Response of Soybean Sudden Death Syndrome to Subsoil Tillage

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ABSTRACT

Vick, C. M., Chong, S. K., Bond, J. P., and Russin, J. S. 2003. Response of soybean sudden death syndrome to subsoil tillage. *Plant Dis.* 87:629-632.

The soilborne pathogen *Fusarium solani* f. sp. *glycines* causes sudden death syndrome (SDS) of soybean. Previous research indicated that soil compaction related directly to disease foliar symptoms. Therefore, we hypothesized that decreasing soil compaction would increase soil porosity and provide a more aerated root zone that would hinder root infection by the fungus and decrease SDS foliar symptom severity. Two experimental areas (110 by 120 m) were established to evaluate the relationship between soil variables and SDS. Across the experimental area, strips (9.14 m wide) were subsoiled perpendicular to soybean rows to a depth of 40 to 45 cm, which alternated with strips that were not tilled. In both 1999 and 2000, subsoiling dramatically reduced foliar symptoms of SDS. Compared with no-till plots, subsoiled plots had lower soil bulk density, greater soil porosity, and less soil moisture. In areas where SDS occurs and soil compaction exists, the use of subsoiling can be used to reduce severity of foliar symptoms of SDS.

Sudden death syndrome (SDS) of soybean (*Glycines max* (L.) Merr.) is caused by *Fusarium solani* f. sp. *glycines*, a slow-growing, blue-pigmented soilborne fungus (19,21). This disease primarily is a problem in the Mississippi and Ohio River regions of the United States (20).

Infection of soybean roots by *F. solani* f. sp. *glycines* occurs throughout the growing season and can be detected as early as 15 to 30 days after planting (11,16). Foliar symptoms usually first appear during early reproductive stages of the plant (20). In moderate and severe cases, necrosis of leaf tissue and even leaf drop is possible (20). In very severe cases, the plant will lose all leaves and most, if not all, pods, leaving only a bare stem with the petioles remaining. Foliar symptoms may be caused by phytotoxins translocated from roots to leaves (9).

Fungal root colonization and severity of foliar symptoms seem to depend on environmental (25) as well as soil physical (26), chemical (24), and biological factors (13,14). Severity of SDS varies among years, which suggests that variations in

environmental conditions such as soil moisture and temperature affect disease development (30). Reports indicate that high levels of soil moisture and low soil temperatures, especially in early reproductive stages of the soybean, increase severity of SDS (8). Soil compaction also can increase SDS due to its relationship with soil moisture (20,24,26). Increased soil compaction inhibits soil profile drainage and increases duration of soil saturation. Soil compaction can be reduced in the upper few centimeters by conventional tillage practices, and this tactic has reduced or delayed foliar symptoms of SDS (6,30).

No-till fields generally are more anaerobic, cool, and moist than tilled fields (29,30). Hilderbrand et al. (7) reported that, in no-till fields, areas with high soil moisture and reduced macroporosity supported more severe SDS. The objectives of this study were to identify effects of subsoiling on (i) soil physical, chemical, and biological properties and (ii) SDS foliar symptoms and root infection by *F. solani* f. sp. *glycines*.

MATERIALS AND METHODS

In 1999 and 2000, a farmer's field located 1 km south of Desoto, IL consisted of two adjacent 110-by-120-m areas. These areas had not been tilled for two years prior to implementation of the experiment and had a history of SDS. The soil type (1) for the 1999 experimental area was Camden silt loam (fine-silty, mixed, mesic Typic Endoaqualfs), whereas the 2000 experimental area contained a mixture of Camden silt loam and Stark silt loam (fine-silty, mixed, mesic Aeric Endoaqualfs). Each experimental area was divided into 12 strips (9 by 120 m) and these strips

alternated between two treatments (no-till and subsoil). Because of constraints related to both site slope and previous SDS patterns, a decision was made to alternate tillage strips rather than subject them to randomization. This would ensure sufficient comparison between tillage treatments regardless of where SDS might occur. Subsoil treatments were implemented to a depth of 40 to 45 cm using a three-shank subsoiler with 76-cm shank spacing. Two passes were made over each subsoiled strip in order to ensure uniform distribution of tillage. Subsoiling occurred in fall 1998 for the 1999 experimental area and fall 1999 for the 2000 experimental area.

Each strip was divided into 10 subplots (9 by 12 m), and each subplot contained 12 rows (76-cm row spacing) of soybean cv. Pioneer 9492RR. This cultivar has a maturity of 4.9 and is resistant to *Heterodera glycines* race 3 and mildly resistant to race 14, but susceptible to SDS. Planting dates were 21 May 1999 and 13 May 2000. Fertilizer (0-0-60 at 112 kg/ha and 18-46-0 at 168 kg/ha) application occurred on 16 May 1999 and 2 May 2000.

Four cores (2.5 cm in diameter by 15 cm deep) from the center four rows of each subplot were collected for soil chemical analyses. In April, prior to fertilizer application, soil sampling occurred for both years. Soil pH was determined using the water method described by McLean (12). The amount of available phosphorus (P) was determined using the Bray P1 extraction solution described by Olsen (17). Potassium (K) was measured using 1 N ammonium acetate as described by Knudsen (10). Organic matter was obtained by Schnitzer's method (27).

Soil moisture was measured within a small area (1 by 1 m) at the center of each subplot. Moisture (percent by volume) was measured at three arbitrary locations within this area to a depth of 20 cm using a time domain reflectometer (TDR). The TDR measures the time it takes a microwave pulse to travel a known length of transmission line that is buried in the soil. The time difference that is detected is expressed as a percentage by volume measurement of soil moisture (TDR; Soil Moisture Equipment Corp., Santa Barbara, CA). These measurements were averaged to determine plot values prior to analysis. Soil moisture was measured 36 to 48 h after each ≥ 2 -cm rain event at the research site. Soil moisture sampling occurred five times in 1999 and six times in 2000.

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Support for this research was provided in part by Illinois Department of Agriculture Conservation 2000 Sustainable Agriculture Grant Program, Illinois Council for Food and Agricultural Research, and the Illinois Soybean Program Operating Board.

Accepted for publication 19 December 2002.

Soil bulk density (28) was determined from a single soil core (12.5 cm in diameter by 11 cm deep) removed from the center two rows in the middle of each subplot, where tillage occurred, after harvest. A golf green cup cutter was used to remove soil cores. Total porosity (%) of the soil was calculated from bulk density and particle density (assumed to be 2.65 g cm⁻³; 28). Macroporosity then was determined by the differences of total porosity and water content measured between 36 and 48 h after each ≥ 2 -cm rain event (2).

Root colonization was measured using two approaches (i.e., the percentage of taproot pieces infected by *F. solani* f. sp. *glycines*, herein referred to as root colonization [%], and the number of CFU of the fungus per gram of taproot, herein referred to as root colonization [CFU/g]). In each subplot, six root systems were collected from rows four and nine, and the center four rows of each subplot were left undisturbed for yield and disease rating purposes. Root samples consisted of collections at growth stage R7 (3).

Root colonization (%) by *F. solani* f. sp. *glycines* was determined using the method described by Rupe et al. (22). Root samples were washed thoroughly with water, the lateral roots removed, and taproots cut transversely into disks 5 mm thick. All root pieces for each subplot were combined, surface sterilized in NaOCL (5.25%) for 2 min, rinsed twice in sterile water, and then blotted on sterile paper towels. Twenty root pieces were arbitrarily selected from each subplot and plated on four petri plates. The plates contained a modified Nash and Snyder's medium (15) (20 g of agar, 20 g of sucrose, 1 g of KH₂PO₄, 0.5 g of MgSO₄ · 7H₂O, 0.5 g of KNO₃, and 1 liter of distilled H₂O) that was amended with 0.1 g of chlortetracycline, 0.23 g of pentachloronitrobenzene, 0.3 g of streptomycin sulfate, 0.1 g of neomycin, and 0.05 g of rifampicin (22). Plates were incubated under constant light at 24°C for 10 days. The number of taproot pieces yielding *F. solani* f. sp. *glycines* was identified by colony morphology and spore type (18). The counts were recorded, and root colonization was expressed as a percentage.

Root colonization (CFU/g) by *F. solani* f. sp. *glycines* was determined from six root samples collected at R7 from rows four and nine of each subplot. Roots were washed thoroughly with water and lateral roots were removed. Taproots were surfaced sterilized in NaOCL (5.25%) for 2 min, rinsed three times with sterile distilled H₂O, and dried at ambient temperature for 48 h. Each dried sample was ground using a Wiley Mill (Thomas Scientific Inc., Swedesboro, NJ) to pass through a 425- μ m pore sieve. A subsample (2 g) of ground root was dilution plated on modified Nash and Snyder's medium with amendments. Each dilution was replicated on five plates and incubated under constant light at 24°C for 10 days. Colonies that were consistent with *F. solani* f. sp. *glycines* morphology and spore type were counted on each plate (20). Counts were expressed as CFU/g of taproot.

Population densities of *F. solani* f. sp. *glycines* per gram of soil, herein referred to as soil populations (CFU/g), were determined from six soil samples removed from rows four and nine of each subplot at R7. A subsample (2 g) of soil was dilution plated on modified Nash and Snyder's medium with amendments. Plates were incubated under constant light at 24°C for 10 days. Colonies were counted as previously described. From these counts, numbers of CFU/g of soil were calculated.

Foliar symptoms of SDS were first observed on 28 August 1999 and 7 August 2000 and were rated according to the 0-to-9 scale described by Gibson et al. (4). An area (3 by 6 m) within the center four rows of each subplot was used for disease ratings. Plots were scored only once in 1999 (R6.0) because of late development of SDS and low SDS severity, but four times (R5.0, 5.2, 6.0, and 6.2) in 2000. Scores for disease incidence (DI) and disease severity (DS) were used to obtain a foliar disease index (DX) score, which was calculated as $DI \times DS/9$ (4).

Soybean yield was determined from the same area used for foliar symptom assessment (3 by 6 m) in the center four rows of each subplot. Harvest dates were 4 October 1999, and 10 October 2000, and grain yields were adjusted to 13% moisture.

Precipitation amounts were recorded for June, July, and August at the study sites in both years using a rain gauge (Bendux Aviation Corporation, Baltimore, MD). Precipitation measurements were taken weekly and summed to calculate monthly precipitation. Data for average rainfall during the times of the study were provided by the Southern Illinois Airport, which is located about 1 km southwest of the study site.

Main effects of subsoiling on measured variables were determined using the GLM procedure of SAS (version 6.01; SAS Institute, Cary, NC.). Treatments were blocked and subplots treated as nested measurements within treatments. Because the study examined only two tillage treatments, these were compared using the *F* statistic. Limited correlation analysis was accomplished using the CORR procedure of SAS.

RESULTS

Subsoiling changed soil physical characteristics in both 1999 and 2000 (Table 1). Soil bulk density was less in subsoiled than in no-tilled treatments. Because soil bulk density relates inversely to soil porosity (7), subsoiling also increased porosity and reduced soil moisture on all sampling dates in 1999 and the final four dates in 2000 (Table 1).

Subsoiling had no detectable effect on soil chemical properties in either year (*data not presented*). Test values for *P* (38.1 to 56.0 kg ha⁻¹), organic matter (1.36 to 1.54%), and pH (6.8 to 6.9) were adequate but values for K (157.9 to 178.1 kg ha⁻¹) were deficient in both years (5). There was no relationship detected between any soil variables and DX in 1999 but, in 2000, there was a weak positive correlation between soil organic matter (*r* = 0.312, 0.269, 0.265, and 0.217) and potassium (*r* = 0.269, 0.292, 0.271, and 0.280) for all four DX evaluation dates.

Amounts and patterns of rainfall during June through August differed between years (Fig. 1). Rainfall amounts were below average in 1999 but above average in 2000. Markedly more rainfall occurred in 2000 (615 mm) than in 1999 (168 mm), with the greatest differences between years

Table 1. Effects of subsoiling on selected soil physical properties at Desoto, IL^a

Year, tillage	Bulk density (g/cm ³)	Porosity (%)	Soil moisture (cm ³ cm ⁻³) ^b					
			Date 1	Date 2	Date 3	Date 4	Date 5	Date 6
1999			3 June	23 June	9 July	12 July	16 July	9 August
No till	1.62	0.47	0.28	0.21	0.30	0.21	0.28	0.17
Subsoiled	1.50	0.51	0.26	0.17	0.25	0.16	0.25	0.12
<i>P</i> > <i>F</i>	***	***	***	***	***	***	***	***
2000			24 June	29 June	21 July	31 July	10 August	17 August
No till	1.43	0.41	0.32	0.34	0.26	0.25	0.30	0.25
Subsoiled	1.31	0.44	0.31	0.31	0.24	0.23	0.29	0.23
<i>P</i> > <i>F</i>	***	***	ns	ns	***	***	*	***

^a Subsoiling was accomplished to a depth of 40 to 45 cm using a three shank ripper. Within years and columns, ns, *, and *** represent differences between tillage treatments that were not significant or significant at the 0.05 and 0.001 levels, respectively.

^b Dates of measurements varied as shown between 1999 and 2000.

occurring in June and August. Values for DX averaged <2 in 1999 but >40 in 2000 (Table 2).

Subsoiling reduced DX at the single evaluation date in 1999 and at all four dates in 2000 (Table 2). However, subsoiling effects on root colonization varied with method used to detect the fungus. Roots were ground for CFU/g both years but, due to low levels of SDS in 1999 and the inability of the method used to provide consistent counts, only 2000 data are presented. Root colonization (CFU/g) by *F. solani* f. sp. *glycines* was lower in 2000 in subsoiled than in no-till treatments (Table 2). However, there was no difference in root colonization (%) between tillage treatments in either year. Subsoiling had no effect on *F. solani* f. sp. *glycines* populations in soil in either year (Table 2), and

yield was not affected by subsoiling in either year (Table 2).

DISCUSSION

Subsoiling reduced severity of SDS foliar symptoms in both years of our study. This effect was consistent in both wet and dry growing seasons when SDS severity was high and low, respectively. Subsoiling altered the soil profile by reducing soil compaction, increasing porosity, and reducing soil moisture by volume compared with those in no-till. These results support previous research that found direct relationships between SDS severity and both soil compaction and soil moisture (7,25). The results of the current study show further that the effect of soil compaction on development of SDS symptoms can be reduced effectively through subsoiling.

There are limited published data on effects of tillage on severity of SDS. Wrather et al. (30) reported that both disc-till and ridge-till practices reduced SDS foliar symptom severity compared with that in no-till. However, these tillage practices have little effect on the soil profile. Disc tillage disrupts only the top 10 cm of the soil profile, whereas ridge-till simply raises soil beds into which soybean is planted. Neither of these approaches disrupts the hard pan, which usually limits soil drainage (20). Results from our current study greatly increase our understanding of tillage effects on SDS and the role of soil compaction on disease expression.

It appears that subsoiling does not prevent root infection from taking place but may slow the development of foliar symptoms. Subsoiling may delay infection of the soybean roots by the pathogen or reduce the pathogen's ability to colonize root tissue due to drier conditions in the root zone, more rapid and expansive growth of roots in tilled soil, or some other unidentified factor.

Not surprisingly, there were no differences detected between subsoiled and no-till treatments and soil chemical properties in either year. It is unlikely that subsoiling would alter any chemical property substantially. The data shows inconsistent relationships between DX and soil chemical properties. There was no relationship between DX and soil chemical properties in 1999 but, in 2000, weak correlations were observed between DX and both soil potassium and organic matter. Sherm et al. (26) also found that higher levels of available potassium enhanced disease expression. Previous research conducted by Rupe et al. (24) showed direct relationships between severity of SDS and levels of phosphorus, organic matter, sodium, calcium, and magnesium. The relationship between SDS and soil chemical properties is still unclear but may be site or soil specific.

Severity of SDS foliar disease, which was much lower in 1999 than in 2000, mirrored differences in rainfall amounts and patterns during the growing season.

Fig. 1. Comparison of rainfall received during the growing season in 1999 and 2000. The average rainfall is from 1910 to 2001 at the Southern Illinois airport, which is located 1 km southwest of the experiment site.

Table 2. Effect of subsoiling on foliar symptoms of sudden death syndrome, soybean yield, and root colonization by *Fusarium solani* f. sp. *glycines* at Desoto, IL in 1999 and 2000^a

Year, tillage	Foliar disease index (DX) ^b				Yield (kg/ha)	Root colonization		Soil populations
	11 August	18 August	24 August	1 Sep/30 Aug ^c		% ^d	CFU/g	CFU/g
1999								
No till	...	...	...	1.9	2,315	17	...	1,150
Subsoiled	...	...	...	0.7	2,228	13	...	853
<i>P</i> > <i>F</i>	...	...	...	*	ns	ns	...	ns
2000								
No till	5.7	15.0	27.0	41.0	1,663	48	2,076	834
Subsoiled	2.7	8.5	19.0	30.0	1,735	47	910	678
<i>P</i> > <i>F</i>	***	***	***	***	ns	ns	**	ns

^a Subsoiling was accomplished to a depth of 40 to 45 cm using a three shank subsoiler. Within years and columns, ns, *, **, and *** represent differences between tillage treatments that were not significant or significant at the 0.05, 0.01, and 0.001 levels, respectively.

^b Foliar disease index = (foliar disease incidence × foliar disease severity)/9.

^c DX measured 1 September 1999 and 30 August 2000.

^d Percentage of taproot pieces colonized at soybean growth stage R7 by *F. solani* f. sp. *glycines*.

During 2000, the highest amounts of rainfall occurred in June (i.e., early in the growing season). The rainfall total for June 2000 was four times the average for that month. Increased rainfall at this time likely was important in the SDS epidemic that developed that year. These observations agree with previous research that found direct relationships between SDS severity and increased soil moisture, especially early in the growing season (8,19,25). Early-season rainfall, however, may not be the only important factor. August rainfall amounts also were higher in 2000 than in 1999. High rainfall later in the growing season (i.e., during pod set and filling) also may have contributed to the disease problem in 2000. A similar role for late-season rainfall was suggested by Rupe et al. (23), who observed that SDS did not increase when rainfall was limited after disease onset.

Subsoiling reduced incidence and severity and slowed development of SDS foliar symptoms compared with those in no-till, regardless of disease levels. These results were due to reduced soil compaction that resulted from subsoiling. However, effects of subsoiling on SDS may vary depending on location. This treatment probably is best suited for entire fields or areas within fields that have compacted soils or poor drainage. Duration of these subsoiling effects on SDS is under investigation.

ACKNOWLEDGMENTS

We thank P. Pinnon and J. Klein for their assistance in preparing the field plots and data collection.

LITERATURE CITED

- Anonymous. 1998. Keys to Soil Taxonomy, eighth ed. Pocahontas Press, Blacksburg, VA.
- Chong, S. K., Klubek, B. P., and Varsa, E. C. 1991. Teaching the concepts of soil physical and static water properties in introductory soil science. *J. Agron. Educ.* 20:153-155.
- Fehr, W. R., Caviness, C. E., Burmoud, D. T., and Pennington, J. S. 1971. Stages of development descriptions for soybean, *Glycine max* (L.) Merrill. *Crop Sci.* 11:929-931.
- Gibson, P. T., Shenaut, M. A., Njiti, V. J., Suttner, R. J., and Myers, O., Jr. 1994. Soybean varietal response to sudden death syndrome. *Am. Seed Trade Assoc. Soybean Res. Conf.* 24:20-40.
- Gray, M., Hager, A. G., Hoeft, R. G., Hollinger, S. E., Kirby, H. W., et al. 1998. Illinois Agronomy Handbook. University of Illinois Extension, Urbana.
- Hershman, D. E., Hendrix, J. W., Stucky, R. E., Bachi, P. R., and Henson, G. 1990. Influence of planting date and cultivar on soybean sudden death syndrome in Kentucky. *Plant Dis.* 74:761-766.
- Hilderbrand K. K., Chong, S. K., Myers, O. Jr., Lou, Y., Varsa, E., and Indorante, S. J. 1998. Mapping soybean sudden death syndrome (SDS) as related to soil properties using global positioning system. Page 119 in: *Agronomy Abstracts. American Society of Agronomy, Madison, WI.*
- Hirrel, M. C. 1987. Sudden death syndrome of soybean: New insights into development. *Am. Seed Trade Assoc. Soybean Res. Conf.* 16:95-104.
- Jin, H., G. L., Hartman, Nickell, C. D., and Widholm J. M. 1996. Phytotoxicity of culture filtrates from *Fusarium solani*, the causal agent of sudden death syndrome of soybean. *Plant Dis.* 80:922-927.
- Knudsen, D., Peterson, G. A., and P. F., Pratt. 1982. Lithium, sodium, and potassium. In: *Methods of Soil Analysis, Part 2. Chemical and Microbiology Properties*, second ed. A. L. Page, R. H. Miller, and D. R. Keeney, eds. Monograph 9:199-224.
- Luo, Y., Myers O., Lightfoot, D. A., and Schmidt, M. E. 1999. Root colonization of soybean cultivars in the field by *Fusarium solani* f. sp. *glycines*. *Plant Dis.* 83:1155-1159.
- McLean, E. O. 1982. Soil pH and lime requirement. In: *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, second ed. A. L. Page, R. H., Miller, and D. R. Keeney, eds. Monograph 9:199-224.
- McLean, K. S., and Lawrence, G. W. 1995. Development of *Heterodera glycines* as affected by *Fusarium solani*, the causal agent of sudden death syndrome of soybean. *J. Nematol.* 27:70-77.
- Melgar, J., Roy, K. W., and Abney, T. S. 1994. Sudden death syndrome of soybean: Etiology, symptomatology, and effects of irrigation and *Heterodera glycines* on incidence and severity under field conditions. *Can. J. Bot.* 72:1647-1653.
- Nash, S. M., and Snyder, W. C. 1962. Quantitative estimations by plate counts of propagules of the bean root rot *Fusarium* in field soils. *Phytopathology* 52:567-577.
- Njiti, V. N., Shenuat, M. A., Suttner, R. J., Gray, L. E., Gibson, P. T., and Lightfoot, D. A. 1997. Rate-reducing resistance to *Fusarium solani* f. sp. *phaseoli* underlies field resistance to soybean sudden death syndrome. *Crop Sci.* 37:132-138.
- Olsen, S. R., and Sommers, L. E. 1982. Phosphorus. In: *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, second ed. A. L. Page, R. H. Miller, and D. R. Keeney, eds. Monograph 9:403-430.
- Roy, K. W. 1997. *Fusarium solani* on soybean roots: Nomenclature of the causal agent of sudden death syndrome and identity and relevance of *F. solani* form B. *Plant Dis.* 81:259-266.
- Roy, K. W., Lawrence, G. W., Hodges, H. H., Mclean, K. S., and Killebrew, J. F. 1989. Sudden death syndrome of soybean: *Fusarium solani* as incitant and relation of *Heterodera glycines* to disease severity. *Phytopathology* 79:191-197.
- Rupe, J. C., Rupe, J. C., Hershman, D. E., and Abney, T. S. 1997. Sudden death syndrome of soybean. *Plant Dis.* 81:1100-1111.
- Rupe, J. C. 1989. Frequency and pathogenicity of *Fusarium solani* recovered from soybeans with sudden death syndrome. *Plant Dis.* 73:581-584.
- Rupe, J. C., Becton, C. M., Williams, K. J., and Yount, P. 1996. Isolation, identification, and evaluation of fungi for control of sudden death syndrome. *Can. J. Plant Pathol.* 18:1-6.
- Rupe, J. C., and Gbur, E. E., Jr. 1995. Effect of plant age, maturity group, and the environment on disease progress of sudden death syndrome of soybean. *Plant Dis.* 79:139-143.
- Rupe, J. C., Sabbe W. F., Robbins R. T., and Gbur, E. E., Jr. 1993. Soil and plant factors associated with sudden death syndrome of soybean. *J. Prod. Agric.* 6:218-221.
- Scherm, H., and Yang, X. B. 1996. Development of sudden death syndrome of soybean in relation to soil temperature and soil water potential. *Phytopathology* 86:642-649.
- Scherm, H., Yang, X. B., and Lundeen, P. 1998. Soil variables associated with sudden death syndrome in soybean fields in Iowa. *Plant Dis.* 82:1152-1157.
- Schnitzer, M. 1982. Organic matter characterization. In: *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, second ed. A. L. Page, R. H. Miller, and D. R. Keeney, eds. Monograph 9:581-594.
- Thien, S. J., and Gravel, J. G. 1997. Laboratory Manual for Soil Science, Agricultural and Environmental Principles, seventh ed. Wm. C. Brown, Chicago.
- Tyler, D. D., Overton, J. R., and Chambers, A. Y. 1983. Tillage effects on soil properties, disease, cyst nematodes, and soybean yields. *J. Soil Water Conserv.* 38:374-376.
- Wrather, J. A., Kendig, S. R., Amand, S. C., Niblack, T. C., and Smith, G. S. 1995. Effect of tillage, cultivar, and planting date on percentage of soybean leaves with symptoms of sudden death syndrome. *Plant Dis.* 79:560-562.