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Managing Plant Disease Risk in Diversified Cropping Systems

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ABSTRACT

Diversification of cereal cropping systems with alternative crops, such as oilseed, pulse, and forage crops, furnishes producers with a range of agronomic and economic options. Crop diversification also improves management of plant diseases through manipulation of host factors such as crop and cultivar selection; interruption of disease cycles through crop rotation, fungicide application, and removal of weeds and volunteer crop plants; and modification of the microenvironment within the crop canopy using tillage practices and stand density. Management practices, such as seed treatment, date and rate of seeding, balanced fertility, control of weeds, field scouting, harvest management, and record keeping, can also be utilized to manage plant diseases. This review evaluates the risks to diversified crop production systems associated with the major plant diseases in the northern Great Plains and the influence of host, pathogen, and environmental factors on disease control. Principles to help producers reduce and manage the risk from plant diseases are presented, and discussion includes strategies for countering fusarium head blight (*Fusarium* spp.), commonly called scab; and leaf spot diseases in cereals; sclerotinia stem rot [*Sclerotinia sclerotiorum* (Lib.) De Bary] in oilseed and pulse crops; and ascochyta blight (*Ascochyta lentis* Vassil.; teleomorph: *Didymella lentis* Kaiser, Wang & Rogers) and anthracnose blight [*Colletotrichum truncatum* (Schwein.) Andrus & W.D. Moore] in pulse crops. Producers should not rely exclusively on a single management practice but rather integrate a combination of practices to develop a consistent long-term strategy for disease management that is suited to their production system and location.

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Cereal grains are major crops in the northern Great Plains dryland area. Over the years, a cereal–fallow sequence has been used to reduce the risk of crop failure due to lack of soil moisture. With the adoption of reduced tillage practices or conservation tillage, soil moisture is conserved, and annual cropping becomes a viable option for producers. Alternative crops such as oilseeds, pulses, and forages are used to diversify cereal grain cropping systems. These alternative crops provide producers with a range of agronomic and economic options and help to avoid a buildup of pests associated with cereal grains.

Even under dryland conditions of this geographic area, plant diseases can limit crop production. The presence and severity of a plant disease is determined by the dynamic interaction of a susceptible crop (host), a causal agent (pathogen), and favorable environmental conditions (Fig. 1). This interaction is known as the plant disease triangle. All three factors are required for disease development.

Management practices that modify the host, pathogen, or environment will influence the incidence and severity of diseases. For example, using a resistant cultivar reduces the impact of disease because the incidence and severity of disease are severely reduced. Pathogens survive on seed, locally in plant residue or the soil, or in remote locations from which they are then airborne to susceptible crops. Using seed treatments can eliminate seed-borne pathogens such as the cereal smuts. Crop rotation reduces pathogen carryover on crop residue or in the soil. In contrast, reduced tillage increases the quantity of crop residue on the soil surface. This residue directly supports survival of residue-borne pathogens by providing substrates for growth and by positioning

Abbreviations: FHB, fusarium head blight.

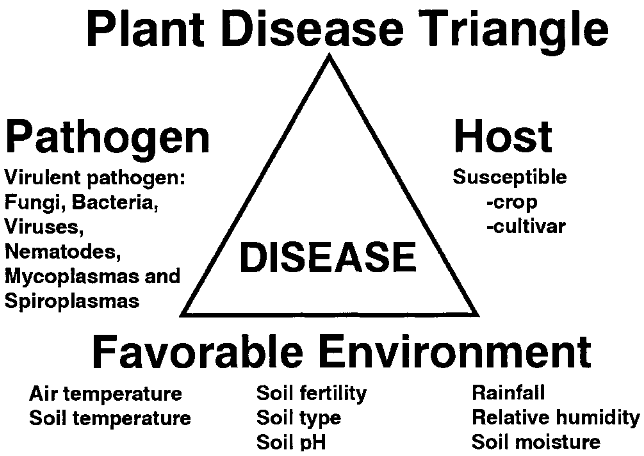

Fig. 1. A host, pathogen, and favorable environment are required for the development of a plant disease.

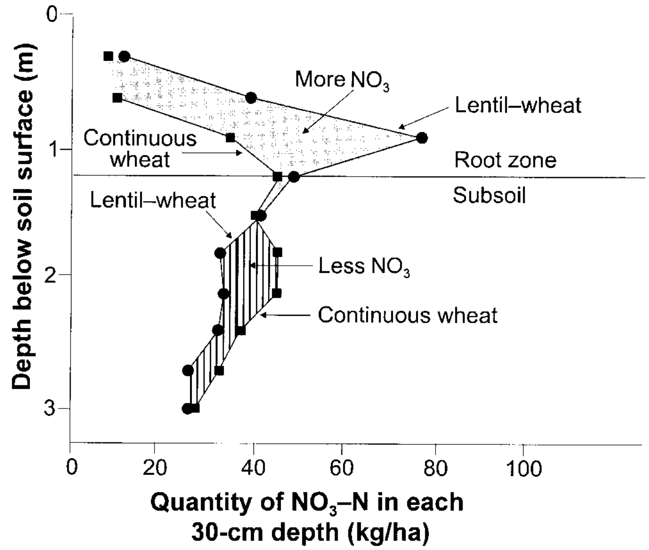

Fig. 2. A contrast of the quantity of NO_3 present in soils under a continuous spring wheat system and a wheat–lentil system (Reynolds et al., 1995).

the pathogens at the soil surface where spore release can occur. Modifications to the microenvironment influence the biological activity of microorganisms (both beneficial and pathogenic) in the crop canopy and in the soil. Reduced tillage indirectly defines the species composition of the soil microbial community by improving the retention of soil moisture and modifying soil temperature.

Knowledge of the major crop diseases and their common hosts at a regional, local, or even field level is the initial step in managing diseases and selecting management practices. Field scouting and record keeping of individual fields, including the correct identification of diseases, disease impact, and when susceptible hosts were grown, provide valuable information on which management strategies are based. Individual management practices (Fig. 2) may not provide dramatic levels of control, but they can be combined to reduce the impact of diseases and enhance crop yields. This review evaluates the risks to diversified crop production systems from major plant diseases in the northern Great Plains; discusses how these diseases can be influenced by host, pathogen, and environment; and suggests strategies for managing and minimizing plant diseases within these systems.

HOST AND PATHOGEN INFLUENCE DISEASE RISKS

Crop Selection

Generally, pathogens attack specific plant species or a family of plants. For example, common disease problems on cereals do not affect broadleaf crops such as sunflower (*Helianthus annus* L.), pea (*Pisum sativum* L.), canola (*Brassica* spp.), or bean (*Phaseolus vulgaris* L.) and vice versa. Thus, diseases can be avoided with crop selection and crop rotation to nonhost crops, most effectively for pathogens that are soil or residue borne. Appropriate crop rotations lengthen the time between crop types so that pathogen populations have time to decline. For some diseases, rotation to nonhosts for a sufficient period of time will allow for decomposition of infested crop residues and/or a reduction in the viability of pathogen survival structures, eliminating one source of primary inoculum. By increasing the diversity of crops grown within a rotation, the pathogens in the soil or on residue from the previous crop usually will not infect the subsequent crop grown. Crop rotation can be one of the most effective biological control options available to producers (Cook and Veseth, 1991).

Crop selection may influence disease risk because of its place in the rotation sequence, through the crop's inherent susceptibility or resistance to a disease, or by affecting the pathogen's ability to survive and spread. Knowledge of the host range of the major plant pathogens in a region is important for selecting an appropriate crop sequence. Host range information is available in publications such as *Diseases of Field Crops in Canada* (Martens et al., 1984) or the compendium series from the American Phytopathological Society, e.g., *Compendium of Wheat Diseases* (Wiese, 1987). Disease risks associated with various crop rotations used in the northern Great Plains have been summarized (Anonymous, 1994; Krupinsky et al., 1997b; McMullen and Lamey, 1999) (Table 1). Within similar crop types, such as the cereals, some are more susceptible to certain diseases than others (McMullen and Lamey, 1999; Schatz, 1998). Rotations between cereals and noncereal crops generally reduce disease risk from residue- or soil-borne diseases. The inclusion of a pulse crop in rotations, especially with no tillage, enhances the population and activity of beneficial soil organisms and minimizes the impact of cereal root diseases. For example, the pathogen [*Cochliobolus sativus* Ito & Kurib.; anamorph: *Bipolaris sorokiniana* (Sacc.) Shoemaker] that causes common root rot of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) is not a pathogen of broadleaf crops. Following 5 yr of rotation with nonsusceptible crops in Canada, common root rot severity declined by more than 50% compared with severity following continuously cropped small grains (Ledingham, 1961).

Table 1. Disease risks associated with various crop rotations in the northern Great Plains (Anonymous, 1994; Krupinsky et al., 1997b; McMullen and Lamey, 1999).

Rotation	More risk of	Less risk of
Canola, barley, barley, flax, durum, wheat	Leaf spots (cereals) FHB†, scab (cereals) Common root rot (cereals) Take-all (cereals)	Blackleg (canola) Sclerotinia (canola)
Wheat, canola–flax, oat–barley, field pea–flax	FHB (cereals) Flax wilt Sclerotinia (pea, canola, flax)	Ascochyta (pea) Leaf spots (cereals) Root rots (cereals)
Wheat, pea, oat–barley, canola–sunflower	Sclerotinia (pea, canola, sunflower) FHB (cereals)	Blackleg (canola)
Wheat, pea, winter wheat, canola–sunflower	Sclerotinia (canola, pea) Leaf spots (cereals) FHB (cereals)	None
Canola, lentil–pea, wheat	Ascochyta (lentil) Sclerotinia (canola, pea, lentil) Blackleg (canola)	Most diseases
Canola, lentil–pea, flax, cereal, canola, forage, forage, forage, cereal, cereal	Leaf spots (cereals) Common root rot (cereals, grasses)	Blackleg (canola) Ascochyta (pea, lentil) Sclerotinia (canola, lentil, pea)

† FHB, fusarium head blight.

Good crop rotations require appropriate intervals among susceptible hosts to allow pathogen populations to decline. For some diseases, the rotation interval is critical for successful disease management. With tan spot on wheat [*Pyrenophora tritici-repentis* (Died.) Drechs.], the fungus survives on wheat residue, and a short break of 1 to 2 yr decreases inoculum and disease risk (Bailey et al., 1992; Duczek et al., 1999). With blackleg on canola [*Leptosphaeria maculans* (Desmaz.) Ces. & De Not.], the largest numbers of fungal spores are produced on canola residue that is 2 to 3 yr old, so the risk of blackleg infection is higher in canola planted into older stubble than in 1-yr-old stubble (Petrie, 1994).

Unfortunately, crop rotation and increased diversity is less effective with some diseases, particularly with those organisms (*Fusarium* spp., *Pythium* spp., and *Sclerotinia* spp.) that have a wide host range and good survival mechanisms. For example, *S. sclerotiorum* has a wide host range, causing sclerotinia disease (i.e., white mold, stem rot, and wilt) on broadleaf crops and weeds. With rare exceptions, this pathogen does not affect cereals and grasses (Boland and Hall, 1994). Broadleaf hosts vary in their reaction to this disease. Sunflower and dry bean are very susceptible to sclerotinia disease while crops such as flax (*Linum usitatissimum* L.) or buckwheat (*Fagopyrum esculentum* Moench) suffer much less damage (McMullen and Lamey, 1999; Schatz, 1998). The pathogen forms sclerotia, which are hard fungal bodies that may survive for at least 3 to 5 yr in the soil and pose a threat to subsequent susceptible crops (Adams and Ayers, 1979; Cook et al., 1975). It is generally not economical for producers to grow only cereals or grasses for this duration, so a diverse crop rotation sequence includes a crop susceptible to sclerotinia disease several times within this period. Thus, use of a broadleaf crop with less susceptibility, or one that produces fewer sclerotia, may be important for the next broadleaf crop grown in the rotation (Krupinsky et al., 1997b; Schatz, 1998).

However, crop rotation does not provide effective control of all diseases that affect crops in the region. Inoculum for many diseases comes from a variety of sources and includes not only infested residue, but also soil, seed, and airborne sources. Rotation is ineffective for controlling a disease like barley loose smut [*Ustilago nuda* (C.N. Jensen) Rostr.] because this disease is seed borne. The most effective methods for managing loose smut are use of seed treatment, pathogen-free seed, or a resistant cultivar. Pathogens that are transported long distances by wind currents, such as wheat leaf rust (*Puccinia recondita* Rob ex. Desm. f. sp. *tritici*), cannot be controlled by crop rotation. For these types of diseases, producers need to develop an integrated approach where cultivar resistance, seed quality, fungicides, and crop rotation are used to provide more consistent disease management.

Host Resistance

Plant pathogens require a susceptible host crop and a susceptible cultivar to infect and cause disease. Resistant cultivars can be used to reduce disease risk for many pathogens. With the diversity of diseases that may attack any crop species, it is not realistic for a plant breeder to incorporate resistance to all of the major pathogens in a single cultivar. Success has been achieved in cereals with cultivars that are resistant to leaf rust, stem rust (*Pu. graminis* Pers. f. sp. *tritici* Eriks. & Henn.), and some leaf spot pathogens. However, this resistance is not static because pathogen pathotypes may shift in predominance or new races may emerge. For example, in 1999, wheat leaf rust became severe in spring wheat fields in the northern Great Plains. Abundant inoculum was produced in the southern plains states, and frequent rains in the spring wheat regions favored infection. In addition, a large, diverse population of leaf rust races occurred, and many spring wheat cultivars were susceptible to the prevalent races (Long and Hughes, 1999). In Alberta, the increased prevalence of virulent races of scald [*Rhynchosporium secalis* (Oudem.) J.J. Davis] on barley has lead to increased scald severity on barley cultivars previously rated as resistant (Turkington et al., 1998a). This demonstrates the need for continued screening and selection for resistance. If a high level of disease resistance is not available, then cultivars with the best resistance available should be used to reduce disease risk. Following a devastating fusarium head blight (FHB) epidemic in 1993, wheat producers in the northern Great Plains quickly switched to cultivars that were the least susceptible to FHB (Stack, 1999).

Pathogen Survival and Spread

The infection, dispersal, and survival mechanisms of each pathogen affects disease risk. Pathogens with air-borne spores are more likely to cause infections over a wide area and be introduced into new areas quickly. Urediospores of *Pu. graminis*, the causal agent of stem rust of wheat, are transported from the southern USA northward to Canada by air currents. Long-distance movement is more limited for pathogens that are mainly restricted to host tissues in the soil, such as *Gaeumannomyces graminis* (Sacc.) von Arx & Olivier, the causal agent of take-all on cereals and grasses.

Crop residue determines the survival and carryover of several important pathogens. In cereal crops, early seedling infections result from leaf spot pathogens sporulating on crop residue. The number of pycnidia (flask shaped spore-producing structures) on crop residue was greater in the spring following an overwintering period than in the previous fall for the fungus *Stagonospora nodorum* (Berk.) E. Castellani & E.G. Germano [teleomorph: *Phaeosphaeria nodorum* (E. Miller) Hedjaroude], the cause of stagonospora nodorum blotch (Duczek et al., 1999). In comparison, conidial spore production by two other leaf-spotting fungi, *B. sorokiniana* (Sacc.) Shoemaker and *Pyr. teres* Drechs., was greater in the fall and declined after an overwintering period (Duczek et al., 1999). Survival of these pathogens may be extended by their ability to sporulate on other hosts. For example, the wheat pathogen *St. nodorum* can also sporulate as a saprophyte on barley residue and the cereal pathogen *Bi. sorokiniana* can infect and sporulate on some forage grasses (Duczek et al., 1996; Duczek et al., 1999). Survival and reproduction of pathogens on non-host crops should be considered when planning crop rotations.

Some pathogens survive on seed and can infect seedlings. Seed treatments may be used to reduce the risks associated with many seed- or soil-borne pathogens. Pathogen-free seed offers a means of keeping some of these diseases out of a field and preventing the introduction of virulent races into a field or region. For example, in Alberta, *Lep. maculans*, causal agent of blackleg of canola, was declared a pest under the Agricultural Pests Act (http://www.agric.gov.ab.ca/ministry/acts/regs/ar406-86.html; verified 8 Nov. 2001). Initially, there was a requirement that all seed sold in Alberta be tested to ensure the absence of virulent blackleg. This helped slow the progress of virulent blackleg in Alberta until canola cultivars with effective levels of resistance became commercially available in the 1990s.

Volunteer crop plants and weeds can be hosts or reservoirs of many crop diseases or their insect vectors. The wheat curl mite (*Aceria tulipae* Keifer), which vectors the wheat streak mosaic virus, needs a green, living gramineous host to survive. Between susceptible crops, volunteer wheat or other grassy weeds may harbor the virus and serve as the bridge for survival of the mite and virus from one host crop to the next. Destruction of volunteer wheat plants and grassy weeds in the field and in adjacent areas is required before planting a new wheat or barley crop (McMullen and Lamey, 1999). Crop rotations that maintain at least a 1-yr interval between susceptible crops help to reduce the risk of wheat streak mosaic as long as susceptible volunteer wheat plants and grass hosts are controlled in the non-host phase. Other management practices include using planting dates that will reduce the opportunity for mites to infest the crop and host resistance (Holtzer et al., 1996).

ENVIRONMENT AND MANAGEMENT PRACTICES INFLUENCE DISEASE RISKS

Location and Climate

Climatic factors can have an important impact on disease risk (Coakley, 1988). For most of the important foliar diseases in the northern Great Plains region, the risk of disease outbreak is greatest in areas where long-term mean rainfall levels and production potential are highest. Intermittent wet–dry periods often limit progress of foliar disease in this region. Climate also influences the prevalence of root pathogens. Continuous wheat crops grown with no tillage develop severe, yield-limiting root rots (*Fusarium* spp., take-all, and *Pythium* spp.) in the Pacific Northwest (Cook, 1982). These problems are not as severe in western Canada because drier soils restrict the development and survival of these pathogens (Bailey et al., 1989; Nilsson, 1969).

Each species of microorganism (both pathogens and beneficials) has an optimum temperature and moisture regime for growth and survival. Small changes in environment can favor one species and inhibit another. For example, the fungal pathogens that cause leaf spot diseases on barley in western Canada have slightly different temperature optima: Scald (*R. secalis*) does best at 15 to 20°C, net blotch (*Pyr. teres*) at 20 to 25°C, and spot blotch (*Bi. sorokiniana*) at 25 to 30°C (Mathre, 1997). As a result, the relative prevalence of these species differs among regions and seasons, with scald more common in northern regions and in years when mean temperatures are low and spot blotch more common in southern regions and in years of above-normal temperature.

Location influences this interaction through factors such as climate and soils. Crop management practices such as type of tillage, seeding rate, and even seeding date can affect the environment within a field, which can in turn affect pathogen populations. As a result, the risk of disease and the optimum combination of management techniques for a particular pathogen can differ from site to site or can be similar across vast regions, depending on a complex interaction among the pest, the crop, and the ecology of the region.

Most crops are particularly vulnerable to diseases during germination and establishment and again during crop senescence at harvest. The risk of seed establishment problems is higher in diversified rotations than in cereal-based systems because dicot crops are more susceptible to damping-off (decay or death of seeds or seedlings) than are cereals. As the use of diverse susceptible crops increases, greater use of seed treatments may be required to reduce the risk of poor stand establishment under cool, wet conditions in the spring.

Disease levels usually increase within the crop during the growing season because the crop canopy closes, providing optimum conditions for the spread of microorganisms. By harvest, pathogen inoculum in the crop is often at high levels, and many crops are vulnerable to attack by foliar pathogens and even saprophytes. Periods of rainfall can delay harvest and result in yield and quality losses due to disease (Gossen and Morrall, 1984). Early maturing cultivars and planting dates that are staggered to permit rapid harvest can be used to reduce these risks. Varied planting dates also reduce the risk of all fields reaching a particular growth stage at the same time, which might coincide with weather conditions having a high risk of diseases like FHB.

Soil Biology

Maintaining a diverse and balanced population of biologically active microbial species creates a healthy soil and contributes to improved crop production. Many microbial species are natural enemies of soil-borne plant pathogens, affecting pathogens through competition, antagonism, or parasitism (Cook and Veseth, 1991). Despite the fact that ecosystem function is mainly governed by soil microbial dynamics (Kennedy and Smith, 1995), the microbial component of the soil is largely unknown, with <13% of all existing species having been identified. Only 8% of the total soil C exists as microbial biomass, but microbes contribute 60 to 80% of the total metabolic activity in soil. The relative number of microbial propagules per gram of soil from the top 15 cm comprises 10^9 bacteria, 10^8 actinomycetes, 10^6 fungi, and 10^5 algae (Brady, 1974, p. 115–116). Their role in the soil includes decomposition of organic matter, mineralization and immobilization of nutrients for plant growth, N fixation, environmental remediation, plant growth promotion, disease initiation by plant pathogens, and biological control for crop protection. In cereal–fallow cropping systems, reduced microbial diversity results from low organic matter and limited plant diversity from monoculture and weed eradication. Incorporating management practices that increase and stabilize microbial populations, such as manipulating the source (i.e., crop residue) and placement of microbial food substrates, will help to maintain a diverse and active population of microorganisms, which antagonize root pathogens (Cook and Veseth, 1991).

Reduced tillage practices enhance species diversity and support larger microbial populations in the upper layers of soil. Cultivation redistributes the microorganisms throughout the upper and lower soil layers (Doran, 1980; Kennedy and Smith, 1995; Lupwayi et al., 1998). In the wheat phase of different cropping rotations, soil microbial biomass and bacterial diversity was greater in reduced tillage systems (Lupwayi et al., 1998, 1999). Ergosterol content (an indicator of fungal biomass) is greater with no tillage (Monreal et al., 2000). However, increases in microbial biomass may include increases in both beneficial and pathogenic microorganisms.

The crop residues that are available for microbial breakdown are determined by the crop rotation as well as by the crop species and cultivar selected in each phase of the rotation. This in turn determines the structure, nature, and size of the microbial community (Rothrock et al., 1995). Soil microbial biomass was greater in soils sown to wheat when the preceding crop was red clover (*Trifolium pratense* L.) and lowest after summer fallow (Lupwayi et al., 1999). Microbial diversity was higher under wheat preceded by leguminous crops (red clover and field pea) than following wheat or summer fallow (Lupwayi et al., 1998). Diversity in crop rotation provides a heterogeneous food base for microorganisms that offers more ecological niches and encourages microbial diversity. Reduced tillage contributes to this diversity because heterogeneous residues accumulate on the soil surface over time.

Under conventional tillage and traditional crop production systems, the soil's natural ability for biological control of plant diseases tends to decline. An exception is the take-all disease of wheat grown in monoculture. Continuous monocropping of wheat leads to an increased suppressiveness of the soil to the take-all fungus due to microbial activity (Cook and Baker, 1983). Vilich and Sikora (1998) proposed the term *biological system management* to describe the concept of managing relationships between the biological elements of the agroecosystem and the biological elements of the crop production system to develop new or altered crop production techniques that contribute to a self-regulating system. Manipulation of agronomic factors relating to residue management, such as tillage, crop rotation, choice of crop species, and cultivar selection, provide the framework by which *natural biocontrol* may be enhanced. Cook and Veseth (1991) stated that, "biological control is the flywheel of nature," and practices that upset activities of natural agents should be avoided.

Tillage

Agricultural systems use tillage to bury crop residues; level, consolidate, and warm the seedbed in the spring; reduce surface compaction; break up a hardpan; incorporate pesticides and fertilizers; and reduce weed and disease problems. After one or two tillage operations, little residue from the previous crop is left on the soil surface, which contributes to soil erosion by wind and water. Tillage increases water loss due to surface runoff and increases evaporation by leaving the soil exposed to heat and wind. Tillage also contributes to the loss of organic matter. In contrast, surface residues from reduced tillage operations act as an insulator, reflecting solar radiation and conserving soil moisture. Under reduced tillage, soils warm more slowly in the spring and are cooler during the growing season than soils under conventional tillage. Moisture retention is also improved under reduced tillage because of reduced evaporation, increased snow trapping, and reduced surface runoff due to better water infiltration (Cook and Veseth, 1991).

Reduced tillage increases the risk of foliar disease epidemics compared with conventional tillage because increased levels of primary inoculum are present on crop residue at the soil surface. Many pathogens continue to sporulate longer on soil surface residue than on residue buried by tillage. For example, *Mycosphaerella pinodes* (Berk. & Bloxam) Vestergren, the cause of mycosphaerella blight of pea, survives much longer in pea residue at the soil surface than when buried (Sheridan, 1973). However, the survival of other pathogens such as *Col. truncatum*, the cause of anthracnose of lentil (*Lens culinaris* Medik.), is higher on buried residue than at the soil surface (Buchwaldt et al., 1996).

Once a pathogen is established in the crop, local weather conditions determine how quickly the disease progresses. Therefore, levels of primary inoculum on crop residue are likely to have a more consistent and predictable impact on disease risk where conditions conducive to pathogen dissemination and infection (e.g., rainfall events) occur frequently than in regions like the northern Great Plains where conducive conditions occur sporadically. Changes in the prevalence of individual pathogens (and the associated risk of crop loss) in response to changes in tillage practice have been difficult to predict. For example, reduced tillage is associated with increased root diseases of wheat in parts of North America, but levels of common root rot were lower under reduced tillage than conventional tillage in a 12-yr trial in southern Saskatchewan (Bailey et al., 1992; Bailey and Gossen, unpublished data, 1999). Similarly, reduced tillage often results in increased foliar disease severity, but these differences are not always economically important in the more arid regions of the northern Great Plains (Anderson et al., 1999; Bailey and Duczek, 1996; Bailey et al., 1992, 2000).

With reduced tillage, other management practices may have an impact on diseases. For example, the application of glyphosate [*N*-(phosphonomethyl)glycine] herbicide reduces sporulation of *Lep. maculans*, the cause of blackleg on canola and oilseed rape (*Br. napus* L.) (Humpherson-Jones and Burchill, 1982; Petrie, 1995). This herbicide is commonly used in reduced tillage management systems where it may reduce levels of inoculum for blackleg. Good crop rotations should also be integrated with reduced tillage (Bockus and Shroyer, 1998).

Tillage operations may influence the soil microbial community by the placement of crop residues and by the modification of soil moisture and soil temperature. Changes in tillage system can affect the risk of root rot disease epidemics because the higher soil moisture levels under reduced tillage affect the prevalence of fungal species. For example, the prevalence of *Coc. sativus* on cereal roots declined under reduced tillage, but the prevalence of *Fusarium* spp. increased (Bailey, 1996; Bailey and Duczek, 1996). Reduced tillage is occasionally associated with reduced survival of fungal overwintering structures, such as sclerotia of *S. sclerotiorum*, because it favors the bacteria that breakdown these structures (Nasser et al., 1995). Reduced tillage systems may increase the sustainability of production systems by taking advantage of natural biological processes for pest management.

Stand Density

Stand density has an important impact on disease risk because higher plant densities and denser plant canopies result in conditions more conducive to disease increase and spread. Row spacing and seeding rate affect disease risk by changing the proximity of individual plants and plant parts, which influences the movement of pathogens from plant to plant. Seeding date can also impact canopy structure and stand density. Stand density influences air movement, shading, and moisture retention within the canopy. For example, narrower rows and denser canopies result in higher levels of damage by sclerotinia disease than in thinner stands of grain legumes (Blad et al., 1978; Grau and Radke, 1984; Haas and Bolwyn, 1972; Steadman et al., 1973). Similarly, soybean [*Glycine max* (L.) Merr.] cultivars with a more compact, dense, and vine-like canopy tend to have more severe symptoms of sclerotinia disease than those with an upright, open, and bushy canopy (Schwartz et al., 1978). High levels of N fertilizer and frequent irrigation also promote the development of dense plant stands and increase risk of sclerotinia disease on bean (Blad et al., 1978). Similarly, botrytis stem and pod rot (*Botrytis cinerea* Pers.) is often more severe in dense stands of lentil than in thinner stands (Gossen, unpublished data, 1999). In canola, Turkington and Morrall (1993) found that incidence of sclerotinia disease in commercial canola crops was significantly related to canopy density. As noted with sclerotinia disease in soybean, plants in dense stands must compete for light, moisture, and nutrients and so may not fully express their disease resistance potential compared with plants in thinner stands (Pennypacker and Risius, 1999). Lower disease resistance of individual plants in dense stands would further increase disease risk.

Effects of management practices can be subtle. For example, increasing seeding rates may have the unintended affect of increasing primary disease inoculum in the field if the causal agent is carried on seed. Dense populations of weeds in a field may contribute to disease development by increasing the density of the plant canopy or serving as an inoculum reservoir in the absence of a susceptible host crop, or they may reduce disease incidence by trapping spores that might have landed on the susceptible crop (Duczek et al., 1996).

Plant Nutrition

Balanced and adequate fertility for any crop reduces plant stress, improves physiological resistance, and decreases disease risk. For example, wheat fields with low levels of soil N often have higher levels of tan spot disease than adequately fertilized fields (Fernandez et al., 1998; Krupinsky et al., 1997a). Micronutrients may also play an important role in plant health. Chloride, applied as KCl, has been shown to reduce foliar and root rot diseases of small grains when Cl levels are <33.6 kg ha^{-1} (Fixen et al., 1986). Copper deficiency was associated with increased leaf and head diseases in wheat at some sites (Evans et al., 1990; Franzen and McMullen, 1999). Research in Scotland on oilseed rape has shown that adequate S fertilization may help to decrease the severity of alternaria blackspot (*Alternaria* spp.) (Walker and Booth, 1994). Balanced fertility may be better maintained with a diverse cropping rotation because each crop species has different nutritional requirements for optimum growth and development and so draws individual nutrients from the soil at different rates.

INTEGRATED MANAGEMENT PRACTICES FOR REDUCING DISEASE RISK

Producers in the northern Great Plains have a number of disease management practices at their disposal (Fig. 2). However, the particular strategy that a producer chooses will depend on a number of factors. An important consideration will be whether or not the crop cultivar being considered is resistant to the important diseases in the region. The potential for yield and quality loss will have an influence on the strategy that is used. Producers are more likely to use expensive management practices such as foliar fungicides when both the potential for loss and the potential to recover their investment are high. Commodity prices will also have an influence on the strategy that is used. For canola or malt barley, which have relatively high returns, fungicide application will be more readily considered for in-crop disease control than in lower value crops, such as feed barley.

The value of field scouting and record keeping should not be underestimated. They are crucial management practices for effective disease management. For the producer, systematic in-crop inspections provide information on the diseases that are present in a field and the impact they are having. This information helps the producer schedule management practices for the current growing season and develop management strategies for the future. Although producers have the option of scouting themselves, professional field scouts are becoming more common.

The use of resource information and identification services is also a basic step in managing diseases. For effective disease management, correct identification of the disease and causal agent is critical. The biology of the disease, understanding how the pathogen survives and develops, will help producers choose the most appropriate and effective management practices available to them. Obtaining information on the best available control measures for a particular disease is important. Producers have access to a variety of publications and resources through local government extension offices, government and university researchers, professional societies, university bookstores, producer and commodity organizations, service industries, and websites via the Internet (Table 2). Decision-support systems that help producers with the economics and reliability of in-crop fungicide applications have been relatively rare in the northern Great Plains. Recently, forecasting systems for sclerotinia stem rot in canola (Morrall et al., 1991; Anonymous, 2001; Turkington and Morrall, 1993); FHB and leaf spots in wheat; and foliar diseases of lentil, field pea, and chickpea (*Cicer arietinum* L.) have become available to producers on the Internet (Table 2).

Producers in the northern Great Plains need to integrate a number of control strategies to provide consistent long-term disease management (Fig. 2). Management practices for plant diseases include: crop and cultivar selection, seed quality, seed treatment, date and rate of seeding, balanced fertility, control of weeds and volunteers, in-crop fungicide application, field scouting, record keeping, and harvest management. Producers should not rely exclusively on a single management practice, such as the use of disease resistance, as this creates an opportunity for the pathogen to circumvent that particular strategy, resulting in losses in yield and

Table 2. Internet resources for additional information on plant diseases (verified 7 Dec. 2001).

Managing Disease:
Canadian Phytopathological Society: http://res.agr.ca/lond/pmrc/cps/cpshome.html
American Phytopathological Society: http://www.apsnet.org/
Alberta Agriculture, Food and Rural Development's "Ropin' the Web": http://www.agric.gov.ab.ca/
Saskatchewan Agriculture and Food: http://www.agr.gov.sk.ca
Manitoba Agriculture: http://www.gov.mb.ca/agriculture/crops/diseases/index.html
Minnesota Association of Wheat Growers, Small Grains: The Internet Source For Small Grain Growers: http://www.smallgrains.org/
Disease Forecasting:
North Dakota Wheat Leaf Diseases and Fusarium Head Blight: http://www.ag.ndsu.edu/cropdisease/
Sclerotinia Risk Forecast Maps: http://www.canola-council.org/ or http://www.gov.mb.ca/agriculture/news/ace/sclerotinia/sclerotinia.html
Manitoba Fusarium Head Blight Risk: http://www.gov.mb.ca/agriculture/crops/diseases/index.html
Pulse Crops. Agriculture and Agri-Food Canada: http://paridss.usask.ca/specialcrop/pulse_diseases/
Fusarium Head Blight:
Fusarium head blight in Canada: http://www.cgc.ca/Pubs/fusarium/fusarium-e2.htm
U.S. Wheat and Barley Scab Initiative: http://www.scabusa.org
USDA Cereal Research Lab: http://www.crl.umn.edu/scab/scab.html
North Dakota State's Crop Disease Forecasting Models: http://www.ag.ndsu.nodak.edu/cropdisease/
ACE-Manitoba Agriculture's Forecast Map: http://www.gov.mb.ca/agriculture/crops/diseases/index.html

quality. Commodity prices may force producers into intensive production of one crop species due to its potentially higher rate of return. In this situation, producers who use an integrated management strategy may be able to compensate for the lack of crop rotation for a sufficient period of time.

INTEGRATION OF MANAGEMENT PRACTICES FOR SPECIFIC DISEASES

Leaf Spots of Cereals

Leaf spot injury on cereals in the northern Great Plains is caused by several different fungal pathogens acting together as a disease complex. The diseases present on wheat are tan spot (*Pyr. tritici-repentis*), stagonospora nodorum blotch (*St. nodorum*), septoria tritici blotch [*M. graminicola* (Fückel) J. Schrt. in Cohn], stagonospora avenaria blotch [*Phae. avenaria* (G.F. Weber) O.E. Erikss. f. sp. *triticea* T. Johnson], and spot blotch (*Bi. sorokiniana*). The diseases present on barley are the net form (*Pyr. teres* f. *teres* Drechs.) and spot form (*Pyr. teres* f. *maculata* Smedeg.) of net blotch, scald (*R. secalis*), spot blotch (*Bi. sorokiniana*), septoria speckled leaf blotch (*Phae. avenaria* f. sp. *triticea* and *Septoria passerinii* Sacc.), and stagonospora nodorum blotch (*St. nodorum*).

Although leaf spot diseases can be found across the region, their distribution and severity generally reflect differences in moisture, temperature, and frequency of cereal crops but are also influenced by the predominant cultivars grown and their level of leaf spot resistance (Mathre, 1997). The key risk factors that favor the build-up of pathogen populations on crop residues include production of a susceptible cultivar, favorable weather conditions for disease development, short rotations, or continuous wheat or barley production. Seed-borne inoculum represents a relatively minor source of pathogen inoculum. Wheat and barley leaf spot diseases are polycyclic in nature (Mathre, 1997) and, as a consequence, have the potential to build up to damaging levels in a relatively short period of time (i.e., life cycle of 7–10 d) with a favorable environment.

Management practices that reduce risk of leaf spot diseases include the use of resistant cultivars, tillage, balanced fertility, fungicides, and crop rotation, particularly with reduced tillage systems (Krupinsky, 1999). Cultivars with moderate levels of resistance to leaf spot diseases are available, so producers should avoid susceptible cultivars in areas where leaf spot diseases are frequently severe. Spraying wheat with fungicides can protect a susceptible crop if the potential yield justifies the cost of application, but the cost of spraying may not be economical for moderately resistant cultivars (Bailey et al., 2000; Krupinsky et al., 1997b). Fungicide application increases yield, thousand-kernel weight, and kernel plumpness in susceptible barley cultivars (Bailey et al., 2000; Orr and Turkington, 1997). Foliar fungicides have little effect on malt quality although it may increase kernel plumpness (Basson and Greeff, 1990; Newton et al., 1998). Crop rotations that include wheat or other cereals every third year minimize the carryover inoculum of the leaf spot diseases (Duczek et al., 1999; Wiese, 1987). The disease severity of leaf spot pathogens is higher in wheat grown after wheat than after flax or lentil although the effects are only obvious in years with high disease pressure (Fernandez et al., 1998).

Tillage reduces surface residue and promotes its decomposition, which helps to reduce the carryover of pathogen inoculum. Reduced tillage practices may increase, decrease, or have no effect on plant diseases, depending on the soil type, location, and prevailing environment (Bailey and Duczek, 1996; Bockus and Shroyer, 1998). Low N levels tend to increase disease severity of the wheat leaf spot diseases; the impact is greater with reduced tillage and in dry years (Fernandez et al., 1998; Krupinsky, 1999; Krupinsky et al., 1998; Tompkins et al., 1993). In a study of commercial barley fields conducted from 1995 through 1997 in Alberta, scald and net blotch severity were similar among conventional and reduced tillage systems (Turkington et al., 1998b). Other crop production factors, such as environmental variation among regions and years, crop rotation, seed-borne inoculum, and choice of cultivar (level of disease resistance), will likely have a much larger impact on the risk of disease than will the type of tillage system used (Anderson et al., 1999; Bailey and Duczek, 1996; Turkington et al., 1998b).

Fusarium Head Blight of Small Grains

Fusarium head blight, commonly called scab, can be a devastating disease in small grains. The disease was severe in wheat and barley fields in the 1990s, causing hundreds of millions of dollars in economic loss due to fewer bushels, lighter test weights, and market grade reductions from the presence of a fungal mycotoxin called deoxynivalenol (McMullen et al., 1997). The disease is caused by several fungi that overwinter and persist in residue of small grains, corn (*Zea mays* L.), and grasses. *Fusarium graminearum* Schwabe (teleomorph: *Gibberella zeae* Petch) is the predominate species associated with the disease, but other species, such as *Fu. avenaceum* Corda ex Fr., *Fu. culmorum* Smith Sacc., *Fu. poae* (Peck) Wollenweb., and *Fu. sporotrichioides* Sherb., may also be associated with the disease, depending on location and crop (Clear et al., 1996; Salas et al., 1999). These fungi infect small grain crops from flowering to grain filling. Corn is an important host because *Fu. graminearum* on infested corn debris can serve as a source of spores for the next crop. Continued moist weather and saturated soil conditions favor development of the pathogen on residue.

Fusarium head blight may only be controlled by integrating multiple management practices. The least susceptible, best-adapted cultivars for a location should be grown. Although true resistance to FHB in wheat and barley is not yet available, substantial progress has been made in breeding for resistance (Bai and Shaner, 1994; Stack, 1999). Several wheat-breeding programs are now ready to release cultivars that have resistance to the disease (Stack, 1999). Disease risk is reduced when wheat or barley are not planted into wheat, barley, or corn residue in high-rainfall environments because the pathogen can survive for extended periods on these residues (Windels and Kommedahl, 1984). Research with corn, wheat, or soybean as the previous crop indicated that FHB severity is highest and yield lowest when wheat was planted after corn while severity is lowest and yield highest when wheat was planted after soybean (Dill-Macky and Jones, 1999). Use of staggered planting dates or selection of cultivars with different maturities reduces the risk that the most susceptible growth stages will coincide with infection periods. Some producers use winter wheat in their rotation because it flowers earlier and can escape infection, but it will become infected if wet periods occur early in the season. Recent research has indicated that fungicides can suppress FHB and may be economical if applied appropriately during the flowering period of wheat (McMullen et al., 1997; Stack, 1999). Several disease-forecasting systems have been developed and are accessible via the Internet (Table 2).

Sclerotinia Disease in Oilseed and Pulse Crops

In the northern Great Plains, sclerotinia diseases of oilseed and pulse crops (i.e., white mold, stem rot, and wilt) caused by *S. sclerotiorum* have the potential to cause substantial losses in yield from shriveled seed, shattering, and dockage (Dueck and Sedun, 1983; Morrall et al., 1976), but epidemics are sporadic in occurrence. Crop lodging may increase losses because mycelia readily grow from one plant to another. Sclerotia produced in or on infected tissue contaminate soil, stubble, and harvested seed (Kolte, 1985; Thomas, 1984).

Crop diversification has increased the risk of sclerotinia diseases by bringing more dicot crops into traditional cereal-growing regions. For example, growing sunflower in rotation with canola increases the risk of future sclerotinia epidemics because more sclerotia are produced in infected sunflower plants than in infected canola (Pearse, 1995). Similarly, including field pea or dry bean in the rotation also increases disease risk (Davies, 1991). Other pulses, such as lentil and chickpea, are also highly susceptible but are rarely produced where conditions are wet enough for epidemic outbreaks of *S. sclerotiorum*.

Management of these diseases has focused on cultural practices and foliar-applied fungicides. Crop rotation and sanitation are only partially effective because of the longevity of sclerotia, the pathogen's capacity for long-range dispersal via wind-borne ascospores, and its wide host range (Adams and Ayers, 1979; Morrall and Dueck, 1982; Purdy, 1979; Schwartz and Steadman, 1978; Williams and Stelfox, 1979). Deep ploughing is sometimes recommended to bury infected crop residue because survival of the sclerotia is greater at the soil surface than when buried; secondary tillage is not recommended because this moves sclerotia back to the surface (Merriman et al., 1979). In contrast, survival of sclerotia may decline quickly under no-tillage if large amounts of organic matter are present at the soil surface (Nasser et al., 1995). Strategies involving irrigation management and canopy modification may reduce maximum yields (Steadman, 1979). Host resistance has been difficult to achieve (Krüger, 1980; Morrall and Dueck, 1982; Purdy, 1979; Steadman, 1983).

Effective control of *S. sclerotiorum* in canola is available using foliar-applied fungicides at flowering (Morrall et al., 1985, 1989). However, the costs of fungicides and the sporadic nature of this disease make routine application uneconomical. Currently, producers identify fields where disease risk is high and fungicide application is worthwhile with three methods. The first method uses percentage of petal infestation with *S. sclerotiorum* as an indication of disease risk (Morrall et al., 1991). The second is a checklist of qualitative factors affecting disease risk to develop a decision threshold (Evans and Thomas, 1995). The third method involves risk maps, which give a regional indication of areas where environmental conditions have been favorable for development of sclerotinia disease (Anonymous, 2001).

Ascochyta Blight and Anthracnose in Pulse Crops

The most important diseases of lentil on the northern Great Plains are ascochyta blight, caused by *As. lentis* Vassil. (teleomorph: *D. lentis* Kaiser, Wang & Rogers), and anthracnose, caused by *Col. truncatum* (Morrall, 1997). *Ascochyta lentis* overwinters on infected seed and on crop residue (Gossen and Morrall, 1986). Although both mating types are present, the sexual stage has never been found in nature in this region (Ahmed et al., 1996). This has important implications for the spread of the pathogen because asexual conidial spores are rain-splash dispersed (Pedersen and Morrall, 1995) while the sexual spores (ascospores) are airborne and can be moved long distances by wind. Control of ascochyta blight may be achieved with partially resistant cultivars (Ahmed and Morrall, 1996), which have recently become available commercially. More typically, the use of clean seed and crop rotation reduces the risk of disease (Gossen and Morrall, 1986; Gossen et al., 1997b) with fungicides applied (Pedersen and Morrall, 1994) as required to manage disease epidemics. Because the pathogen survives longer at the soil surface than when buried (Gossen and Derksen, 1999; Kaiser and Hannan, 1986), tillage can be used to reduce inoculum of this pathogen in lentil residue.

Anthracnose of lentil produces microsclerotia under warm, wet conditions. Microsclerotia are readily dispersed by wind during harvest but only survive for prolonged periods when buried (Buchwaldt et al., 1996). Partially resistant lentil lines have been identified (Chongo et al., 1999) but are not yet commercially available. Also, more than one race of the pathogen occurs in the region (Buchwaldt et al., 1999), so management based on partial resistance to a single race is unlikely to be effective in the long term. The main strategy for reducing disease risk is crop rotation. Fungicide applications are effective under low and intermediate disease pressure but do not provide adequate control when disease pressure is high (Chongo et al., 1999).

Mycosphaerella blight caused by *M. pinodes* (anamorph: *As. pinodes* L.K. Jones) is the most important disease on field pea. It causes severe root rot in young seedlings (from seed-borne inoculum) and spreads rapidly on leaves and stems under warm, wet conditions via airborne ascospores from infected stubble (Warkentin et al., 1996; Xue et al., 1996). Survival of the pathogen declines quickly when infected residue is buried (Sheridan, 1973); however, crop rotation and tillage regime have little or no influence on blight severity (Gossen et al., 1997a, 1997b), probably because of the prevalence of airborne inoculum from adjacent fields. The pathogen population is genetically diverse (Xue et al., 1998), so breeding for resistance has been slow and difficult. Foliar fungicide application reduces blight severity (Warkentin et al., 1996) but often does not result in yield improvement (Deneka et al., 1996). At present, selecting pea cultivars with improved resistance to lodging is the best option to minimize disease risk.

SUMMARY

Shifts towards crop diversification and reduced tillage in cereal cropping systems has been beneficial for the management of plant diseases in the northern Great Plains. Crop diversification in combination with other reliable host management factors, such as cultivar selection, interruption of disease cycles through crop rotation, fungicide application, and removal of volunteer crop plants, has provided producers with opportunities to manage plant diseases. Additional opportunities have been provided by modifying the microenvironment within the crop canopy using tillage practices and stand density. New options for controlling plant pathogens will evolve as we develop a better understanding of the complex interaction between residue and microorganisms (both pathogens and beneficials). Other common management practices are also available for managing disease risk: seed quality, seed treatment, seeding date, balanced fertility, control of weeds, field scouting, record keeping, and harvest management, to name a few. Resource information and identification services can provide producers with the knowledge to develop integrated disease management strategies that are suited to their production system and location. Economic and environmental situations may pressure producers to make decisions that do not favor pest management, but producers that use an integrated management strategy will have more opportunity to cope with problems than those who rely on a single approach.

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