Effects of Chloride and Ammonium Salts on the Incidence of Phytophthora Root and Stem Rot of Soybean

C. H. Canaday and A. F. Schmitthenner, Department of Plant Pathology, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster 44691

ABSTRACT

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In growth chamber experiments using field soil naturally infested with *Phytophthora sojae*, addition of KCl at 150 to 400 μg of K per gram of dry soil increased the incidence of *Phytophthora* root and stem rot on susceptible soybean (*Glycine max*) compared with a distilled water control. Other potassium salts at 150 to 400 μg of K, phosphorus salts at 20 to 317 μg of P, and sulfate salts of K, Ca, Mg, Na, and Al at 491 μg of SO_4 per gram of soil did not affect disease incidence. Application of chloride salts of K, Na, Mg, Ca, NH_4 , Al, Fe, and Sr at 250 μg of Cl per gram of soil all increased disease incidence compared with the distilled water control. Addition of other ammonium salts also increased disease incidence. Disease incidence increased when KCl at 300 μg of K per gram soil was applied to naturally infested Blount silt loam but not to naturally infested Hoytville silty clay. The effects of chloride salts on plant growth and on natural inoculum of *P. sojae* were investigated. At 450 μg Cl/g of soil, addition of NaCl increased plant fresh weight but had no effect on germination, emergence, transpiration, height, and dry weight of plants grown in pasteurized, pathogen-free soil. When soybean plants were grown without a deplasmolytic shock and without promoting zoospore release by saturating the soil, the addition of chloride salts at 304 μg of Cl per gram of soil increased disease. In a leaf-disc-baiting bioassay, leaf infection by *P. sojae* zoospores decreased when 0.01 or 0.02 M KCl was added to soil extracts from flooded soil but was unaffected by KCl at 150 to 600 μg of K per gram of soil applied to the soil 5 days before baiting. Energy-dispersive X-ray analysis of tap-roots of 5-day-old soybean plants indicated a reduction in the calcium content of the outer cell layers with KCl at 400 μg of K per gram of soil but not with K_2SO_4 . Disease increases with addition of KCl appear to be due to the presence of chloride and may be associated with changes in the micropartitioning of root calcium.

Phytophthora root and stem rot is one of the most important diseases of soybean *Glycine max* (L.) Merr. in Ohio. The causal pathogen, *Phytophthora sojae* Kaufm. & Gerd., attacks soybean at all stages of growth, causing pre- and post-emergence damping-off, root and stem rot, stunting, wilting, and death of older plants (22,39). It is particularly a problem in northwest Ohio, where many of the soils are lacustrine, fine textured, and poorly drained. Soil saturation, a common occurrence after

heavy rains, promotes zoospore release (28) and subsequent disease. An integrated control program combining improved surface and subsurface drainage with resistant or tolerant sensu Mussell (29) soybean cultivars plus a fungicide seed treatment are currently used to minimize losses to this disease (16,34,36,37). One component of an integrated disease control program that needed study was the effect of fertilization of Ohio soils on disease. Soybean plants require substantial amounts of potassium and phosphorous fertilization for maximum yield. Some soils, especially high clay soils in Ohio, require higher potassium levels to support optimum crop growth (46). Fertilizers can increase, decrease, or have no effect on diseases caused by *Phytophthora* spp. (35). Nitrogen fertilization has been reported to increase *Phytophthora* root and stem rot of soybean (11). Ammonium ions were implicated in the observed disease enhancement. Dirks et al. (15) observed increased disease severity using a complete fertilizer and suggested that the increase was due to the nitrogen component. Pacumbaba et al. (30) reported that muriate of potash increased the incidence of *Phytophthora* rot of soybean in a northern Alabama soil whereas a complete fertilizer reduced dis-

ease. Potassium chloride has been associated with increases in the incidence of other seedling diseases of soybean and snap bean (8–10). The following experiments were initiated to evaluate the potential effects of potassium and phosphorus fertilizer salts on *Phytophthora* root and stem rot of soybean using Ohio soils naturally infested with *P. sojae*. Other salts were included in subsequent studies to ascertain the probable reason for effects observed with potassium chloride. A preliminary report has been published (14).

MATERIALS AND METHODS

Soils and their analyses. Soil naturally infested with *P. sojae* was used in all experiments. Over 1,400 kg of moist Fulton silty clay (fine, illitic, mesic Aeric Ochraqualf) collected from the North Central Branch of the Ohio Agricultural Research and Development Center (OARDC) near Vickery, OH, was used for most experiments. Small quantities (90 kg of moist soil) of a naturally infested Hoytville silty clay (fine, illitic, mesic, Mollic Ochraqualf) from the Northwestern Branch of OARDC near Hoytville, OH, and of a naturally infested Blount silt loam (fine, illitic, mesic, Aeric Ochraqualf) from a farm near Van Wert, OH, were collected and used to compare results obtained with the Fulton silty clay. The three soils were representative of those typically found in northern and northwest Ohio, where *Phytophthora* root and stem rot is particularly a problem.

Soils were stored at the moisture content at which they were collected (19.1 to 28.6% H_2O by weight) in sealed polyethylene bags at 5°C for 4 to 14 months before use. Representative subsamples were used to develop wetting and drying moisture-characteristic curves using Buchner funnel tensiometers and ceramic pressure plates (21,33). The curves were used to estimate soil water matric potential (ψ_m) in experiments based on the average soil moisture content of the soil in experimental units. Two representative subsamples of each soil were sent to the Research-Extension Analytical Laboratory, OARDC, Wooster, for analysis of soil pH; cation exchange capacity; available P; and exchangeable K, Ca, and Mg by standard methods. Samples were also sent to G. Taylor and M. Ransom, Department of Agronomy, The Ohio State University, for soil particle analysis by standard methods.

Corresponding author: C. H. Canaday
E-mail: ccanaday@utk.edu

Current address of C. H. Canaday: Department of Entomology and Plant Pathology, The University of Tennessee, West Tennessee Research and Education Center, Jackson 38301.

Portion of Ph.D. dissertation of C. H. Canaday.

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A modified quantitative bioassay that uses leaf-disc baits (13) was used to determine the best soil incubation temperature to maximize zoospore release. Two samples of the Fulton silty clay were packed into 600-ml beakers at a bulk density of 1.15 g/cm³. Sufficient glass-distilled water (DW) was then added to each beaker to bring the soil moisture up to a ψ_m of -20 to -45 kPa before placing the beakers in polyethylene bags. Bagged beakers were incubated in the dark at 15, 20, 25, or 30°C. Five 10-g subsamples of moist soil were removed every fourth day from each beaker, placed in 50-ml beakers, flooded with 20 ml of DW at 20°C, and baited with 21 leaf-disc baits freshly punched with a handheld paper punch from the unifoliolate leaves of 12- to 14-day-old Amsoy soybean. Debris was removed from the water surface with a piece of tissue paper before adding the leaf discs. Baits were placed with the upper leaf surface in contact with the water, removed after 2.5 h, and plated on clarified V8 juice agar supplemented with yeast extract, sucrose, cholesterol, pentachloronitrobenzene, benomyl, neomycin sulfate, rifampicin, and hymexazol (VYS/PBNRH) (12). The forceps used to transfer the baits to the selective medium were flamed and cooled between each leaf disc.

General design and experimental units. Cardboard milk cartons (1.9-liter) were used as potting containers in growth-chamber experiments and were the experimental units for treatment applications. Tops were cut off to create 9.7-by-9.7-by-13-cm containers without drainage holes. Collected Fulton silty clay was removed from 5°C storage, passed through a 1.2-cm mesh screen, and thoroughly mixed. Aliquots of soil (595 g dry wt) were packed into cartons at a bulk density of 1.15 g/cm³ to a depth of 5.5 cm. Sufficient DW was then added to each carton to bring the soil moisture up to a ψ_m of -20 to -45 kPa before placing the cartons in sealed polyethylene bags. Bagged cartons were incubated in the dark at 22 to 25°C for 9 to 20 days before removing them, planting soybean seed, and adding treatments.

Randomized complete block designs were used in all tests. To increase the sensitivity of detection of treatment effects, the susceptible soybean cv. Sloan with little tolerance or partial resistance to *Phytophthora* root and stem rot was used for all experiments (17). Twelve seeds treated with captan (Orthocide 75; Chevron Chemical Co., Ortho Division, San Francisco) at 0.8 g a.i./kg of seed were placed on the surface of the soil in each carton. Seed were covered with an aliquot of soil (150 g) and the topsoil packed by dropping a 9-by-9-by-32-cm board (1.1 kg) onto the soil from a height of 5 cm. Test salts were then added in 25 ml of DW to the surface of the topsoil. Controls in all experiments received DW only. Analytical-grade re-

agents were used in all experiments except when urea was used. The latter was applied as a commercial fertilizer (45-0-0) in two of the tests. Sufficient additional DW was then added to each carton to bring the soil moisture up to a ψ_m of -3 kPa. Cartons were then sealed in polyethylene bags to prevent drying of the soil and placed in a 24 to 25°C growth chamber with a 14-h photoperiod of 340 $\mu\text{E}/\text{m}^2 \text{ s}^{-1}$ from fluorescent + incandescent lighting.

Four days after planting, cartons were removed from the bags. The soil was then saturated with DW to 0.5 cm above the surface of the soil to permit zoospore release (28). Once evapotranspiration had removed excess free water, cartons were watered regularly by weight to equalize the soil moisture of all cartons. Seed germination was recorded as the percentage of seed observed to emerge or partially emerge during an experiment. Soil moisture was gradually reduced by watering cartons to a lower weight each day until a ψ_m of approximately -700 kPa was reached. Cartons were then watered daily to a soil moisture of approximately -5 kPa ψ_m until the end of experiments 15 to 22 days after planting, when further post-emergence damping-off appeared to be ceasing. Diseased seedlings were collected during experiments, surface disinfected in 1% sodium hypochlorite for 10 to 30 s, and plated on VYS/PBNRH medium. At the end of experiments, the mean height from soil surface to growing point of the remaining plants was recorded to the nearest whole centimeter. Plant hypocotyls were then split and examined for internal necrosis. Disease incidence was recorded as [(plants killed + plants with internal hypocotyl necrosis)/seed germination] $\times$ 100%. Arcsine-transformed percentages were used in analysis of variance using PC SAS (version 9.1; SAS Institute, Cary, NC). Original percentages are used in tables but letters following means are based on mean separation tests of arcsine-transformed data.

Effects of K, P, SO₄, Cl, and NH₄ salts on disease incidence and plant height.

Using the above procedures, a series of growth chamber experiments was conducted to evaluate the effects of potassium, phosphorus, sulfate, chloride, and ammonium salts on the incidence of *Phytophthora* root and stem rot and on plant height. Treatments were replicated six times in the first four tests. All these tests included the DW control. The initial test included KCl and K₂SO₄ at 150 and 200 μg of K, KNO₂ at 100 μg of K, KNO₃ at 200 μg of K, Ca(H₂PO₄)₂ at 20 and 40 μg of P, and K₂HPO₄ at 40 μg of P per gram of soil. Disease incidence and plant heights were recorded after 15 days.

In a second test, higher rates of potassium, chloride, and sulfate salts included KCl, K₂SO₄, KH₂PO₄, K₂HPO₄, and KHCO₃ at 400 μg of K per gram of soil.

The KCl was applied both with and without metalaxyl. Metalaxyl (Ridomil 2E; Ciba-Geigy Ltd. Greensboro, NC) was applied at 5 μg a.i./g of soil in the KCl treatment solution to confirm that disease losses were due solely to fungal pathogens in the order Peronosporales (38). Chloride salts of Na and Mg at 363 μg of Cl; CaSO₄ at 491 and 982 μg of SO₄; and sulfate salts of Na, Mg, and Al at 491 μg of SO₄ per gram of soil were included in the test to examine further the effects of SO₄ and Cl salts on disease incidence and plant height. Disease incidence and plants heights were recorded after 18 days.

The third test looked at the effects of six potassium salts with K at 300 $\mu\text{g}/\text{g}$ of soil: KCl, K₂SO₄, KNO₃, K₂HPO₄, KH₂PO₄, and KHCO₃. A fourth test looked at the effects of nine chloride salts with Cl at 250 $\mu\text{g}/\text{g}$ of soil: KCl, NaCl, MgCl₂, CaCl₂, NH₄Cl, AlCl₃, FeCl₂, FeCl₃, and SrCl₂. Disease incidence and plant heights were recorded after 22 days. The electrical conductivity of the soil solution in cartons was determined after the end of the third and fourth experiments on three randomly selected replicates or treatment by resaturating the soil cartons with DW, pouring off the excess free water after 24 h, and measuring the conductivities of the clear, filtered extracts using a solu bridge (model SD-B15; Beckman Instruments Inc., Cedar Grove, NJ).

Additional tests were conducted to further verify the nature of disease incidence increases that had been observed with chloride and ammonium salts. NH₄NO₃, NaCl, NaNO₃, NH₄Cl, and urea with Cl at 304 $\mu\text{g}/\text{g}$ of soil or N at 120 $\mu\text{g}/\text{g}$ of soil were evaluated for 20 days for their effects on disease incidence and plant height. Urea was evaluated both with and without a pyroxyfur seed treatment (Grandstand; Dow Chemical Co., Midland, MI). The pyroxyfur was included to determine whether or not the seed treatment could minimize disease losses to *P. sojae* (36). Treatments were replicated eight times. The same salts were tested in another experiment in which pyroxyfur seed treatment was not included. In this test, disease incidence was assessed in the absence of moisture stress or a deplasmolytic shock by never saturating the soil to induce zoospore release. After planting and adding sufficient additional water to bring the soil moisture up to a ψ_m of -5 kPa, each soil carton was sealed in its own polyethylene bag and returned to the growth chamber. The soybean plants were grown for 11 days in the bags and disease incidence then recorded. Treatments were replicated eight times.

The effects of KCl, K₂SO₄, CO(NH₂)₂, (NH₄)₂SO₄, NH₄Cl, Ca(NO₃)₂, NaNO₃, and KCl + Ca(NO₃)₂ at 300 μg of K, 272 μg of Cl, or 108 μg of N per gram of soil also were evaluated in the Hoytville silty clay and the Blount silt loam. Disease

incidence and plant heights were recorded after 18 days. Treatments were replicated six times.

Finally, the effect of a chloride salt on plant growth in the absence of disease was assessed by growing Sloan soybean in cartons of pasteurized Fulton silty clay with and without NaCl with Cl at 450 µg/g of soil. Soil was pasteurized prior to planting by heating the soil cartons in sealed polyethylene bags in a water bath for 10 h at 50 to 55°C. This eliminated any detectable inoculum of *P. sojae* using the leaf-disc bioassay (13). Treatments were replicated six times. Seedling emergence was recorded as the number of seedlings 4 days after planting with cotyledons above the soil surface and germination as the number of seedlings visible 9 days after planting. Evapotranspiration was determined by the change in weight of the cartons over a 37-h period 20 to 21 days after planting. Plants were excised below the cotyledonary node on the 21st day, weighed, and dried for 48 h at 45°C.

Effects of K salts on nutrient levels in soybean seedlings. The effect of potassium salts on nutrient levels in soybean root tissues was determined with energy-dispersive X-ray (EDX) analysis. Sloan soybean plants were grown in cartons of pasteurized Fulton silty clay with KCl or K₂SO₄ at 400 µg of K per gram of soil. The control had only DW. Plants were grown for 5 days without soil saturation, then collected for EDX analysis. A portion of the taproot of each collected seedling was wiped clean of adhering soil with cotton swabs dampened with DW. Segments, 1 cm long, were cut from these portions and immediately oven dried at 45°C. Intact taproot segments were mounted horizontally on carbon plachettes with silver paint for EDX analysis. Analyses were conducted using an International Scientific Instruments scanning electron microscope, model ISI-40, interfaced with an EDX 9100 X-ray analyzer. The scanning electron microscope was operated at an accelerating voltage of 30 kV with a 23-mm working distance and 45° tilt. Elemental analyses at a magnification of ×500 were conducted at a counting rate of 3,050 ± 150 counts/s until total counts exceeded three times full scale. Analyses of Mg, P, S, Cl, K, and Ca were made along lines

perpendicular or oblique to the axis of the specimens. Treatments were replicated four times and four analyses were made per replication. EDX analysis was also used to analyze leaf discs (0.5 cm in diameter) punched from unifoliolate leaves of 17-day-old Sloan soybean grown in naturally infested soil with and without KCl at 300 µg of Cl per gram of soil.

Sloan soybean plants were also grown in cartons of pasteurized Fulton silty clay for 10 days with KCl or K₂SO₄ at 400 µg of K per gram of soil or with only DW. The soil in all treatments was saturated with DW 5 days after planting. Stems and leaves of eight plants from each of these cartons were collected 10 days after planting for conventional mineral analyses. Collected stems and leaves were oven dried at 45°C, then ground in a Wiley mill with a 30-mesh screen. Ground samples were digested in perchloric or nitric acid and analyzed for Ca and Mg using a Varian model AA-475 Atomic Absorption Spectrophotometer. Potassium was determined by atomic emission spectrophotometry. Sulfur was determined using turbidimetric techniques (6). Phosphorus was determined by a modified Murphy-Riley method (23). Treatments were replicated four times.

Effect of KCl on inoculum of *P. sojae*. A quantitative leaf-disc baiting bioassay (13) was used to assess the effects of KCl on natural inoculum of *P. sojae* in soil. A soil slurry was prepared by mixing naturally infested Fulton silty clay with cold (5°C) DW (1:1) in a Waring blender for 1 min. Aliquots of slurry (80 g) were poured into cylinders (PVC pipe couplings, 6.0-cm inner diameter) with bottom ends covered with a single layer of cheesecloth secured with a rubber band to retain the slurry. Cylinders were placed on stacks of paper towels in a 5°C cooler to prevent oospore germination while excess water was absorbed from the slurry. After approximately 5 days, the slurry had dried to a "soil cake" with a ψ_m of -50 kPa. Nine soil cubes, each 1.2 by 1.2 by 1.0 cm and weighing 2.0 g (dry wt), were cut from each soil cake using a household vegetable cutter and placed in 50-ml beakers. Beakers were then capped with squares of cellophane wrap secured with rubber bands and placed in trays. Trays of beakers were sealed in polyethylene bags and incubated

in the dark at 20°C for 13 days. Excess soil from the cakes was used to determine the percent H₂O of the soil cubes. Subsamples of slurried soil were used to develop wetting and drying moisture-characteristic curves using Buchner funnel tensiometers and ceramic pressure plates to estimate the soil water ψ_m in soil cubes.

After incubation, KCl was applied by micropipette to the cubes with K at 0, 150, 300, 450, or 600 µg/g of soil in 40 µl of DW. Beakers were recapped with cellophane wrap and incubated as above for 4 days. Cubes were then flooded by adding 30 ml of DW at 20 ± 1°C to each beaker and baited with 0.5-cm-diameter leaf discs punched from the unifoliolate leaves of 17-day-old Sloan soybean seedlings. Twenty leaf-disc baits were used per beaker. After 2 h, baits were removed, blotted, and plated on VYS/PBNRH medium. The number of leaf discs infected with *P. sojae* was recorded after 4 days. Excess water was poured out of the beakers and the beakers placed in a drying oven at 110°C. The dry weight of soil baited was determined after 24 h. Leaf-disc infection was corrected for multiple infections by transforming the proportion of discs infected (x) to $\ln 1/(1 - x)^{-1}$ prior to analysis of variance (45). Treatments were replicated seven times.

Because flooding cubes with DW greatly diluted the KCl treatments, the bioassay was modified to more closely approximate the KCl concentrations of saturated soil solutions in growth-chamber experiments. Soil cubes were incubated in the dark for 18 days, then flooded with either soil extract, obtained from saturated soil as described above, or soil extract plus 0.01 or 0.02 M KCl. Treatments were replicated six times. The electrical conductivities of the flooding solutions were measured with the solu bridge. To distinguish the effects of KCl from the osmotic effects of the flooding solutions, soil extract only was compared with soil extract plus 0.01 M NH₄NO₃.

RESULTS

More than 260 diseased plants were collected and plated on VYS/PBNRH medium during the above experiments. *P. sojae* was isolated from 95% of the plated seedlings. *Pythium* spp. were isolated from

Table 1. Physical and chemical properties of soils used in experiments comparing effects of fertilizer salts on Phytophthora root rot of soybean^v

Soil series	Particle analysis (%)				pH	Exchangeable cations (kg ha ⁻¹)				CEC (meq g ⁻¹) ^x	Base (%) ^y	Elect. ^z
	Sand	Silt	Clay	OM (%) ^w		P	K	Ca	Mg			
Fulton	9.0	50.3	40.7	2.7	6.7 b	74 a	482 a	5,465 b	1,586 a	0.20 a	94 a	0.39
Hoytville	16.7	42.1	41.2	5.1	6.9 a	76 a	473 a	6,928 a	928 b	0.21 a	95 a	0.18
Blount	18.2	55.2	26.6	3.5	6.6 b	75 a	306 b	4,120 c	1,004 b	0.15 b	92 b	0.16

^v Values in the same column followed by the same letter are not significantly different ($P = 0.05$).

^w Organic matter.

^x Cation exchange capacity.

^y Base saturation.

^z Electrical conductivity (mmho cm⁻¹).

10%, generally in association with *P. sojae*. Representative seedlings with and without necrotic hypocotyls were collected and plated on VYS/PBNRH medium. *P. sojae* was isolated from 80% of the necrotic hypocotyls; no pathogens were isolated from healthy hypocotyls. No disease developed in cartons with pasteurized soil. With the exception of KNO₂ in the initial test, no significant differences in seed germination or seedling emergence with treatment were observed in any experiment. Seedlings usually appeared healthy until 2 to 3 days after soil saturation, when discoloration of the hypocotyls of some seedlings became evident and damping-off began. Post-emergence damping-off increased over the next 2 to 3 days, then gradually abated, except with chloride and ammonium salt treatments. With these treatments, occasional seedlings would develop hypocotyl lesions, wilt, and die throughout the remainder of experiments. At the end of experiments, 8 to 15% of the surviving plants with Cl salt treatments had internal hypocotyl necrosis compared with 5% with other treatments.

Soil analyses. There were significant differences in the nutrient availability among the three collected soils. The Fulton silty clay had more exchangeable Mg than the other two soils while the Hoytville silty clay had more exchangeable Ca and the highest pH (Table 1). The Blount silt loam had the lowest cation exchange capacity and the lowest levels of exchangeable K and Ca. Incubating naturally infested Fulton silty clay at 25°C maximized leaf disc infection with *P. sojae* in the bioassay (Fig. 1). Therefore, this temperature was used as the incubation temperature in subsequent growth-chamber experiments.

Effects of K, P, SO₄, Cl, and NH₄ salts on disease incidence and plant height. Treatments significantly ($P = 0.0228$ to <0.0001) affected disease incidence in all experiments. Addition of KCl at 150 and 200 µg of K per gram of soil increased disease incidence and decreased plant height compared with the untreated control (Table 2). K₂SO₄ and KNO₃ at similar rates of potassium did not increase disease to levels significantly higher than that observed in the untreated control. Disease incidence with KNO₂ was also higher and plants shorter than with the untreated control. KNO₂ also significantly reduced seed germination compared with all other treatments (F value = 9.38; $P = 0.001$). Phosphorus salts at 20 to 40 µg of P had little effect on disease incidence or plant growth. In the experiment with K salts with K at 400 µg/g of soil, KCl again increased disease incidence and decreased plant height compared with the untreated control (Table 3). However, when metalaxyl was applied with the KCl, no *Phytophthora* rot was observed, and plant height was greater than in all other treatments. Chloride salts of Na and

Mg applied at a rate equal to the amount of chloride in the KCl treatment also increased disease incidence relative to the untreated control. KHCO₃ and CaSO₄ (982 µg of SO₄) also increased disease incidence but neither significantly affected plant height compared with the untreated control. Sulfate salts of Ca, Na, Mg, and Al at 491 µg of SO₄ had no significant effects on disease incidence or plant height.

When six potassium salts with K at 300 µg/g of soil were compared with an untreated control, only KCl increased disease incidence (Table 4). Plant height was lower than the untreated control with KCl, KNO₃, and KH₂PO₄, with the greatest reduction occurring with KCl. Eight of nine chloride salts with Cl at 250 µg/g of soil increased disease incidence compared with the untreated control (Table 5). Only

Fig. 1. Number of Amsoy soybean leaf disc baits infected with *Phytophthora sojae* after incubating naturally infested Fulton silty clay for 4 to 24 days at 15, 20, 25, or 30°C. Values are the means of two replications with five subsamples/replication and 7 to 8 g of dry soil per subsample. Values for the same day with the same letter are not significantly different ($P = 0.05$).

Table 2. Effects of potassium at 150 or 200 µg/g of soil and phosphorus salts on disease incidence (DI) and height of Sloan soybean plants grown in Fulton silty clay naturally infested with *Phytophthora sojae*^z.

Salt	Rates (µg/g of soil)				DI (%)	Height (cm)
	K	P	SO ₄	Cl		
Control	0	0	0	0	12.5 c	11.8 a
KCl	150	0	0	136	31.2 a	9.7 b
KCl	200	0	0	181	26.5 a	9.9 b
K ₂ SO ₄	150	0	184	0	20.3 abc	11.3 a
K ₂ SO ₄	200	0	246	0	22.4 abc	11.3 a
KNO ₂	100	0	0	0	32.4 a	9.4 b
KNO ₃	200	0	0	0	18.8 abc	11.3 a
Ca(H ₂ PO ₄) ₂	0	20	0	0	12.3 bc	11.4 a
Ca(H ₂ PO ₄) ₂	0	40	0	0	11.0 c	11.4 a
K ₂ HPO ₄	100	40	0	0	14.9 bc	11.2 a

^z Values in the same column followed by the same letter are not significantly different ($P = 0.05$).

Table 3. Effects of phosphorus, sulfate, and chloride salts with K at 0 or 400 µg/g of soil on disease incidence (DI) and height of Sloan soybean plants grown for 18 days in a growth chamber in Fulton silty clay naturally infested with *Phytophthora sojae*^x.

Salt	Rates (µg/g of soil)				DI (%)	Height (cm)
	K	P	SO ₄	Cl		
Control	0	0	0	0	13.3 e	12.5 bc
KCl	400	0	0	363	47.2 ab	10.2 d
KCl + metalaxyl ^y	400	0	0	363	0.0 f	15.7 a
K ₂ SO ₄	400	0	491	0	21.0 de	12.7 bc
KH ₂ PO ₄	400	317	0	0	14.7 e	12.2 bc
K ₂ HPO ₄	400	159	0	0	17.2 e	12.3 bc
KHCO ₃	400	0	0	0	31.3 cd	12.5 bc
CaSO ₄ ^z	0	0	491	0	24.5 cde	12.8 b
CaSO ₄ ^z	0	0	982	0	30.9 cd	12.3 bc
NaCl	0	0	0	363	36.5 bc	11.5 c
Na ₂ SO ₄	0	0	491	0	21.7 de	12.2 bc
MgCl ₂ ·6H ₂ O	0	0	0	363	52.4 a	11.5 c
MgSO ₄ ·7H ₂ O	0	0	491	0	24.5 cde	12.0 bc
Al ₂ (SO ₄) ₃ ·18H ₂ O	0	0	491	0	21.6 de	12.8 b

^x Values in the same column followed by the same letter are not significantly different ($P = 0.05$).

^y Soil was drenched with metalaxyl at 5 µg a.i. g⁻¹ dry soil.

^z Dry CaSO₄ was mixed with soil as cartons were packed.

FeCl₃·6H₂O failed to increase disease incidence over the untreated control. The greatest reduction in plant height occurred with this treatment, however. The mean disease incidences with the potassium and chloride salts in these two tests were strongly correlated with the mean electrical conductivity of the soil extracts ($R = 0.9153$; $P < 0.001$).

When the effects of NH₄NO₃ and NaCl were tested and compared with the effects of NaNO₃, NH₄Cl, urea, and the control, all salts except NaNO₃ increased disease in the saturated-soil experiment (Table 6). In

the experiment where the soil was never saturated, NaNO₃ also increased disease incidence to a level greater than the untreated control (Table 6). The increase in disease incidence over that in the control with NH₄Cl was greater than the increase with NaCl or the increase with NH₄NO₃ (Table 6). The reduction in plant height with NH₄Cl was also greater than with NaCl or with NH₄NO₃ (Table 6). The increase in disease incidence with NH₄Cl was observed whether or not the soil was saturated to release zoospores (Table 6). Urea, which rapidly hydrolyzes in soils to

ammonium carbonate (44), also increased disease incidence. When seed were treated with pyroxyfur and the soil saturated, the increase in disease incidence with urea was not observed (Table 6). Increases in disease incidence and decreases in plant height relative to the water control occurred when Blount silt loam but not Hoytville silty clay was treated with KCl at 272 µg of Cl per gram of soil (Table 7). However, disease incidence was increased in both soils when NH₄Cl at 272 µg of Cl per gram of soil was applied. The salt combination of KCl at 272 µg of Cl + Ca(NO₃)₂ at 108 µg of N also increased disease incidence in both soils compared with the control (Table 7).

A high rate of NaCl (450 µg of Cl) did not appreciably affect soybean plants grown in pasteurized Fulton silty clay (Table 8). Seed germination, plant emergence, transpiration, height, and dry weight were essentially unaffected by the added NaCl compared with the water treatment. Only plant fresh weight was significantly increased by the addition of NaCl. No disease developed in the pasteurized soil.

Effects of K salts on nutrient levels in soybean seedlings. Application of KCl but not K₂SO₄ decreased the amounts of S and Ca and increased the amount of Cl in taproots relative to the levels found in the untreated control (Table 9). Conversely, KCl treatment was associated with higher levels of Ca and lower levels of Mg in stems and leaves than the control or K₂SO₄ treatments. K₂SO₄ was associated with less Ca in stems and leaves than the other two treatments (Table 9). Application of KCl or K₂SO₄ significantly increased the amount of K in stem and leaves. When soybean plants were grown for 17 days in naturally infested soil treated with KCl at 300 µg of Cl per gram of soil, EDX analysis indicated that the unifoliolate leaves contained 20× more Cl and 2.5× more Ca with added KCl than in the untreated control.

Effect of KCl on inoculum of *P. sojae*. Additions of KCl to soil cubes 5 days before flooding and baiting with leaf discs apparently had little effect on leaf infection by *P. sojae* ($P > 0.65$; data not shown). However, using soil extracts with 0.01 or 0.02 M KCl to flood the soil cubes apparently adversely affected zoospore infection of leaf discs ($P < 0.001$). The probit-transformed value for leaf infection was 0.83, whereas no leaf infection was observed with extract plus 0.01 M KCl or extract plus 0.02 M KCl. The electrical conductivities of the solutions were 0.97, 2.27, and 3.58 mmho/cm, respectively. When soil extract alone was compared with soil extract plus 0.01 M NH₄NO₃, no difference in leaf infection was observed. The electrical conductivities of these solutions were 1.05 and 2.32 mmho/cm, respectively.

Table 4. Effects of six potassium salts on disease incidence (DI) and height of Sloan soybean plants grown for 22 days in a growth chamber in Fulton silty clay naturally infested with *Phytophthora sojae* and their effects on soil electrical conductivity^y

Salt	Rates (µg/g of soil)		DI (%)	Height (cm)	Conductivity (mmho cm ⁻¹) ^z
	K	Cl			
Control	0	0	14.4 bc	12.9 a	0.93 d
KCl	300	272	35.0 a	10.6 c	2.06 a
K ₂ SO ₄	300	0	25.9 ab	12.3 ab	1.52 c
KNO ₃	300	0	26.4 ab	11.8 b	1.75 b
KHCO ₃	300	0	11.5 c	12.3 ab	0.96 d
K ₂ HPO ₄	300	0	12.8 c	12.0 ab	0.98 d
KH ₂ PO ₄	300	0	10.0 c	11.5 bc	1.01 d

^y Values in the same column followed by the same letter are not significantly different ($P = 0.05$).

^z Electrical conductivity of water collected from saturated soil after harvesting plants.

Table 5. Effects of nine chloride salts on disease incidence (DI) and height of Sloan soybean plants grown for 22 days in a growth chamber in Fulton silty clay naturally infested with *Phytophthora sojae* and their effect on soil electrical conductivity^y

Salt	Rates (µg/g of soil)		DI (%)	Height (cm)	Conductivity (mmho cm ⁻¹) ^z
	K	Cl			
Control	0	0	13.3 c	14.8 a	0.91 e
KCl	276	250	28.2 ab	14.0 ab	1.96 cd
NaCl	0	250	38.0 a	13.4 bcd	2.04 bcd
MgCl ₂ ·6H ₂ O	0	250	28.3 ab	13.7 bcd	2.12 abc
CaCl ₂ ·2H ₂ O	0	250	33.6 ab	12.9 cd	2.21 ab
NH ₄ Cl	0	250	40.4 a	13.2 bcd	2.29 a
AlCl ₃ ·6H ₂ O	0	250	28.8 ab	13.3 bcd	1.88 d
FeCl ₂ ·4H ₂ O	0	250	20.3 bc	12.8 d	1.95 cd
FeCl ₃ ·6H ₂ O	0	250	28.3 ab	13.8 abc	1.87 d
SrCl ₂ ·6H ₂ O	0	250	32.8 ab	13.1 bcd	1.89 d

^y Values in the same column followed by the same letter are not significantly different ($P = 0.05$).

^z Electrical conductivity of water collected from saturated soil after harvesting plants.

Table 6. Effects of chloride and ammonium salts on disease incidence and height of Sloan soybean plants grown in a growth chamber in Fulton silty clay naturally infested with *Phytophthora sojae* in two experiments, one with and one without soil saturation^x

Salt ^y	Rates (µg/g of soil)		Height (cm)	Disease incidence (%)	
	Cl	N		Saturated	Not saturated ^z
Control	0	0	14.4 a	4.3 c	7.5 c
NH ₄ NO ₃	0	120	12.1 cd	22.3 b	24.8 b
NaCl	304	0	11.8 d	25.4 b	26.0 b
NaNO ₃	0	120	13.9 ab	8.4 c	22.1 b
Urea	0	120	11.6 d	25.2 b	30.3 b
NH ₄ Cl	304	120	9.3 e	48.3 a	55.4 a
Urea + pyroxyfur	0	120	13.0 bc	4.3 c	ND

^x Soybean plants were grown for 20 days with soil saturation and 11 days without soil saturation in separate experiments which were conducted and analyzed separately. Values in the same column followed by the same letter are not significantly different ($P = 0.05$); ND = no data.

^y Urea = commercial urea fertilizer (45-0-0) and pyroxyfur = Grandstand seed treatment fungicide (Dowco 444).

^z Soil never saturated: plants were grown in sealed polyethylene bags without saturating the soil to release zoospores.

DISCUSSION

Recently, Elmer (20) summarized the many reports of chloride salts affecting plant diseases. Although the beneficial effects of chloride for disease suppression were well described, the negative effects (disease enhancement) were discussed only briefly. Applications of potassium chloride to the Fulton silty clay consistently increased the incidence of *Phytophthora* root and stem rot on a susceptible soybean cultivar in the studies reported here. The increases appeared to be related to the rate of KCl applied, increasing from 27 to 35 to 47% as the application rate was increased from 200 to 300 to 400 µg of K per gram of soil. In contrast, K₂SO₄ did not affect disease incidence at application rates of 150 to 400 µg of K. Other potassium salts, most sulfate salts, and phosphorus salts also did not affect disease incidence. The addition of chloride salts, however, consistently increased disease, demonstrating that the increase in disease incidence with applications of KCl was probably due to the presence of chloride. Previously reported increases in *Phytophthora* rot with use of a complete fertilizer containing KCl (15) or with muriate of potash (30) may also have been due, in part, to the presence of chloride. Ammonium salts also increased disease, and these increases were particularly enhanced when combined with chloride with applications of NH₄Cl.

A few exceptions to the overall trends were observed. In the initial test, added KNO₂ increased disease incidence and reduced plant height compared with the control. It also reduced seed germination, possibly due to nitrite toxicity. In the tests comparing effects of chloride and ammonium salts (Table 6), NaNO₃ increased disease incidence only when the soil was never saturated. This may have been due to a change in denitrification with a change in the partial pressure of oxygen in the sealed polyethylene bags (44) and accumulation of nitrite. The mechanism behind the chloride effect is unclear. The significant decrease in infection in the leaf-disc bioassay when KCl was added to the flooded soil solution suggests reduced activity of zoospore inoculum. This reduced activity may be due to rapid encystment of zoospores in

the presence of K (7) or decreased release of zoospores (43). Less disease, rather than more, would be expected. Decreases in disease were not observed, possibly due to retention of K⁺ on the negatively charged soil colloids (4).

Disease increases were associated with increases in the electrical conductivity of soil extracts, indicating increases in the osmotic potential of the soil solution (32) and suggesting that salinity stresses may be involved. High salt concentrations have been reported to both increase and decrease the severity of diseases caused by *Phytophthora* spp. (35). Beech (3) attributed increased damping-off of tomato seedlings with fertilizer salts to a growth advantage of pathogen over host when both were under osmotic stress. This mechanism appears unlikely here because growth of the host was largely unaffected by chloride salt concentrations two to three times greater than those at which significant increases in disease first became evident, whereas growth of *Phytophthora* spp. is generally reduced by increasing the osmotic potential of media with additions of chloride salts (40,41).

MacDonald (26) reported increased *Phytophthora* root rot of chrysanthemum with pulsed exposures of roots to salinity stress and suggested that predisposition of roots to zoospore infection as a result of the deplasmolytic shock may have been involved. In our studies, disease was increased with chloride salts when plants were grown in soil at a ψ_m of -5 to -15 kPa in sealed polyethylene bags without ever saturating the soil. Under these conditions, a deplasmolytic shock was probably

not incurred. It seems likely that a mechanism other than deplasmolytic shock must have been involved.

Changes in host physiology with chloride uptake offer an alternative explanation for observed results. Borys (5) noted an increase in the susceptibility of potato leaves to infection by *P. infestans* when plants were grown in sand culture to which chloride salts were added. MacDonald (27) has demonstrated that salinity stresses using chloride salts also appear to increase the susceptibility of host roots to infection by *P. cryptogea*. Details of the mechanism for this effect were largely unknown. In experiments reported here, the calcium content of roots of plants receiving KCl was lower and the calcium content of stems and leaves higher than those of the water control. However, the calcium content of roots was not affected with K₂SO₄. Increases in resistance or tolerance of plant tissues to fungal infection with increases in calcium content have frequently been reported (1,2,19,25,31). Recent reports have also identified the importance of the calcium ion as an important signaling messenger in plant defense mechanisms (18,24). The EDX analyses of intact soybean roots in this report probably reflect the calcium concentration in the outer two or three layers of cells. Movement of calcium out of or through root tissues and into shoots with uptake of chloride could possibly render roots more susceptible to infection. Calcium compounds have recently been reported to reduce the severity of *Phytophthora* root and stem rot of soybean (42,43). Additional studies are needed to determine whether changes in root calcium

Table 8. Response to sodium chloride of Sloan soybean seedlings grown in pasteurized Fulton silty clay

Variable measured ^y	No NaCl	With NaCl ^z
Seedling emergence 4 DAP (%)	97.2	97.2
Final germination 9 DAP (%)	98.6	98.6
Evapotranspiration rate 21 DAP (g/plant/day)	10.2	9.8
Plant height (cm)	20.3	20.2
Plant fresh weight (g)	1.66	1.84**
Plant dry weight (g)	0.214	0.216

^y DAP = days after planting.

^z Added at 450 µg Cl/g of soil. Value followed by ** differs significantly from the control ($P = 0.0065$).

Table 7. Effects of KCl, K₂SO₄, and nitrogen salts on disease incidence (DI) and height of Sloan soybean plants grown in a growth chamber for 18 days in Hoytville silty clay or Blount silt loam naturally infested with *Phytophthora sojae*^z

Salt	Rates (µg/g of soil)			Hoytville silty clay		Blount silt loam	
	K	Cl	N	DI (%)	Height (cm)	DI (%)	Height (cm)
Control	0	0	0	13.0 b	13.8 a	6.9 c	14.2 a
KCl	300	272	0	13.7 b	12.7 a	35.1 ab	11.8 cd
K ₂ SO ₄	300	0	0	16.2 b	13.2 a	14.4 c	14.7 a
CO(NH ₂) ₂	0	0	108	32.6 ab	12.5 a	24.7 bc	13.3 abc
(NH ₄) ₂ SO ₄	0	0	108	21.3 ab	13.8 a	21.9 c	13.7 ab
NH ₄ Cl	0	272	108	42.2 a	13.3 a	53.9 a	12.0 bcd
Ca(NO ₃) ₂	0	0	108	12.2 b	14.8 a	12.3 c	13.7 ab
NaNO ₃	0	0	108	28.6 ab	13.7 a	24.0 bc	13.8 a
KCl + Ca(NO ₃) ₂	300	272	108	42.6 a	13.7 a	54.6 a	10.3 d

^z Values in the same column followed by the same letter are not significantly different ($P = 0.05$).

Table 9. Elemental analyses of Sloan soybean seedlings grown in pasteurized soil with and without addition of KCl or K₂SO₄^w

Treatment ^z	Taproot segments (counts s ⁻¹) ^x						Stems and leaves (%) ^y					
	Mg	P	S	Cl	K	Ca	Mg	P	S	Cl	K	Ca
No salt	58.3 a	27.8 a	85.9 a	135.8 b	237.1 b	58.1 a	0.58 a	0.52 a	0.44 b	NA	3.62 b	0.96 b
KCl	37.3 a	30.8 a	52.9 b	342.6 a	395.3 ab	29.9 b	0.49 b	0.53 a	0.42 b	NA	4.08 a	1.04 a
K ₂ SO ₄	36.9 a	19.6 a	96.6 a	97.1 b	536.4 a	44.0 ab	0.55 a	0.51 a	0.55 a	NA	4.26 a	0.87 c

^w Values in the same analysis column followed by the same letter are not significantly different ($P = 0.05$); NA = not analyzed.

^x Taproot segments from 5-day-old seedlings by energy-dispersive X-ray analysis.

^y Stems and leaves from 10-day-old seedlings using conventional methods for mineral analysis (see text for methods used).

^z No salt = control. Potassium salts were added to the soil at 400 µg of K per gram of soil.

content associated with chloride uptake might affect the susceptibility of roots to infection or pathogen colonization.

The experiments reported here demonstrate that applications of KCl can potentially increase the incidence of *Phytophthora* root and stem rot on soybean seedlings. Additional studies with other soybean cultivars and soils are needed to corroborate these observations. Further exploration of the possible reason for the increase in seedling disease incidence with chloride salts is also needed. Potassium chloride is by far the most widely used potassium fertilizer (44). The possible confounding effects of chloride should be a consideration in any study of the effects of potash fertilizers on seedling diseases.

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LITERATURE CITED

- Bateman, D. F. 1964. An induced mechanism of tissue resistance to polygalacturonase in *Rhizoctonia*-infected hypocotyls of bean. *Phytopathology* 54:438-445.
- Bateman, D. F., and Lumsden, R. D. 1965. Relation of calcium content and nature of the pectic substances in bean hypocotyls of different ages to susceptibility to an isolate of *Rhizoctonia solani*. *Phytopathology* 55:734-738.
- Beech, W. S. 1949. The effects of excess solutes, temperature and moisture upon damping-off. *Penn. Agric. Exp. Stn. Bull.* 509.
- Bohn, H. L., McNeal, B. L., and O'Connor, G. A. 1979. *Soil Chemistry*. John Wiley & Sons, New York.
- Borys, M. W. 1964. Influence of calcium, magnesium, chloride and sulphate nutrition on the resistance of potato leaves to *Phytophthora infestans* de Bary. *Acta Microbiol. Pol.* 13:221-226.
- Butters, B., and Chenery, E. M. 1959. Rapid method for the determination of total sulphur in soils and plants. *Analyst* 84:239-245.
- Byrt, P. N., Irving, H. R., and Grant, B. R. 1982. The effect of cations on zoospores of the fungus *Phytophthora cinnamomi*. *J. Gen. Microbiol.* 128:1189-1198.
- Canaday, C. H., and Mengistu, A. 2008. Effects of directed fungicide sprays and potash form on charcoal rot of soybean, 2007. *Plant Disease Management Reports* (online) Report 2:FC015. DOI:10.1094/PDMR02.
- Canaday, C. H., and Mengistu, A. 2009. Effects of potash form, seed treatments, and in-furrow fungicide sprays on soybean diseases, 2008. *Plant Disease Management Reports* (online) Report 3:FC012. DOI:10.1094/PDMR03.
- Canaday, C. H., Sams, C. E., Wyatt, J. E., and Schmitthenner, A. F. 1999. Increases in the incidence of seedling diseases associated with chloride salts. (Abstr.) *Phytopathology* 89:S93.
- Canaday, C. H., and Schmitthenner, A. F. 1979. The effect of nitrogen on *Phytophthora* root rot of soybeans. (Abstr.) *Phytopathology* 69:539.
- Canaday, C. H., and Schmitthenner, A. F. 1982. Isolating *Phytophthora megasperma* f. sp. *glycinea* from soil with a baiting method that minimizes *Pythium* contamination. *Soil Biol. Biochem.* 14:67-68.
- Canaday, C. H., and Schmitthenner, A. F. 1982. Quantification of treatment effects on natural inoculum of *Phytophthora megasperma* f. sp. *glycinea*. (Abstr.) *Phytopathology* 72:996.
- Canaday, C. H., and Schmitthenner, A. F. 1983. Effect of potassium fertilization and chloride ion on *Phytophthora* rot of soybeans. (Abstr.) *Phytopathology* 73:811.
- Dirks, V. A., Anderson, T. R., and Bolton, E. F. 1980. Effect of fertilizer and drain location on incidence of *Phytophthora* root rot of soybeans. *Can. J. Plant Pathol.* 2:179-183.
- Dorrance, A. E., and McClure, S. A. 2001. Beneficial effects of fungicide seed treatments for soybean cultivars with partial resistance to *Phytophthora sojae*. *Plant Dis.* 85:1063-1068.
- Dorrance, A. E., and Schmitthenner, A. F. 2000. New sources of resistance to *Phytophthora sojae* in the soybean plant introductions. *Plant Dis.* 84:1303-1308.
- Du, L., Ali, G. S., Simons, K. A., Hou, J., Yang, T., Reddy, A. S. N., and Poovaiah, B. W. 2009. Ca²⁺/calmodulin regulates salicylic-acid-mediated plant immunity. *Nature* 457:1154-1158.
- Edgington, L. V., and Walker, J. C. 1958. Influence of calcium and boron nutrition on development of *Fusarium* wilt of tomato. *Phytopathology* 48:324-326.
- Elmer, W. H. 2007. Chlorine and plant disease. Pages 189-202 in: *Mineral Nutrition and Plant Disease*. L. E. Datnoff, W. H. Elmer, and D. M. Huber, eds. American Phytopathological Society, St. Paul, MN.
- Griffin, D. M. 1972. *Ecology of Soil Fungi*. Syracuse Univ. Press, Syracuse, NY.
- Hildebrand, A. A. 1959. A root and stalk rot of soybeans caused by *Phytophthora megasperma* Drechsler var. *sojae* var. nov. *Can. J. Bot.* 37:927-957.
- John, M. K. 1970. Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. *Soil Sci.* 109:214-220.
- Lecourieux, D., Ranjave, R., and Pugin, A. 2006. Calcium in plant defence-signalling pathways. *New Phytol.* 71:249-269.
- Lee, B. S., and Zentmyer, G. A. 1982. Influence of calcium nitrate and ammonium sulfate on *Phytophthora* root rot of *Persea indica*. *Phytopathology* 72:1558-1564.
- MacDonald, J. D. 1982. Effect of salinity stress on the development of *Phytophthora* root rot of chrysanthemum. *Phytopathology* 72:214-219.
- MacDonald, J. D. 1984. Salinity effects on the susceptibility of chrysanthemum roots to *Phytophthora cryptogea*. *Phytopathology* 74:621-624.
- MacDonald, J. D., and Duniway, J. M. 1978. Influence of the matric and osmotic components of water potential on zoospore discharge in *Phytophthora*. *Phytopathology* 68:751-757.
- Mussell, H. 1980. Tolerance to disease. Pages 39-52 in: *Plant Disease, an Advanced Treatise*. Vol. V. How Plants Defend Themselves. J. G. Horsfall and E. B. Cowling, eds. Academic Press, New York.
- Pacumbaba, R. P., Brown, G. F., and Pacumbaba, R. O., Jr. 1997. Effect of fertilizers and rates of application on incidence of soybean diseases in northern Alabama. *Plant Dis.* 81:1459-1460.
- Rahman, M., and Punja, Z. K. 2007. Calcium and plant disease. Pages 79-93 in: *Mineral Nutrition and Plant Disease*. L. E. Datnoff, W. H. Elmer, and D. M. Huber, eds. American Phytopathological Society, St. Paul, MN.
- Richards, L. A. 1954. Diagnosis and improvement of saline and alkali soils. U. S. Dep. Agric. Agric. Handb. 60.
- Richards, L. A. 1965. Physical conditions of water in soil. Pages 128-152 in: *Methods of Soil Analysis. Part I. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling*. C. A. Black, ed. Am. Soc. Agron., Madison, WI.
- Schmitthenner, A. F. 1985. Problems and progress in control of *Phytophthora* root rot of soybean. *Plant Dis.* 69:362-368.
- Schmitthenner, A. F., and Canaday, C. H. 1983. Role of chemical factors in development of *Phytophthora* diseases. Pages 189-196 in: *Phytophthora: Its Biology, Taxonomy, Ecology and Pathology*. D. C. Erwin, S. Bartnicki-Garcia, and P. H. Tsao, eds. American Phytopathological Society, St. Paul, MN.
- Schmitthenner, A. F., and Kroetz, M. E. 1982. Pyroxyfur seed treatment for integrated control of *Phytophthora* root rot of soybean. (Abstr.) *Phytopathology* 72:971.
- Schmitthenner, A. F., and Walker, A. K. 1979. Tolerance versus resistance for control of *Phytophthora* root rot of soybeans. Pages 35-44 in: *Rep. Soybean Seed Res. Conf., 9th Am. Seed Trade Assoc. Publ.* 9.
- Schwinn, F. J. 1983. New developments in chemical control of *Phytophthora*. Pages 327-334 in: *Phytophthora: Its Biology, Taxonomy, Ecology, and Pathology*. D. C. Erwin, S. Bartnicki-Garcia, and P. H. Tsao, eds. American Phytopathological Society, St. Paul, MN.
- Skotland, C. B. 1955. A *Phytophthora* damping-off disease of soybeans. *Plant Dis. Rep.* 39:682-683.
- Sommers, L. E., Harris, R. F., Dalton, F. N.,

- and Gardner, W. R. 1970. Water potential relations of three root-infecting *Phytophthora* species. *Phytopathology* 60:932-934.
41. Sterne, R. E., Zentmyer, G. A., and Bingham, F. T. 1976. The effect of osmotic potential and specific ions on growth of *Phytophthora cinnamomi*. *Phytopathology* 66:1398-1402.
 42. Sugimoto, T., Watanabe, K., Yoshida, S., Aino, M., Irie, K., Matoh, T., and Briggs, A. R. 2008. Select calcium compounds reduce the severity of *Phytophthora* stem rot of soybean. *Plant Dis.* 92:1559-1565.
 43. Sugimoto, T., Watanabe, K., Yoshida, S., Aino, M., Matsuyama, M., Maekawa, K., and Irie, K. 2007. The effects of inorganic elements on the reduction of *Phytophthora* stem rot disease of soybean, the growth rate and zoospore release of *Phytophthora sojae*. *J. Phytopathol.* 155:97-107.
 44. Tisdale, S. L., and Nelson, W. L. 1975. *Soil Fertility and Fertilizers*. Macmillan, New York.
 45. van der Plank, J. E. 1975. *Principles of Plant Infection*. Academic Press, New York.
 46. Vitosh, M. L., Johnson, J. W., and Mengel, D. B. 1995. Tri-state fertilizer recommendations for corn, soybeans, wheat and alfalfa. *Ohio State Univ. Ext. Bull.* E-2567.