Pathotypes, Distribution, and Metalaxyl Sensitivity of *Phytophthora sojae* from North Dakota

B. D. Nelson, I. Mallik, D. McEwen, and T. Christianson, Department of Plant Pathology, North Dakota State University, Fargo, ND 58102

ABSTRACT

Nelson, B. D., Mallik, I., McEwen, D., and Christianson, T. 2008. Pathotypes, distribution, and metalaxyl sensitivity of *Phytophthora sojae* from North Dakota. Plant Dis. 92:1062-1066.

Phytophthora root rot, caused by *Phytophthora sojae*, is the most important disease of soybean (*Glycine max*) in North Dakota. Because of the expansion of soybean hectares and appearance of disease on cultivars with resistance genes, we investigated the pathotypes, distribution, and metalaxyl sensitivity of *P. sojae* in North Dakota. Soil from 347 soybean fields in 20 counties in eastern North Dakota was collected between 2002 and 2004, and *P. sojae* was baited from the soil with the susceptible cultivar McCall. The virulence phenotype of each isolate was determined on eight differentials, and all isolates were tested for sensitivity to metalaxyl incorporated into V8 agar. The pathogen was recovered from 80 fields located in five counties. Sixteen pathotypes, which included 14 known races and two previously reported pathotypes that had not been assigned a race, were identified out of 157 isolates. A single pathotype was recovered from 61 fields, 2 pathotypes from 14 fields, 3 pathotypes from 4 fields, and 4 pathotypes from 1 field. Pathotypes with virulence phenotypes 1a,1c,7 (race 4; 39%) and 1a,7 (race 3; 28%) were the most common, representing 67% of the total isolates. One or both of these pathotypes was found in 79% of the fields where *P. sojae* was recovered. Seven of the 157 isolates showed limited growth on metalaxyl after 14 days of incubation. In the past 10 years, the number of pathotypes of *P. sojae* in North Dakota has increased from 4 to 16, and pathotypes have developed that can attack the three most common resistance genes found in soybean cultivars for the region.

Phytophthora root rot, caused by *Phytophthora sojae* M.J. Kaufm. & J.W. Gerd., is one of the most important soybean diseases in the United States, Canada, and other soybean producing countries (2,27,34–36,38). The disease is commonly associated with high soil moisture and can cause substantial losses (30,35,36). *P. sojae* is highly diverse with at least 55 races described (see Dorrance et al. (9) and Grau et al. (11) for complete references). In addition, new virulence types that have not been assigned a race number have been reported in recent studies (9,14,21,38). Although race is commonly used to designate virulent types of *P. sojae*, referring to virulent types as pathotypes and describing them by their virulence phenotype (i.e., the resistance genes defeated) is a convenient and meaningful method to present virulence (9,21).

Soybean (*Glycine max* (L.) Merr.) is the most important row and oilseed crop in North Dakota, with a value of \$702 million in 2006 (17). Due to crop diversification, low small grain prices, and devastating

Fusarium head blight epidemics on wheat and barley during the 1990s, many growers switched from the traditional small grain crops to row crops such as soybean, canola, corn, and sunflower. Soybean plantings have increased dramatically in the past 25 years from 95,105 ha in 1981 to 1,578,330 ha in 2006. Soybean production was primarily concentrated in a few southeastern counties along the Red River Valley during the 1980s, but production expanded to the west and north during the 1990s and now occurs throughout the eastern half of North Dakota.

Phytophthora root rot (22) is commonly found in the southeastern counties of Richland and Cass, where there is a longer history of soybean production, along with heavy clay soils that promote disease development during periods of flooding or heavy rainfall. Other root rots caused by *Fusarium solani* and *Rhizoctonia solani* (23,24) are also important in the area, but the main concern of growers has been Phytophthora root rot. Only recently was soybean cyst nematode discovered in southeastern North Dakota (3).

The first study to document the virulence diversity of *P. sojae* in North Dakota was conducted in the early 1990s in the southeastern counties bordering the Red River Valley (22). In that study, race 3 was the dominant pathotype and only three other pathotypes were identified. At that time, there were few soybean cultivars

with resistance genes effective against race 3, but they rapidly appeared on the market and were used by growers to control disease. Since the late 1990s, there have been increasing reports from growers on the occurrence of Phytophthora root rot on cultivars with resistance genes *Rps1c* and *1k*. These genes began to be deployed in soybean cultivars by the mid-1990s, when high summer rainfall during that period promoted disease development and increased concern about Phytophthora root rot. Growers in areas where disease is common also have been using metalaxyl as a seed treatment to protect young plants, especially if they have a history of disease in their fields or have observed disease on cultivars with *Rps* genes. Although no control failures have been reported in North Dakota, *Phytophthora* spp. are known to develop resistance to the fungicide (6). Because of these reports, the increase in soybean hectares, and the fact that virulence diversity of *P. sojae* in North Dakota had not been examined for about 10 years, this research was initiated. The objectives were to characterize the pathotype diversity of *P. sojae* in soybean fields in North Dakota, determine the distribution of the pathogen, and determine if there was resistance to metalaxyl in the population of *P. sojae*. A preliminary report of this work was published (26).

MATERIALS AND METHODS

Soil sampling and conditioning. Soil was collected from 347 soybean fields in 20 counties (Fig. 1) in the eastern half of North Dakota from July to September in 2002 to 2004. Beginning 30 m from the field edge, six 300 cm³ cores of soil were taken from the upper 15 cm of soil along a 50-m transect into the field. In Richland, Cass, and Traill counties, where there is a high proportion of agricultural land in soybean and a history of severe Phytophthora root rot, a systematic survey based on a grid pattern was conducted. This area was likely to have the greatest diversity of pathotypes. North-south and east-west county roads were followed, and fields were sampled at 5-mile intervals or until a field was located. Some areas in these counties have no soybean production, and those areas were avoided. In counties where there has been a more limited history of soybean production and few to no reports of Phytophthora root rot, the survey was less intensive. Major roads that

Corresponding author: B. D. Nelson
E-mail: berlin.nelson@ndsu.edu

Accepted for publication 28 February 2008.

doi:10.1094/PDIS-92-7-1062
© 2008 The American Phytopathological Society

traversed those counties in areas where soybean fields were known to occur were followed. Fields bordering those roads were also selected at 5-mile intervals. The geographic coordinate of each field was recorded using a portable global positioning system (GPS) receiver (Garmin Etrex Legend, Garmin Ltd., Cayman Islands). The coordinates were uploaded to geographic information system (GIS) software (ArcView, Environmental Systems Research Institute, Redlands, CA) to produce a map showing field locations.

Soil samples from individual fields were bulked, mixed, and a subsample was conditioned to enhance baiting of the pathogen by inducing oospore germination and sporangia formation (31). Soil was placed in 473-ml plastic cups and flooded for 1 h, drained, and then air-dried until the soil pulled away from the sides of the cup. Cups with soil were then placed in polyethylene bags to halt further drying and maintained at room temperature for 2 weeks.

Baiting and isolations. The cultivar McCall (19), highly susceptible to *P. sojae*, was used to bait the pathogen from the soil. Ten seeds per cup were planted in the conditioned soil, watered, and allowed to germinate for 4 days on a greenhouse bench. The cups were then placed in plastic tubs, the soil was flooded for 24 h, and then cups were returned to the greenhouse bench. Greenhouse temperatures ranged from 18 to 26°C, and plants were illuminated for 16 h/day with high-pressure sodium lamps (1,000 $\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Plants were monitored daily for 10 days for evidence of wilting or lesions on stems. Plants were then removed from the cups, and roots were examined for lesions. When no diseased plants developed after one planting, the test was repeated up to four times to bait the pathogen. In cases where no plants emerged from the soil, we attempted to isolate directly from decaying seeds; however, seeds decayed rapidly and success at isolating *P. sojae* was poor. Therefore, with such soils we baited the pathogen by germinating seeds in rag dolls (Anchor Paper, St. Paul, MN), and 5-day-old seedlings were transplanted into the soil, allowed to grow for 3 to 4 days, then the soil was flooded again, and plants were monitored for disease. This test was also repeated when no diseased plants were obtained in the first attempt. Experiments were conducted between October and March.

Diseased plant tissue was washed in tap water, surface-disinfested for 30 s in 0.05% NaOCl, and air-dried. Five to 10 mm long pieces were placed under 2 × 2 cm blocks of PBNIC selective medium (32) and incubated at 23°C in the dark. When mycelial growth appeared on the surface of the agar, a subculture was made to selective medium. Cultures were then hyphal tipped and transferred to V8 agar

(sucrose 0.1%, calcium carbonate 0.06%, yeast extract 0.02%, V8 juice 4%, agar 2%) and full-strength potato dextrose agar (PDA) (Difco, Becton Dickinson and Company, Franklin Lakes, NJ). Cultures growing on PDA were discarded since *P. sojae* does not grow on PDA (16). All other cultures were compared to a known culture of race 3 and examined for oospore and other characteristics (16) to verify that isolates were *P. sojae*.

Pathotype evaluation. Pathotypes of *P. sojae* were determined using the hypocotyl inoculation technique (12,31) to infect differential cultivars carrying the eight standard *Rps* genes that have been used to characterize virulence (8,13,32). The differential cultivars were: 'Harlon' (*Rps1a*), 'Harosoy 13XX' (*Rps1b*), L85-129 (*Rps1c*), 'Haro16' (*Rps1d*), 'Williams82' (*Rps1k*), PI 171442 (*Rps3a*), 'Harosoy 62XX' (*Rps6*), and 'Harosoy' (*Rps7*). The universal susceptible cultivar was either Williams or McCall (8,19).

Differentials were planted in 473-ml foam cups (six seeds per cup) in a soil mix of steam pasteurized sifted soil (Glyndon sandy loam), peat, and vermiculite (1:1:1 vol/vol/vol) and maintained in the greenhouse. Greenhouse temperatures and illumination were as previously stated. At 9 to 10 days following planting, 10 to 12 plants per differential were inoculated and placed in a growth room at 23 ± 2°C under fluorescent lights. Plants were misted with water and covered with plastic for 24 h. Plants were evaluated daily, and the numbers of living and dead plants were recorded within 7 to 10 days. Tests were repeated once with the exception of those isolates that killed 'Haro 16' plants carrying the *Rps1d* gene. In previous experience with the *Rps1d* gene, we had observed varying results between runs of the same experiment; thus for isolates that killed plants carrying *Rps1d*, we often repeated inoculations more than twice to verify results.

Pathotypes were designated by their virulence formula (*Rps* genes defeated by the isolate) (32). A differential was considered resistant if 80% or more of the inoculated plants survived. In the case of *Rps1d*, a susceptible interaction was designated only when 80% or more plants were killed to eliminate the possible false positives associated with an intermediate resistant reaction on the differential. Virulence formulas were compared with published formulas to determine race identification and if the virulence phenotype was reported elsewhere.

Metalaxyl resistance. All isolates of *P. sojae* were tested for sensitivity to metalaxyl (technical grade; Gustafson Inc., Plano, TX) at a concentration of 5 $\mu\text{g}/\text{ml}$ V8 agar. Metalaxyl was prepared in a stock solution in distilled water, filter sterilized, then added to the V8 agar after it was autoclaved. Isolates were grown on regular V8 medium at 23°C for 4 to 5 days, and then a 4-mm mycelium + agar plug was transferred onto the amended V8 agar in 60 × 15 mm petri plates containing 12 ml of medium. Controls were grown simultaneously on regular V8 agar. Cultures were incubated at 23°C in the dark. There were three replicates (one plate per replicate), and the test was repeated. Three measurements on different areas of the agar plug were taken, and the mean radial growth in millimeters was recorded at 7 and 14 days of incubation.

RESULTS AND DISCUSSION

P. sojae was recovered from 80 of 347 fields, and 157 isolates were obtained. These 80 fields were located in five counties (Richland, Cass, Traill, Grand Forks, and Steele) of the 20 counties sampled (Fig. 1). Sixteen pathotypes were identified (Table 1), which included 14 known races and two previously reported pathotypes that had not been assigned a race number (1,13–15,37). A single pathotype was recovered from 61 fields, two patho-

Fig. 1. Distribution of *Phytophthora sojae* in eastern North Dakota. Circles represent soybean fields sampled, and black circles indicate fields where the pathogen was detected. Names are the 20 counties sampled. Not all 347 fields are indicated by a circle on the map because some circles overlap.

types from 14 fields, three pathotypes from four fields, and four pathotypes from one field. Pathotypes with virulence phenotypes 1a,1c,7 (race 4; 39%) and 1a,7 (race 3; 28%) were the most common, comprising 67% of the total isolates. Races three and four were recovered from 29 and 34 fields, respectively, and four of those fields yielded both races. These two races, therefore, were found in 79% of the fields where *P. sojae* was recovered.

The number of pathotypes increased since the last collection of *P. sojae* conducted between 1991 to 1994 (22). At that time, race 3 was the dominant pathotype at 83% of the isolates; race 4 was only 6% of the isolates; and the only other pathotypes identified were races 1 (6%; virulence phenotype 7) and 9 (5%; virulence phenotype 1a,6,7). Race 9 was not detected in the current study. In only 10 years, therefore, there has been a substantial increase in the diversity of the pathotypes of *P. sojae* in North Dakota, from 4 to 16 pathotypes, and a shift in the dominant race from race 3 to race 4.

Although infested fields are still primarily located in the southeastern portion of North Dakota in counties that include the Red River Valley, the infested area has expanded toward the north into Traill and Grand Forks counties, where disease was rarely detected in the early 1990s. The 20 counties sampled in this study accounted for 91% of the soybean production area in North Dakota in 2006. We sampled more soybean fields in three southeastern counties compared with the other counties because that area had the longest history of soybean production and fields with severe disease. Phytophthora root rot was originally found in North Dakota in Cass and Richland counties, and the disease is common there. Cass and Richland counties have some of the highest percentages of

tillable acres in soybean in the United States. In 1981, they had 67,990 ha of soybean, 71% of the state's production area, while in 2006 there were 350,066 ha, which was 22% of the state's soybean hectares (17). Sixty-nine of the 80 fields where the pathogen was detected were in those counties, and *P. sojae* was detected in 40% of the 171 fields sampled. Parts of the counties bordering Minnesota are in the Red River Valley, which is about 30 miles wide on the North Dakota side of the Red River. This area has predominantly heavy clay soils such as the Hegne and Fargo soils that become flooded following heavy rains or when the Red River overflows, favoring disease development.

With the exception of Richland, Cass, and Traill counties, in the other 17 counties where 133 fields were sampled, *P. sojae* was detected in only two fields (Fig. 1). Counties to the west of the Red River Valley have a shorter history of soybean production, have few hectares of the heavy clay soils characteristic of the Red River Valley, and Phytophthora root rot is rarely or never observed in those areas. The results of this study indicate the pathogen is not yet common west of the Red River Valley counties. Based on the data from this study, we estimate that approximately 10.5% of the 1.6 million ha of soybean in North Dakota in 2006 was infested with *P. sojae*.

The virulence diversity of *P. sojae* in North Dakota is not as great as in other states, such as Illinois, Indiana, Michigan, and Ohio, with longer histories of soybean production (1,9,15,21), but the number of pathotypes is similar in the nearby states of Minnesota, Iowa, and Nebraska (18,29,37). Only one pathotype was recovered from 76% of the fields where *P. sojae* was detected, whereas multiple pathotypes are commonly found in fields in Ohio (9).

Races 3 and 4, the two most commonly detected pathotypes in this study, were also reported as common pathotypes in other states, Canada and Australia (1,2,20,21,27,32,37). In contrast, Jackson et al. (14) reported that races 10, 24, and 15 were the most common in Arkansas, but those races were not detected in North Dakota. One unusual result of this study was the detection of only one race 1 isolate. In many recent studies, race 1 has been common (1,2,9,21,27,37). The virulence diversity of the isolates collected in this study would likely have been greater if they were tested on all 13 known differentials. Dorrance et al. (9) found 72 pathotypes when testing with 8 differentials, but 202 different pathotypes when the data were from 13 differentials.

As pointed out by Dorrance et al. (9), the nomenclature used to characterize the diversity of virulence phenotypes is a continuing problem. They evaluated pathotypes in Ohio and presented the virulence data using an octal nomenclature based on the reaction of isolates on 13 resistance genes (*Rps* genes) with the resistance genes divided into five sets, one for each digit of the nomenclature. Many studies on virulence of *P. sojae* in the United States, however, have used only eight genes (1,2,14,18,21,29,32). Thus, the data cannot be directly adapted to the octal system of nomenclature since the five resistance sets as proposed by Dorrance et al. (9) cannot be completed with such data. As more researchers use the 13 resistance genes to characterize virulence, and the known virulence diversity of *P. sojae* expands along with the discovery of new resistance genes, the octal system may become a more useful and necessary tool.

The increase in the diversity of pathotypes in North Dakota over time is similar to what has occurred in other soybean production areas where *P. sojae* is prevalent (9,21,27,32,37). This pathogen has been shown to be highly diverse in virulence and to adapt to changing deployment of *Rps* genes. In North Dakota, several factors have likely been strong forces in the diversity change over the past 10 years. One was the increase in summer rainfall during the 1990s, which promoted soil conditions favorable for disease development and subsequent high levels of inoculum in infested fields. The June through August rainfall was 20% higher during the 1990s as compared to the 1980s (National Climatic Data Center, U.S. Department of Commerce. <http://www.ncdc.noaa.gov/oa/ncdc.html>). Another is the deployment of resistance genes, especially *Rps1c* and *1k*, during the 1990s, which likely put selection pressure on the pathogen to adapt to cultivars using those genes. Prior to the 1990s, most soybean cultivars in early-maturing groups had no *Rps* gene, or a few had *Rps1a*, and most growers in North Dakota did not consider Phytophthora root

Table 1. Pathotypes of *Phytophthora sojae* baited from soybean field soils collected in North Dakota between 2002 and 2004

Virulence phenotype ^a	Race ^b	No. of isolates ^c	No. of fields ^d
7	1	1	1
1a, 7	3	44	29
1a, 3a, 7	21	1	1
1a, 1c, 7	4	61	34
1a, 1d, 7	44	8	6
1a, 1k, 7	34	2	2
1a, 1b, 1k, 7	28	8	8
1a, 1c, 6, 7	5	2	2
1a, 1c, 1d, 7	43	15	12
1a, 1c, 1k, 7	F	1	1
1a, 1d, 6, 7	8	2	2
1a, 1d, 1k, 7	—	1	1
1a, 1b, 1c, 1k, 7	25	7	2
1a, 1b, 1d, 1k, 7	41	1	1
1a, 1c, 1d, 6, 7	—	2	1
1a, 1c, 1d, 1k, 7	40	1	1

^a Virulence phenotype is the list of resistance (*Rps*) genes defeated by the pathotype and is based on the following differentials: 'Harlon' (*Rps1a*), 'Harosoy 13XX' (*Rps1b*), L85-129 (*Rps1c*), 'Haro16' (*Rps1d*), 'Williams82' (*Rps1k*), PI 171442 (*Rps3a*), 'Harosoy 62XX' (*Rps6*), and 'Harosoy' (*Rps7*).

^b Races as reported by Dorrance et al. (9) and Grau et al. (11).

^c A total of 157 isolates were evaluated.

^d Number of fields where pathotype was detected.

rot a major threat. A third factor is short rotations between soybean crops and frequent annual cropping of soybeans with *Rps* genes in the same fields, which has aided the buildup of inoculum. The popularity of soybean does not appear to be diminishing, and if soybean grain prices remain competitive with other crops, the cropping of soybean will remain high and Phytophthora root rot will increase in importance and may spread to other counties.

In North Dakota, the most common *Rps* genes deployed in soybean cultivars are *Rps1c*, 1k, or 6. *Rps1a* is still found in a few cultivars, but it has no value in disease control. *Rps1c* is of limited value since 57% of the isolates collected in this study can attack that gene (Fig. 2) and those isolates were identified in 53 of the 80 fields where the pathogen was detected. A major concern is the number of pathotypes (12% of total) (Table 1; Fig. 2) that can attack the *Rps1k* gene, which is the most commonly used resistance gene in commercial cultivars for this region. These pathotypes were recovered from 14 of the 80 fields (17%). We have observed Phytophthora root rot on cultivars using the *Rps1k* gene in numerous fields, and growers have expressed concern about this disease when using these cultivars. The development of these pathotypes over the past 15 years explains why Phytophthora root rot is now occurring on cultivars with the *Rps1k* gene. Although the damage due to these pathotypes has not been widespread or severe in our area, it does indicate a growing problem for cultivars with the *Rps1k* gene. *Rps6*, which is not as widely used as *Rps1k*, appears to be a very

useful gene for this area. Isolates able to cause disease on plants with this gene represented 4% of the isolate population, and were found in only five fields (Fig. 2). Phytophthora root rot problems have not been observed or reported on cultivars with this gene. No pathotypes were recovered that can defeat both *Rps1k* and 6. Genes such as *Rps3a* or 1b would also appear to be useful for this area (Fig. 2). Other *Rps* genes, such as *Rps8* (5), could be tested in this region.

Single gene resistance is still an effective control measure for Phytophthora root rot in North Dakota if growers know which pathotypes are present in their fields. Growers must be vigilant and watch for changes in the occurrence of disease to know when changing *Rps* genes is needed. The increasing diversity of pathotypes indicates future problems with *Rps* genes and suggests that other control measures such as gene pyramiding, broader use of partial resistance, and tiling for better drainage may be required in the future.

Growth of the *P. sojae* isolates was tested on metalaxyl-amended medium to determine if there was reduced sensitivity to this fungicide in the population. Of the 157 isolates of *P. sojae*, 150 did not grow on metalaxyl-amended medium after 14 days of incubation. Seven isolates, however, showed a small amount of growth. The isolates and the mean radial growth (averaged over two experiments) were the following: 02-56-2 (race 43), 2 mm; 02-72-3 (race 43), 1.5 mm; 03-38-1 (race 25), 11 mm; 03-38-2 (race 25), 9 mm; 03-47-4 (race 3), 11 mm; 03-47-6 (race 3), 10 mm; and 03-55-2 (race 5), 12 mm. The two

isolates of race 43 grew only in the second, but not in the first experiment. The very limited growth of these seven isolates did not begin until 10 days following incubation, and no oospores were formed in the cultures by 14 days. In preliminary experiments, we determined that metalaxyl was still active and not degraded in the V8 30 days after the medium was prepared. Cultures on unamended medium grew to the edge of the petri plate within 5 days. This restricted growth does not appear to be evidence of reduced sensitivity to metalaxyl as observed in other oomycetes (4,10,28,33) where growth of insensitive isolates can be measured in 2 to 7 days. Whether this unusual restricted growth on metalaxyl has any biological implications for disease control remains to be determined. The small amount of growth in those seven cultures would not appear to suggest there are isolates that could overcome metalaxyl seed treatments and attack young plants. These isolates are undergoing further investigation (25) to determine the nature of this ability to grow in the presence of the fungicide and what implications this has for biological activity of the pathogen. Dorrance et al. (7) and Malvick and Grunden (21) reported no evidence of reduced sensitivity to metalaxyl in populations of *P. sojae* in Ohio and Illinois, and there have been no reports in North Dakota of failure of metalaxyl to control this disease on seedlings.

In summary, the diversity of pathotypes of *P. sojae* in North Dakota has increased in the past 10 years, and pathotypes that can defeat the prevalent resistance genes are found in the population. Of the 16

Fig. 2. Percentage of 157 isolates of *Phytophthora sojae* that defeat each of the eight resistance genes (*Rps1a*, 1b, 1c, 1d, 1k, 3a, 6, 7) used to characterize virulence of the pathogen.

pathotypes detected, races 3 and 4 were the most frequently baited from soil. The pathogen is most common in three south-eastern counties bordering the Red River Valley, while counties to the west appear to have few infested fields. Diversity of virulence within fields appears low at the present time; thus judicious use of *Rps* genes is still a sound management technique. Cropping patterns, weather, and the potential for increased virulence diversity in *P. sojae* suggest this disease will increase in the future and additional controls will be necessary.

ACKNOWLEDGMENTS

We thank A. E. Dorrance and T. R. Anderson for supplying seed of differentials and helpful suggestions on this research. Funding was provided by the North Dakota Soybean Council and the North Central Soybean Research Program.

LITERATURE CITED

- Abney, T. S., Melgar, J. C., Richards, T. L., Scott, D. H., Grogan, J., and Young, J. 1997. New races of *Phytophthora sojae* with *Rps1-d* virulence. Plant Dis. 81:653-655.
- Anderson, T. R., and Buzzell, R. I. 1992. Diversity and frequency of *Phytophthora megasperma* f. sp. *glycinea* in soybean fields in Essex County, Ontario, 1980-1989. Plant Dis. 76:587-589.
- Bradley, C. A., Biller, C. R., and Nelson, B. D. 2004. First report of soybean cyst nematode (*Heterodera glycines*) on soybean in North Dakota. Plant Dis. 88:1287.
- Brantner, J. R., and Windels, C. E. 1998. Variability in sensitivity to metalaxyl in vitro, pathogenicity, and control of *Pythium* spp. on sugar beet. Plant Dis. 82:896-899.
- Burnham, K. D., Dorrance, A. E., Francis, D. M., Fioritto, R. J., and St. Martin, S. K. 2003. *Rps8*, a new locus in soybean for resistance to *Phytophthora sojae*. Crop Sci. 43:101-105.
- Cohen, Y., and Coffey, M. D. 1986. Systemic fungicides and the control of Oomycetes. Annu. Rev. Phytopathol. 24:311-338.
- Dorrance, A. E., Bowen, P., and Lipps, P. E. 2004. Characterization of *Pythium* spp. from three Ohio fields for pathogenicity on corn and soybean and metalaxyl sensitivity. Online. Plant Health Progress doi:10.1094/PHP-2004-0202-01-RS.
- Dorrance, A. E., Jia, H., and Abney, T. S. 2004. Evaluation of soybean differentials for their interaction with *Phytophthora sojae*. Online. Plant Health Progress doi:10.1094/PHP-2004-0309-01-RS.
- Dorrance, A. E., McClure, S. A., and deSilva, A. 2003. Pathogenic diversity of *Phytophthora sojae* in Ohio Soybean Fields. Plant Dis. 87:139-146.
- Goodwin, S. B., and McGrath, M. T. 1995. Insensitivity to metalaxyl among isolates of *Phytophthora erythrospectica* causing pink rot of potato in New York. Plant Dis. 79:967.
- Grau, C. R., Dorrance, A. E., Bond, J., and Russin, J. S. 2004. Fungal Diseases. Pages 679-763 in: Soybeans: Improvement, Production and Uses. 3rd ed. Agronomy Monogr. no. 16. H. R. Boerma and J. E. Specht, eds.
- Haas, J. H., and Buzzell, R. I. 1976. New races 5 and 6 of *Phytophthora megasperma* var. *sojae* and differential reactions of soybean cultivars for races 1 to 6. Phytopathology 66:1361-1362.
- Hartman, G. L., Sinclair, J. B., and Rupe, J. C., eds. 1999. Compendium of Soybean Diseases. 4th ed. American Phytopathological Society, St. Paul, MN.
- Jackson, T. A., Kirkpatrick, T. L., and Rupe, J. C. 2004. Races of *Phytophthora sojae* in Arkansas soybean fields and their effects on commonly grown soybean cultivars. Plant Dis. 88:345-351.
- Kaitany, R. C., Hart, L. P., and Safir, G. R. 2001. Virulence composition of *Phytophthora sojae* in Michigan. Plant Dis. 85:1103-1106.
- Kauffmann, M. J., and Gerdemann, J. W. 1958. Root and stem rot of soybean caused by *Phytophthora sojae* n. sp. Phytopathology 48:201-208.
- Knopf, D., Kimmel, G., and Bilden, J., eds. 2007. North Dakota Agricultural Statistics. National Agricultural Statistics Service, North Dakota State University, Fargo.
- Kurle, J. E., and El Araby, E. M. 2001. Changing composition of *Phytophthora sojae* races in Minnesota soils. (Abstr.) Phytopathology 91:S51.
- Lambert, J. W., and Kennedy, B. S. 1979. Registration of McCall soybean. Crop Sci. 19:297.
- Leitz, R. A., Hartman, G. L., Pedersen, W. L., and Nickell, C. D. 2000. Races of *Phytophthora sojae* on soybean in Illinois. Plant Dis. 84:487.
- Malvick, D. K., and Grunden, E. 2004. Traits of soybean-infecting *Phytophthora* populations from Illinois agricultural fields. Plant Dis. 88:1139-1145.
- Nelson, B. D., Hansen, J. M., and Windels, C. E. 1996. Races of *Phytophthora sojae* on soybean in the Red River Valley of Minnesota and North Dakota. Plant Dis. 80:104.
- Nelson, B. D., Hansen, J. M., Windels, C. E., and Helms, T. C. 1997. Reaction of soybean cultivars to isolates of *Fusarium solani* from the Red River Valley. Plant Dis. 81:664-668.
- Nelson, B., Helms, T., Christianson, T., and Kural, I. 1996. Characterization and pathogenicity of *Rhizoctonia* from soybean. Plant Dis. 80:74-80.
- Nelson, B., and Mallik, I. 2006. Growth of *Phytophthora sojae* on media amended with metalaxyl and mefenoxam. (Abstr.) Phytopathology 96:S174.
- Nelson, B. D., Mallik, I., McEwen, D., and Christianson, T. 2005. Pathotypes and metalaxyl sensitivity of *Phytophthora sojae* from North Dakota soybean fields. (Abstr.) Phytopathology 95:S74.
- Ryley, M. J., Obst, N. R., Irwin, J. A. G., and Drenth, A. 1998. Changes in the racial composition of *Phytophthora sojae* in Australia between 1979 and 1996. Plant Dis. 82:1048-1054.
- Sanders, P. L. 1984. Failure of metalaxyl to control Pythium blight on turfgrass in Pennsylvania. Plant Dis. 68:776-777.
- Schimelfenig, J., Giesler, L., and Ziem, A. 2005. Diversity of *Phytophthora sojae* pathotypes in Nebraska soybean fields from 2000 to 2004. (Abstr.) Phytopathology 95:S93.
- Schmitthenner, A. F. 1985. Problems and progress in control of *Phytophthora* root rot of soybean. Plant Dis. 69:362-368.
- Schmitthenner, A. F., and Bhat, R. G. 1994. Useful methods for studying *Phytophthora* in the laboratory. Ohio Agric. Res. Devel. Center, Spec. Circ. 143.
- Schmitthenner, A. F., Hobe, M., and Bhat, R. G. 1994. *Phytophthora sojae* races in Ohio over a 10 year interval. Plant Dis. 78:269-276.
- Shew, H. D. 1985. Response of *Phytophthora parasitica* var. *nicotianae* to metalaxyl exposure. Plant Dis. 69:559-562.
- Sugimoto, T., Yoshida, S., Aino, M., Watanabe, K., Shiwa, K., and Sugimoto, M. 2006. Race distribution of *Phytophthora* on soybean in Hyogo, Japan. J. Gen. Plant Pathol. 72:92-97.
- Wrather, J. A., Anderson, T. R., Arsyad, D. M., Tan, Y., Ploper, L. D., Porta-Puglia, A., Ram, H. H., and Yorinori, J. T. 2001. Soybean disease loss estimates for the top ten soybean-producing countries in 1998. Can. J. Plant Pathol. 23:115-121.
- Wrather, J. A., Stienstra, W. C., and Koenning, S. R. 2001. Soybean disease loss estimates for the United States from 1996 to 1998. Can. J. Plant Pathol. 23:122-131.
- Yang, X. B., Ruff, R. L., Meng, X. Q., and Workneh, F. 1996. Races of *Phytophthora sojae* in Iowa soybean fields. Plant Dis. 80:1418-1420.
- Zhen-dong, Z., Hua-bo, W., Xiao-ming, W., Ru-zhen, C., and Xiao-fei, W. 2004. Distribution and virulence diversity of *Phytophthora sojae* in China. Agric. Sci. China 3:116-123.