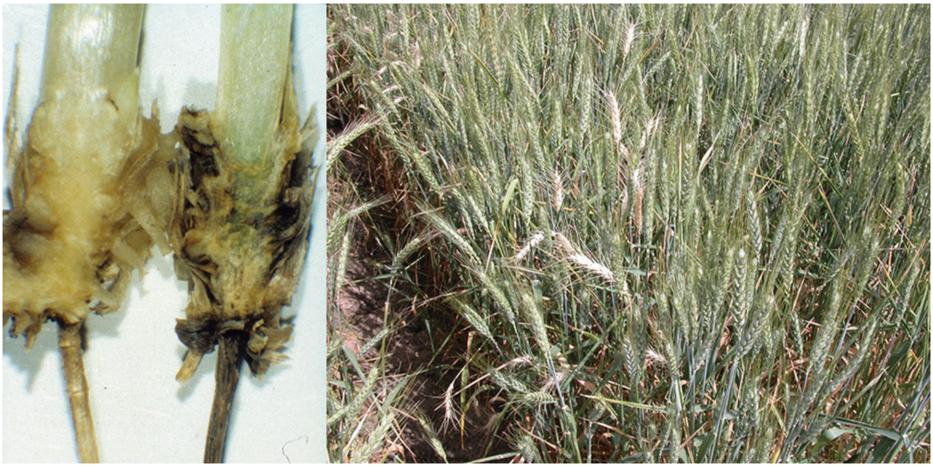

Figure 10-5. Crown damage and whiteheads caused by Fusarium crown rot. (Photos by Richard Smiley, Oregon State University.)

the lower stem cut off the flow of water and nutrients during grain filling. *Fusarium* can easily be isolated from discolored stems, and pinkish mycelium is often seen inside infected culms.

Disease cycle and conditions that favor the pathogen

Disease is often most severe under water stressed conditions and where excess nitrogen has been applied. Drought stress predisposes the pathogen to move into the crown from previous latent infections. When too much nitrogen is applied under dryland conditions, plants produce luxurious vegetative growth, but then run out of water and go into drought stress. Early planting of winter wheat can also result in plants outstripping the water supply and allows for a greater period of time for *Fusarium* to infect in the fall. Both *Fusarium* pathogens can grow under very dry conditions, much drier than most fungi. Both pathogens survive in infected stubble. Poole et al. (2013) found that *F. pseudograminearum* occurred more frequently at lower elevations with higher temperatures than *F. culmorum*, which was found more often at higher, moister, cooler sites. The pathogens can infect roots in the fall (in the case of winter wheat) but can also infect the lower stem and crown at or below the soil line from contact with infected stubble. These infections can proceed into the outer leaf sheaths and into the culm, and later move up 2 or 3 internodes. Both species also produce thick-walled chlamydospores in the soil, which can survive for many years, especially in the case of *F. culmorum*, hence the ineffectiveness of short rotations away from cereals.

Potential effects of climate change

This disease may increase under more frequent drought conditions.

Fusarium management strategies

Prevention

The pathogen is already widely distributed across the dryland PNW, and is not seed transmitted.

Avoidance

There are no resistant wheat or barley varieties at the present time. Crop rotation is not an effective management strategy because the pathogen (especially *F. culmorum*) has the ability to survive for several years between the presence of a host crop. However, rotation may reduce inoculum.

Monitoring

Monitoring field symptoms during the current growing season is critical to making informed management decisions for the following growing season. There are no effective control actions to suppress the disease once symptoms appear in a crop. The disease can easily be identified by looking at discolored crowns and whiteheads, but by then the damage is done. But this can give the grower an idea of the susceptibility of varieties and where the disease is a problem in the field.

Suppression

Chemical

Most seed treatments contain triazoles, and claims have been made that seed treatments can reduce Fusarium crown rot, but good data is lacking. Part of the problem is that this is a crown disease, and most seed treatments do not provide long-term systemic protection to older plants at a time when infection may occur in roots or at the soil line. However, new seed treatment fungicides with different modes of action are currently being tested, but efficacy is unknown.

Resistance

There is no resistance in any commercially available varieties. However, there is a range of susceptibility and some varieties may be more tolerant than others. Growers should avoid highly susceptible varieties.

Other cultural practices

One of the most important suppression strategies is to manage nitrogen and water stress. The fertilizer rates should be based on realistic yield goals dependent on the stored soil moisture so that excessive vegetative growth and depletion of soil water is avoided. Later planting of winter wheat may also avoid outstripping the water supply and reduce the time in the fall when root infections can occur. Rotation with a broadleaf crop or fallow is only effective if there are two or more years out of cereals because of the long survival of the pathogen in the soil. Studies on residue management have been mixed. Burning has not been effective in reducing disease because the fungus can survive in the soil and lower crowns, which do not reach lethal temperature during burning. Stubble sizing and harrowing did not affect disease level probably because the inoculum is then spread around the field. Some studies from Australia have shown that row cleaners to remove stubble from the rows and precision placement of rows between the previous rows may reduce disease.

For more information about Fusarium crown rot, see Smiley et al. (2005; 2012).

Root-Lesion Nematode

Background, causal agents, and distribution

Root-lesion nematodes are tiny, worm-shaped, migratory endoparasites that live throughout the root zone, feed on living plant roots, and are well-adapted to survive between host crop growing seasons. Root-lesion nematodes have multiple hosts (cereals, oilseeds, grain legumes, and grasses) and are adapted to different cropping systems and agroclimatic conditions across the PNW. Management options are limited; inoculum can increase and spread rapidly once introduced in a field. Two species, *Pratylenchus thornei* and *P. neglectus*, are important economically in the dryland region; *P. neglectus* is more prevalent in the inland PNW, whereas *P. thornei* typically causes greater impact worldwide (Table 10-8). The

Table 10-8. Root-lesion nematode characteristics and management options for dryland cereal producers.

Root-lesion nematode	
Background • Causal agents: *Pratylenchus neglectus; P. thornei* • Source: soil, eggs, and host crop roots • Wide distribution across the PNW including driest zones • Wide host range: small grains, grasses, lentils, chickpea, peas, oilseeds, pasture legumes • High risk: continuous cropping	**Economic impact** • Average yield reduction of 5% but can reduce grain yield up to 50% in the PNW; $51 million annual impact **Management options** • Monitor populations and risk (soil test) • Fallow • Eliminate green bridge • Rotate with less susceptible crop such as barley
Key diagnostics • Decrease in number of lateral roots, reduced root mass; presence of root lesions • Stunted, yellowed plants • Can be confused with fungal root rots	**Ongoing research** • Rotation and tillage effects • Development of varieties with both resistance and tolerance to *P. neglectus* and *P. thornei*

damage caused by root-lesion nematodes reduces wheat profitability in the region by an estimated $51 million annually (Smiley 2015b). Root-lesion nematodes have been found in up to 90% of sampled fields in Washington, Oregon, and Idaho, including the driest grain-fallow areas, and reduce small grain yields by an estimated 5% annually in the tri-state region, although damage can be up to 50%. Oregon studies indicate that yields may be reduced when populations exceed a potential damage threshold of 1,000 nematodes per pound of soil. However, relationships between plant-parasitic nematode densities, yield response, and economic damage are difficult to generalize across regions because they are influenced by site-specific interactions with climate, soils, host crop tolerance, and other biotic factors.

Key diagnostic features

Damage caused by root-lesion nematodes is often not recognized and is underestimated. Aboveground symptoms are non-specific, including stunting, reduced tillering, and chlorosis. Moisture or nutrient deficiencies occur earlier than in adjacent healthy plants, limiting yield (Figure 10-6). Root penetration and feeding reduces the number of root hairs and the extent of root branching on intolerant crops, restricting water and nutrient uptake. Symptoms appear on roots when plants are 6–8 weeks old and can be confused with *Pythium* or *Rhizoctonia* symptoms. Lesions caused by nematode penetration of root tissues predispose crops to secondary infections by other root rot pathogens. Typically, root-lesion nematode distribution is variable within fields; crop canopies may show irregular height and growth stages.

Disease cycle and conditions that favor the pathogen

The root-lesion nematode completes its life cycle in 6 to 9 weeks; numbers increase rapidly throughout the growing season. Adult females deposit up to 1 egg per day inside susceptible host roots or in moist soils when temperatures are favorable (68–77°F) and can remain active in cold, moist soil. Juveniles emerge from eggs at around one week; juveniles and adults feed both on and inside plant root tissue.

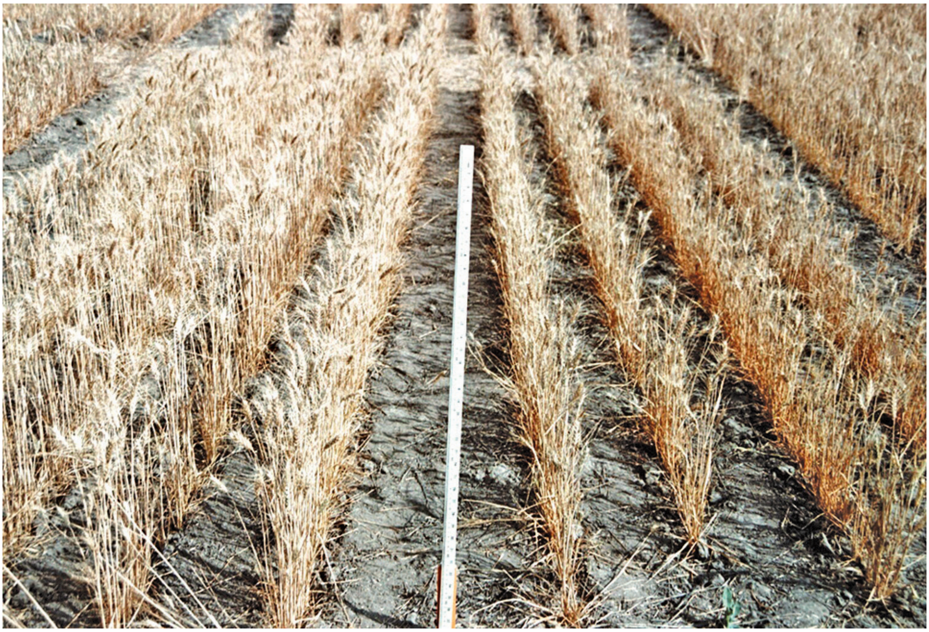

Figure 10-6. Reduced productivity of wheat grown in root-lesion nematode-infested soil (right, untreated) compared to nematicide-treated wheat (left). (Photo by Richard Smiley, Oregon State University.)

Distribution and population are influenced by many agronomic and environmental factors. Continuous cropping with susceptible host crops favors root-lesion nematodes; populations increase with the planting frequency of susceptible small grains, oilseeds, peas, lentils, and chickpeas. Spring wheat is more susceptible than winter wheat; barley is less susceptible than wheat. Volunteer host crops and weeds harbor inoculum between and during growing seasons. Soil texture does not appear to limit population density. Levels that have the potential to be economically harmful occur in both the grain-fallow and the higher precipitation annual areas. However, damage is typically greater in more limited soil moisture conditions. Root-lesion nematodes may move vertically in the soil profile to reach optimal soil moisture. Conservation tillage does not appear to increase populations. However, imazamox-resistant wheat varieties may be impacted by root-lesion nematodes migrating from dying weeds as a result of imazamox applications to control winter annual grassy weed infestations. Conservation Reserve Program (CRP) fields can support high populations.

Potential effects of climate change

The potential effect of climate change on root-lesion nematodes is unknown at this time. However, studies show that distribution and density are impacted by variability in temperature and in winter precipitation levels (Kandel et al. 2013).

Root-lesion nematode management strategies

Prevention

Field and equipment sanitation are the first lines of defense to prevent the introduction of inoculum from infested soil into clean fields. However, these strategies may be of limited utility due to the widespread distribution of these nematodes in the PNW.

Avoidance

Avoidance by host resistance or rotation is not currently an option. All locally adapted commercial wheat varieties that have been tested are susceptible to root-lesion nematodes and a wide range of hosts crops are also susceptible.

Monitoring

From a management perspective, it is highly useful to identify root-lesion nematodes to the species level; crop varieties vary widely in their response to *P. thornei* or *P. neglectus*. These species are very similar and difficult to distinguish. Recently developed DNA-based molecular testing can precisely identify and quantify individual species. Risk of economic damage increases as populations exceed 1,000 nematodes per pound of soil, at any soil depth.

Suppression

Risk can be reduced by decreasing populations; inoculum increases with the frequency of a susceptible crop.

Chemical

There are no foliar or seed-applied treatments to control root-lesion nematodes; no nematicides are currently registered for use in the PNW, and no commercial biological controls are available.

Resistance

No locally adapted commercial wheat varieties are resistant to either *P. neglectus* or *P. thornei*; several varieties show tolerance to *P. neglectus*. Spring wheat varieties with moderate tolerance to both root-lesion nematode species include 'Buck Pronto,' 'Tara 2002,' and 'Jerome.' Barley is less susceptible than wheat and can help reduce inoculum. Barley varieties respond variably to *Pratylenchus*; two-rowed feed barleys 'Camas' and 'Bob' have tolerance to both species and typically perform better than spring wheat varieties. Planting barley in fields transitioning from CRP can reduce risk to a subsequent wheat crop. Regional breeding program goals include developing wheat varieties with dual species resistance and tolerance to reduce damage and eliminate the need to identify root-lesion nematodes by species.

Other cultural practices

Rotation is not an effective standalone management practice. Where economical, a winter wheat-spring barley-summer fallow rotation can help reduce *Pratylenchus* populations in two phases: barley is less susceptible than wheat, and clean fallow controls host plants. Eliminating the green bridge and controlling volunteer and weed hosts during and between crop seasons also help reduce populations.

For further detail on root-lesion nematodes, see Smiley (2015a; 2015b), the primary sources for the information presented in this section.

Cereal Cyst Nematode

Background, causal agents, and distribution

Cereal cyst nematodes are sedentary endoparasites belonging to the *Heterodera avenae* cyst nematode group, which feed on and form egg-bearing cysts in living roots of small grain cereals and grasses. In contrast to root-lesion nematodes, cereal cyst nematodes do not infest broadleaf crops. Two *Heterodera* species, *H. avenae* and *H. filipjevi*, are important economically in the cereal production regions in Oregon, Washington, and Idaho, reducing average annual wheat profitability $3.4 million (Table 10-9). *H. avenae*, found in most major wheat production areas worldwide, was first reported in western Oregon in 1974, and in eastern Oregon and Washington fields in 1984. By 2005, surveys showed that *H. avenae* had become more widespread in the wheat production areas of all three states. *H. filipjevi*, a quarantine pest, was first identified in Union County, Oregon, fields in 2008 and, more recently, *H. filipjevi* was found at sites sampled in southeast Whitman County, Washington, in 2014. *H. filipjevi* will likely be detected in additional locations in the region using recently developed species-specific molecular testing techniques. Currently there is no evidence that *H. filipjevi* causes greater damage than *H. avenae*. The risk of quarantines being required is small since the pathogen is already established in the area.

Molecular identification and quantification data have helped increase our understanding of the distribution and epidemiology of plant parasitic nematodes. *H. avenae* and *H. filipjevi* are closely related; minor morphological differences distinguish them. However, recent studies show that spring wheat and barley cultivars differ in their response to the two species. For example, spring wheat cv. ‘Louise’ is susceptible to both species, cv. ‘WB-Rockland’ is resistant to *H. avenae* but susceptible to *H. filipjevi*, and cv. ‘SY Steelhead’ has resistance to *H. filipjevi* and is

Table 10-9. Cereal cyst nematode characteristics and management options for dryland cereal producers.

Cereal cyst nematode	
Background • Causal agents: *Heterodera avenae, H. filipjevi* • Source: soil, cysts, eggs, and host crop roots • Distribution: *H. avenae* is widespread in region; *H. filipjevi* has been identified in northeastern Oregon and eastern Washington • Hosts: small grains, grasses • High risk: annual cropping of susceptible host; spring wheat more susceptible than winter wheat	**Economic impact** • Yield reductions up to 50% on intolerant varieties; average reductions of 10% • *H. avenae* reduces annual wheat profitability >$3.4 million in the PNW **Management options** • Eliminate green bridge • Rotate with non-host broadleaf crops • Resistant + tolerant varieties and cultivars
Key diagnostics • Bushy proliferation of small, shallow roots at the points of nematode feeding • White females (pinhead sized) protruding from roots at heading • Patches of stunted, yellowed plants • Whiteheads	**Ongoing research** • Distribution surveys and species determination • Screening varieties for resistance plus tolerance • Resistance breeding with known *Cre* (wheat) and *Rha2* (barley) genes • Yield impact

susceptible to *H. avenae*. Races within a species can vary in reproductive capacity, or virulence, complicating risk assessment and resistance breeding. Recent studies indicate that the *H. avenae* and *H. filipjevi* races found in the PNW differ from those already described worldwide.

Key diagnostic features

Similar to root-lesion nematode, cereal cyst nematode symptoms on small grains are often not recognized and are confused with other causes. Growing an untreated susceptible variety next to a nematicide-treated crop helps researchers determine damage potential (Figure 10-7); no nematicides are registered for commercial use in the PNW. Symptoms of

H. avenae and *H. filipjevi* are indistinguishable. Aboveground symptoms are consistent with nutrient and water deficiency symptoms and mimic those caused by other root diseases or environmental stresses due to field variability. Populations may be randomly distributed resulting in irregular patterns or patches of pale, stunted plants across a field. The number, extent, and location of patches depend on the size of the population and their distribution. Root symptoms typically appear when plants are 6–8 weeks old. Tiny juveniles puncture and feed on young wheat and barley root tips causing root division and short, bushy root structure. At the cereal heading stage, white, pinhead-sized adult females become visible on roots. Once embedded in the root to feed, their bodies swell and protrude from the root surface. As infected roots die, females form a protective egg-filled cyst, dark brown (*H. avenae*) or lighter golden brown (*H. filipjevi*) in color. Root damage may predispose plants to secondary infestation by other root-infecting organisms.

Figure 10-7. *Heterodera avenae* symptoms on 'Alpowa' spring wheat (untreated, left) compared to nematicide treatment (right). (Photo by Richard Smiley, Oregon State University.)

Disease cycle and conditions that favor the pathogen

The cereal cyst nematode completes just one generation per cropping season and lives belowground for its entire life cycle. Cyst-encased eggs remain viable in the soil for many years, bridging growing seasons. Second stage juveniles emerge from overwintered cysts the following spring, as soils warm and moisture is favorable. These juveniles migrate to susceptible host crop roots, and puncture and feed on young meristematic tissue at root tips. Some eggs remain in the cyst for years to better ensure emergence of juveniles in an optimal environment. Emergence of *H. avenae* occurs from late February to late May in eastern Oregon, with the peak in mid-April. Emergence patterns of *H. filipjevi* are not yet well-understood; preliminary studies indicate *H. filipjevi* emergence peaks a few weeks ahead of *H. avenae*.

Continuous cropping with wheat or barley and 2-year grain-fallow sequences favor cereal cyst nematode populations; once infested, damage can spread across a field within 3–4 years. Spring wheat is more susceptible than winter wheat or spring barley, and late-planted winter grains are more susceptible than early-planted winter grains. Low fertility and deficient soil water intensify symptoms; plants benefit from adequate nutrition but do not respond to above-optimal rates. Cysts are sensitive to very dry soils. Conservation tillage does not appear to favor populations; no-till may reduce spread of inoculum throughout a field. While relative damage can be higher in sandy or droughty soils, cereal cyst nematodes are found in many soil types and are not restricted by soil texture. Risk of economic damage increases when *H. avenae* populations exceed 1,400 eggs + juveniles (from cysts and soil matrix) per pound of soil. These levels are commonly found in fields in this region. Reducing populations to fewer than 1,000 eggs + 2nd stage juveniles per pound of soil helps minimize damage (Smiley 2016). Yield is expected to decrease as cereal cyst nematode population increases. However, similar to root-lesion nematodes, relationships between population and yield response vary, as they are impacted by interactions of climate, host crop, and soil factors.

Potential effects of climate change

The potential effect of climate change on cereal cyst nematodes is unknown at this time.

Cereal cyst nematode management strategies

Prevention

Eradication is extremely difficult once cereal cyst nematodes become established. Avoid spreading infested soil to non-infested areas via equipment, animals, shoes, or crops. Infested soil may also be dispersed by wind or water.

Avoidance

Winter wheat sown during typical recommended planting dates will have less damage than spring wheat; plants can be well-established with healthy roots prior to peak emergence of juveniles in the spring. Late-planted winter grains are more susceptible than early-planted winter grains; spring grains are more susceptible than winter grains.

Monitoring

Risk of economic damage increases as *H. avenae* populations exceed 1,400 eggs + juveniles per pound soil. Identification of species is useful when a grower's primary control strategy is based on the selection of variety resistance or tolerance. Wheat, barley, and oat varieties may respond differently to *H. avenae* or *H. filipjevi*. DNA-based molecular testing can precisely identify and quantify individual species and is available through regional commercial and research labs.

Suppression

Chemical

There are no foliar or seed treatments to control cereal cyst nematodes, and no nematicides are registered for use in the PNW.

Biological

No commercial biological controls are available. However, existing fungal and bacterial parasites of *H. avenae* may offer potential for study of or development as a biocontrol in the future.

Resistance

Planting wheat and barley cultivars with moderate resistance and tolerance to cereal cyst nematodes can reduce risk. Ideally, a cultivar should be both resistant and tolerant to prevent buildup of inoculum and yield reduction. Breeding programs are focused on developing cultivars with dual resistance and tolerance to both *H. avenae* and *H. filipjevi*. Recent inland PNW trials identified spring wheat and barley varieties that showed resistance to or tolerance of cereal cyst nematodes (Marshall and Smiley 2016; Smiley 2016; Smiley et al. 2013). Response varied by cultivar, location, and species. For example, the hard red spring wheat cultivar 'WB-Rockland' showed both resistance and tolerance to *H. avenae* but was highly susceptible to *H. filipjevi*. Few wheat cultivars showed both resistance and tolerance to either species. Soft white spring wheat 'Louise' showed susceptibility to both species while 'Ouyen' was resistant to *H. avenae* but susceptible to *H. filipjevi*. Idaho studies identified 2-rowed and 6-rowed spring barley feed cultivars that showed moderate resistance plus moderate tolerance to *H. avenae*. Several barley malt cultivars also showed either resistance or tolerance; less is known about spring wheat and barley responses to *H. filipjevi*. 'SY Steelhead' spring wheat showed resistance to *H. filipjevi* but susceptibility to *H. avenae*. Variety resistance ratings are found in Smiley (2016).

Other cultural practices

Crop rotations which include resistant cereal varieties, non-host broadleaf crops, or fallow, with only 1 year of susceptible wheat, barley, or oats in a 3-year period can significantly reduce cereal cyst nematode numbers. Effective rotations include: (1) a 3-year sequence of winter wheat and two years of a non-host. The two non-host years could include two years of a broadleaf (oilseed or grain legume) crop, two years of clean fallow, or a single year of each; and (2) a 3-year sequence of winter wheat, spring wheat, and fallow or a broadleaf crop, where a resistant variety of spring wheat, winter wheat, or both are used. The traditional 2-year winter wheat-fallow rotation can be effective in the grain-fallow region if using a resistant winter wheat cultivar. Long rotations away from wheat are likely not going to be economical.

Eliminating the green bridge and controlling volunteer host crops and grass weeds during all phases of a rotation helps reduce inoculum. Maintaining optimal fertility levels supports crop vigor.

For further detail on cereal cyst nematodes, see Smiley (2015a; 2016), the primary sources for the information presented in this section.

Eyespot (Strawbreaker Foot Rot)

Background, causal agents, and distribution

The eyespot pathogens are capable of infecting wheat, barley, oats, rye, and several other grasses. However, winter wheat is the primary economic host, with spring wheat and barley only affected occasionally. Winter wheat losses can be up to 50% with severe infections (Table 10-10). The name eyespot comes from the characteristic eye-shaped lesions that occur on infected stems near the soil surface. This widespread disease in the PNW has been called strawbreaker foot rot locally since the mid-1900s, but the rest of the world knows it as eyespot. The name strawbreaker foot

Table 10-10. Eyespot characteristics and management options for dryland cereal producers.

Rhizoctonia root rot and bare patch	
Background • Causal agents: *Oculimacula yallundae; O. acuformis* • Source: infested crop residue • Wide distribution across PNW; more common in the higher precipitation zones • Host range: mainly winter wheat, but some spring wheat and barley • High risk: early planting, 45–55°F with fall rains, open winter, susceptible variety	**Economic impact** • Up to 50% yield reduction when severe **Management options** • Resistant winter wheat varieties • Foliar fungicide in spring before stem elongation • Delayed fall seeding
Key diagnostics • Eye-shaped lesions on stem or leaf heath (honey-brown with dark centers) • Whiteheads • Multi-directional lodging	**Ongoing research** • New fungicide efficacy testing • Resistance screening of advanced winter wheat lines and wild wheat, determining if eyespot resistance genes are equally effective for both pathogen species

Adapted from Murray 2014a.

rot comes from the disease occurring near the base or foot of the stem and the tendency of infected stems to break and fall over, resulting in widespread lodging (Figure 10-8). An older and now less commonly used name is Cercosporella foot rot, which is derived from the old name of the causal fungus, *Cercosporella herpotrichoides*.

Eyespot is now recognized as being caused by two closely related fungi, *Oculimacula yallundae* and *O. acuformis*. Until about 1989 when the sexual reproductive stage was discovered in South Australia, these fungi were grouped into the single species *Pseudocercosporella herpotrichoides* with varieties *herpotrichoides* and *acuformis*, respectively. At that time, variety *herpotrichoides* (*O. yallundae*) was the predominant eyespot pathogen in the PNW, but now variety *acuformis* (*O. acuformis*) is equally common.

Two other diseases that can be confused with eyespot are sharp eyespot, caused by *Rhizoctonia cerealis*, and Fusarium crown rot, caused by *Fusarium culmorum* or *F. pseudograminearum*. As the name suggests, sharp eyespot has lesions on stems that are eye-shaped with a distinct

Figure 10-8. Lodging of winter wheat caused by eyespot. (Photo by Tim Murray.)

margin, but in the PNW are more superficial and rarely serious enough to cause yield loss. Fusarium crown rot is widespread and potentially damaging, but is distinguished by infected roots, crowns, and stem bases as opposed to eyespot, which only infects stem bases.

Key diagnostic features

Eyespot is very difficult to detect and identify with certainty in the early stages of disease development, and there is no way to determine which of the eyespot fungi is present by looking at stem lesions. The key diagnostic feature of eyespot is the presence of honey-brown, elliptical lesions on the leaf sheaths and true stem (Figure 10-9). Eyespot lesions have a diffuse, dark-brown margin, lighter brown center, and often have dark-colored centers, which is composed of fungal hyphae. One or more lesions can be present on the same stem. As plants age, lesions on true stems may become sunken in the center with bending or breaking of the stem. Lesions can also coalesce into larger lesions when more than one occurs on a stem.

Figure 10-9. Characteristic early season stem lesions of eyespot. (Photo by Tim Murray.)

Dead standing stems known as whiteheads may appear during warm weather after grain begins to develop. Infected stems may also fall over or lodge after grain has begun to develop. In some instances, lodged stems may fall in different directions, a symptom known as "straggling," or they may fall in the same direction, which often occurs after a storm.

Disease cycle and conditions that favor the pathogen

The eyespot fungi survive in the residue of plants that were infected while they were alive and nowhere else. The length of time they can survive depends on the environmental conditions, but typically can survive 3 or more years under PNW conditions (longer under dry conditions). In the fall when temperatures are about 40–50°F and rain is common, these fungi begin producing millions of microscopic spores on the infested residue. Spores spread to nearby seedlings by splashing and blowing rain where they land on leaf sheaths, begin growing, and penetrate and infect the plant. The eyespot fungi grow slowly and colonize the outer leaf sheaths of the developing plant and remain there until the true stem develops in the spring. The true stem becomes infected when it grows up through the colonized leaf sheaths, giving the eyespot fungi an opportunity to penetrate it. Once in the stem, the eyespot fungi colonize it and destroy structural vascular tissues that can result in lodging. Yield can be reduced even when the crop does not lodge, although greatest damage occurs when the crop lodges.

Fall weather is most important for eyespot: cool temperatures from 40–50°F with frequent rain is important. Eyespot is likely to be more severe in years when winter conditions are mild with minimal snow cover because the pathogen can continue to spread and develop in infected plants. In contrast, cold winters with prolonged snow cover reduce the potential for eyespot because the pathogens do not spread, and they develop slowly inside infected plants at the low temperatures under snow.

Early seeding favors eyespot, likely because the larger plants have more susceptible leaf sheaths for infection and are more likely to be contacted when spores are splashing around than smaller plants. Although the worldwide literature on residue management practices is mixed, eyespot is less severe in no-till fields than in conventionally tilled fields in the PNW, and this is likely due to the later seeding dates associated with reduced or no-till and not the presence of residue per se. Short rotations, dense canopy, spring frost, and excess N status may also favor eyespot. Laboratory studies indicate that the rate of asexual sporulation is sensitive to temperature, light, water, and nutrient status, but it is not known how these factors may influence sporulation under field conditions. Increased understanding of population biology and epidemiology are needed to improve eyespot disease management.

Potential effects of climate change

Eyespot may become more severe in years when winter temperatures are warmer and there is less snow cover, as occurred in 2015–2016 because these conditions are more favorable for infection and disease development.

Eyespot management strategies

Prevention

The eyespot pathogens were first reported in the PNW over 100 years ago and are widely distributed, so sanitation practices such as cleaning equipment to prevent infestation of a field are not practical or effective.

Avoidance

Planting an eyespot-resistant variety is the primary recommendation for its control. Several winter wheat varieties with effective eyespot resistance are available, but no resistant spring wheat or barley varieties have eyespot resistance owing to the relative unimportance of this disease in spring cereals.

Monitoring

Fields planted to eyespot-susceptible varieties should be scouted in early spring before stem elongation to determine whether eyespot is present in sufficient amount to justify a foliar fungicide application. Eyespot is favored by moist soil conditions and, consequently, often found in low areas of fields such as draws, swales, and in the toeslope of hills. Collect enough plants from around the field to give 50 stems; wash those stems and determine if they have eyespot lesions. Consider a foliar fungicide when 10% or more of the stems have recognizable eyespot lesions before stem elongation begins.

Suppression

Chemical

There are no seed treatments that control eyespot. Fungicide application should be considered when 10% or more of stems have recognizable lesions before stem elongation begins (Zadok's growth stage 30). Several foliar fungicide treatments are registered for eyespot control: propiconazole + thiophanate-methyl; cyproconazole + thiophanate-methyl; fluxapyroxad + pyraclostrobin; and azoxystrobin + propiconazole. Resistance to the benzimidazole fungicides, thiabendazole, and thiophanate-methyl is present in Washington and Oregon. For this reason, use of a fungicide mixture containing more than one mode of action is recommended.

Resistance

See the Avoidance section.

Other cultural practices

Avoiding early seeding relative to the production area can be helpful in limiting eyespot development, but will not prevent it. Likewise, crop rotation may be useful for eyespot management by allowing time for infested residue to decompose, but again will not prevent eyespot. Planting spring wheat or barley instead of winter wheat in fields with history of severe incidence can suppress damage.

For more information on eyespot disease, see Murray (2006; 2014a).

Cephalosporium Stripe

Background, causal agents, and distribution

Cephalosporium stripe is a chronic disease of winter wheat in the inland PNW. It was first reported in Washington State in the early 1950s, having been described in Japan in 1934. It has since been described in several other areas of the US and Europe. Cephalosporium stripe is a vascular wilt-type disease because the pathogen infects and colonizes the water-conducting tissue (xylem) of the plant while it is alive and, in doing so, spreads throughout the plant.

Cephalosporium stripe is caused by the fungus *Cephalosporium gramineum*, which is an asexually reproducing fungus. Although this fungus has a wide host range among cereals and other grasses, the primary economic host is winter wheat. This disease can cause total loss of a wheat crop when environmental conditions are favorable and a susceptible variety is grown. The pathogen can be found in all precipitation zones in the inland PNW but is more common in the higher precipitation zones (Table 10-11).

Key diagnostic features

Cephalosporium stripe is easy to diagnose when characteristic yellow stripes develop in the leaves (Figure 10-10). Stripes run the length of the leaf blade and then extend down the leaf sheath. Symptoms may be present in late winter to early spring, depending on the susceptibility

Table 10-11. Cephalosporium stripe characteristics and management options for dryland cereal producers.

Cephalosporium stripe	
Background • Causal agent: *Cephalosporium gramineum* • Source: infested crop residue • Wide distribution across PNW; more common in the higher precipitation zones • Host range: cereals, especially winter wheat; fall annual grasses • High risk: early seeding, 45–55°F with fall rains, open winters with soil heaving, low soil pH, susceptible variety	**Economic impact** • Up to 100% yield loss on winter wheat when disease is severe **Management options** • Tolerant varieties • 3-year crop rotation out of winter wheat • Delayed seeding • Reduce residue (fragment or bale) • Liming to raise soil pH > 5.5
Key diagnostics • Vascular wilt, long yellow stripes in leaf blade extending down sheath; brown streaks in yellow stripes • Whiteheads, stunting, double canopy	**Ongoing research** • Resistance screening • Seed transmission • Molecular detection • Transfer of genetic resistance from wheatgrass • Genetic variation

Adapted from Murray 2014b.

Figure 10-10. Characteristic yellow striping of Cephalosporium stripe disease. (Photo by Tim Murray.)

Figure 10-11. Whiteheads (stunted, dead standing stems) on wheat caused by severe Cephalosporium stripe. (Photo by Tim Murray.)

of the variety. Eventually, small, brown, necrotic streaks develop in the center of the stripes and ultimately the entire width of the stripe may turn brown as the tissue dies. Depending on environmental conditions and susceptibility of the variety, stripes may appear in the flag leaf and eventually the head, resulting in dead standing stems known as whiteheads (Figure 10-11). Infected stems are often stunted, resulting in a "double canopy" with heads on healthy stems standing taller than heads on infected stems. Cephalosporium stripe is favored by moist soil conditions and, consequently, often found in low areas of fields such as draws, swales, and in the toeslope of hills.

Disease cycle and conditions that favor the pathogen

C. gramineum survives primarily in the residue of plants that were infected while they were alive. The length of time the pathogen can survive depends on the environmental conditions, but typically it can survive 3 or more years under PNW conditions (longer under dry conditions). *C. gramineum* is also seedborne in very low percentages, but this source of inoculum is not important under PNW conditions. The disease cycle is similar to that of eyespot: in the fall when temperatures are about 40–50°F and rain is common, *C. gramineum* produces millions of microscopic spores on infested residue that are washed into the soil near the roots and crowns of winter wheat plants. Spores germinate and penetrate the plant through wounds in stem bases and roots near the crown. Once inside the plant, the fungus grows into the young xylem tissue and begins producing more spores and toxic materials that result in formation of the yellow stripes. As the plant is dying, the fungus colonizes plant tissues outside the xylem and uses it as a food source for survival. Early seeding of winter wheat is favorable to Cephalosporium stripe because larger plants have larger root systems that are more susceptible to injury and subsequent infection. Open winters with multiple soil freeze-thaw events and short crop rotations (i.e., wheat-fallow) favor development of Cephalosporium stripe. Acid soil conditions can strongly influence development of this disease, with increased incidence and severity as soil pH drops below 5.2.

Potential effects of climate change

The impacts of climate change are difficult to predict with Cephalosporium stripe. In the near term, this disease may become more severe because open winters with frequent freeze-thaw events seem to favor disease development.

Cephalosporium stripe management strategies

Prevention

Cephalosporium stripe is widely distributed in the inland PNW, so sanitation practices such as cleaning equipment and tires to prevent infestation of fields are not practical.

Avoidance

Wheat varieties vary in their response to Cephalosporium stripe, ranging from tolerant to very susceptible; however, none have highly effective resistance.

Monitoring

Cephalosporium stripe is difficult to observe in fields before heading. Moreover, there are no management practices that will mitigate the impact of Cephalosporium after the crop has been planted. A molecular test is available to detect the pathogen in seed intended for export, but it has not been used commercially.

Suppression

Chemical

There are no effective seed-applied or foliar fungicides for the control of Cephalosporium stripe.

Other cultural practices

Avoiding early seeding and planting a tolerant variety can greatly reduce the development and impact of Cephalosporium stripe. Likewise, use of a 3-year crop rotation with winter wheat no more than once every three years can also reduce the impact of Cephalosporium stripe by allowing time for infested residue to decompose. Fragmenting infested residue to speed decomposition can help reduce the impact of Cephalosporium stripe. The literature on the effect of residue management practices on Cephalosporium stripe is mixed, with some reporting greater disease in reduced tillage systems than conventional and vice versa. In the PNW, Cephalosporium stripe is less severe in no-till fields than in conventionally tilled fields; as with eyespot, this response is likely due to the later seeding dates associated with reduced or no-till and not the presence of residue per se. However, no-till fields also have fewer freeze-thaw events and less soil heaving than conventionally tilled fields, which may contribute to reduced disease. Liming of soils to raise pH above 5.5 is beneficial in reducing the impact of Cephalosporium stripe where soil pH is low.

For more information on Cephalosporium stripe, see Murray (2014b), Quincke et al. (2014), and the Cephalosporium stripe page on the WSU Small Grains website.

Wheat Soilborne Mosaic

Background, causal agents, and distribution

Wheat soilborne mosaic (WSBM) disease is caused by the *Soilborne wheat mosaic furovirus* (SBWMV), which is transmitted by the fungus-like organism *Polymyxa graminis*. WSBM is a disease of winter wheat that was discovered in 1919 in Illinois and called "rosette" disease, but it wasn't until the 1960s that *Polymyxa* was identified as the vector. WSBM has been an important disease in the Great Plains, Midwestern, and Northeastern wheat-producing areas since its discovery.

WSBM was first identified in Washington in 2008, but was reported across the border in adjacent Umatilla County, Oregon, in 2005, and before that in the Willamette Valley of western Oregon in 1994. Whether the virus spread from western Oregon or how is not known. In Washington, it appears to be localized in the Walla Walla area. Because this disease is newly recognized in the region, breeding for resistance has not been a priority, and most winter wheat varieties are susceptible. Yield losses can be up to 75% with severe infection of highly susceptible varieties. Spring wheat and spring barley typically do not develop symptoms (Table 10-12).

Key diagnostic features

Symptoms of WSBM disease include a green to yellow mosaic on the leaves that appears in late winter or early spring as plants are beginning to grow. Depending on the virus strain and susceptibility of the variety,

Table 10-12. Wheat soilborne mosaic characteristics and management options for dryland cereal producers.

<table>
<tr><th colspan="2">Wheat soilborne mosaic</th></tr>
<tr><td>Background
Causal agent: Soilborne wheat mosaic furovirus, vectored by Polymyxa graminis
Source: infested soil
Limited distribution: Walla Walla, WA area and adjacent Umatilla County, OR
Host range: wheat, barley, rye, other grasses
High risk: cool, moist soil following seeding</td><td>Economic impact
Varies with cultivar susceptibility and degree of infestation, from minor to over 75% reduction in grain yield
Management options
Field and equipment sanitation (prevent infected soil moving to clean fields)
Resistant varieties
Irrigation management following seeding</td></tr>
<tr><td>Key diagnostics
Green to yellow leaf mosaic
Stunting, chlorosis
Rosetting in very susceptible cultivars</td><td>Ongoing research
Screening PNW cultivars to identify resistance</td></tr>
</table>

plants may be severely stunted, a symptom referred to as a “rosette” because the stems don’t elongate normally (Figures 10-12 and 10-13). Symptoms often appear in patches that range from small to large, occur in low areas or places where water moves, and may appear in patterns associated with tillage operations. The latter symptoms are associated with distribution of the vector, which is favored by high soil moisture and is moved with infested soil. Symptoms fade as temperatures warm and plant growth increases, leading to misdiagnosis as a nutrient problem associated with cold soil. Although symptoms may fade, plants remain damaged and yield is reduced in affected areas of the field. Yield loss ranges from minor to over 75% when the infestation is extensive and the variety is very susceptible.

Disease cycle and conditions that favor the pathogen

SBWMV survives only in association with its vector, *P. graminis*, in soil and is not seed transmitted. Following seeding of winter wheat, when soil is cool (~50°F) and moist, resting spores of *P. graminis* germinate, penetrating and infecting root hairs of young plants carrying SBWMV with

Figure 10-12. Green to yellow mosaic symptoms of wheat soilborne mosaic (WSBM) disease. (Photo by Tim Murray.)

Figure 10-13. Wheat variety trial showing a variety highly susceptible to wheat soilborne mosaic (WSBM) disease (left) next to a highly resistant variety (right). (Photo by Tim Murray.)

it. Once inside the plant, SBWMV replicates and spreads throughout the leaves in the fall and early winter, eventually resulting in the formation of symptoms. Soil conditions following seeding are critical to infection, with cool and moist soils favoring germination of *P. graminis*. Consequently, WSBM disease may develop with early or late seeding, depending on soil moisture and temperature conditions that occur afterwards. Infection declines when soil temperature is below 45°F.

Potential effects of climate change

It is difficult to predict the impact of near-term climate change on the frequency and severity of WSBM.

Wheat soilborne mosaic management strategies

Prevention

SBWMV appears to be a relatively recent introduction to the PNW and its distribution is limited. Consequently, sanitation practices that reduce or prevent movement of soil from infested to non-infested fields are effective in reducing the impact of this disease. Such practices include cleaning equipment, vehicle tires, and even shoes when traveling between fields.

Avoidance

Growing a resistant winter wheat variety is the primary method for managing WSBM. Wheat varieties adapted to the PNW vary in their response from very susceptible to very resistant (Figure 10-13).

Monitoring

Lab tests are available to detect and confirm the presence of SBWMV in symptomatic plants, but there are no post-infection treatments that can mitigate the damage.

Suppression

Chemical

There are no effective seed-applied or foliar treatments that will mitigate damage from SBWMV. Soil fumigation is partially effective in reducing resting spores of *P. graminis*, but does not eliminate the organism and is not cost-effective.

Other cultural practices

Crop rotation has little effect on SBWMV because the resting spores of *P. graminis* are capable of surviving for long periods of time in soil. For irrigated production, irrigation prior to seeding followed by no irrigation for several weeks after seeding may help reduce the impact of SBWMV.

For more information on WSBM disease, see Flowers et al. (2012) and Murray et al. (2009a).

Looking Ahead

Management strategies will continue to evolve in response to increased understanding of pathogen distribution and pathogen response to changing conservation cropping technologies, production practices, or environmental conditions. Continued climate change may affect pathogen distribution, virulence or aggressiveness, and host crop resistance, tolerance, and susceptibility. System-wide monitoring of crop response to current management strategies is an important tool to help determine if climate change or cropping practices reduce effectiveness of current management strategies. Future adaptations may include improved host resistance, altered planting schedules, new chemistries and adjusted timing and rates of application, or biological control methods.

Resources and Further Reading

Publications

Acid Soils: How Do They Interact with Root Diseases? Washington State University Extension Publication FS195E.

http://pubs.wpdev.cahnrs.wsu.edu/pubs/fs195e/?pub-pdf=true

Green Bridge Control Begins in the Fall. STEEP Conservation Tillage Handbook Chapter 4 No.18.

http://pnwsteep.wsu.edu/tillagehandbook/chapter4/041893.htm

Pacific Northwest Plant Disease Management Handbook

http://pnwhandbooks.org/plantdisease/

Small Grain Seed Treatment Guide. Montana State University Extension MT199608AG.

http://store.msuextension.org/publications/AgandNaturalResources/MT199608AG.pdf

2015–2016 Winter Wheat Breeder Variety Portfolio. Washington State University Extension Publication TB15E.

http://cru.cahe.wsu.edu/CEPublications/TB15/TB15.pdf

Websites

Oregon State University Wheat Research

http://cropandsoil.oregonstate.edu/group/wheat

Oregon State University Columbia Basin Agricultural Research Center (plant pathology research)

http://cbarc.aes.oregonstate.edu/plant-pathology/research-projects

Oregon State University Umatilla Co. Cereal Central (pests)

http://extension.oregonstate.edu/umatilla/pests

University of Idaho North Idaho Cereals (Publications: diseases and insect pests)

http://www.uidaho.edu/extension/cereals/north/publications

Washington State University Small Grains (disease resources)

http://smallgrains.wsu.edu/disease-resources/

Washington State Crop Improvement Association Seed Buyers Guide

http://washingtoncrop.com/

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