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Influence of drainage on soybean seedling health

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Abstract: Subsurface tile drainage is a commonly used agricultural practice in Iowa croplands. Little is known about the effect of drainage on soybean (*Glycine max*) disease. Field and greenhouse studies were conducted to study the effect of drainage on seedling health. A field experiment was conducted at the Iowa State University research farm near Crawfordsville, Iowa, in 2012 and 2013. Four treatments were compared: conventional drainage (CvD, subsurface drains installed 1.2 m [3.9 ft] deep with 18 m [59 ft] spacing), shallow drainage (SD, 0.76 m [2.5 ft] deep with 12.2 m [40 ft] spacing), controlled drainage (CtD, 1.2 m [3.9 ft] deep and 18 m [59 ft] spacing with a water table control structure located at the outlet), and no drainage (ND, no artificial drainage). A greenhouse experiment was conducted three times to compare two soil sources (ND and CvD soil from the field experiment), two soybean cultivars (Ripley and Williams 82), and three watering intensities (low, moderate, and saturated). Plants were sampled at the second trifoliate stage to assess root rot severity, root dry weight, root size, and *Fusarium* spp. incidence in roots. In the field, root rot severity was significantly ($p < 0.01$) greater in the ND and SD drainage treatments than in the CvD treatment in 2013 but not in 2012. *Fusarium* spp. were isolated less frequently from roots grown in ND soil than all other drainage treatments, in both years. In the greenhouse study, watering intensity significantly affected root rot on Ripley, with more water causing more root rot ($p < 0.01$). Despite greater rot, roots showed increased root weight, root length, root diameter, and number of root tips with increasing soil water up to saturation for both varieties. *Fusarium* incidence decreased as water amount increased. In summary, fields with high moisture are more prone to root rot, but well-drained soil favors infection of soybean roots by *Fusarium* spp.

Key words: drainage—*Fusarium* spp.—root rot—soybean

Ample water supply is essential for plant growth; however, excessively wet soils cause several problems including inadequate soil oxygen (O_2) supply, reduced nutrient uptake, poor root growth, inadequate nodulation, and decreased photosynthesis, resulting in reduced foliage that ultimately impacts yield (Linkemer et al. 1998). Soybean (*Glycine max* L.) germination and emergence is favored in well-aerated soils (Pavelis 1987). Additionally, lower soil moisture increases soil trafficability, which can lead to earlier planting and germination, which potentially protect plants from possible later season water deficiency (Bornstin and Hedstrom 1982; Mayhew and Caviness 1994; Mengistu and Heatherly 2006). Subsurface drainage covers 12% of the agriculture land in the United States and accounts for 3.6×10^6 ha (8.9×10^6 ac) of cropland in Iowa (Baker et al. 2004; Evans and Fausey 1999; Garrison et al. 1999; Linkemer et al. 1998). Subsurface drainage is one of the most valuable practices to protect the crops as it can remove excess water after a heavy rain or over irrigation from the upper portions of the active root zone. The benefits of drainage include (1) removing excessive water that accumulated below the surface and therefore creating a well-aerated soil condition that favors soybean germination (Evans and Fausey 1999; Pavelis 1987; Tyagi and Tripathi 1983); (2) increasing trafficability by facilitating heavy machinery to operate in the field without excess compaction (Campbell and O'Sullivan 1991; Zhao et al. 2000); (3) decreasing loss of nutrients and pesticides by reducing the surface water runoff (Baker et al. 2004; Dinnes et al. 2002; Fausey et al. 1995; Kladivko et al. 2004); and (4) decreasing greenhouse gas emission (Kumar et al. 2014). A study done by Linkemer et al. (1998) in Louisiana showed 58% soybean yield increase in sites with improved soil drainage compared to no drainage sites.

Though the benefits are evident, there are also possible consequences of subsurface tile drainage. Nitrogen (N) leaching is increased with drainage due to short-circuiting of water straight to surface waters. This is threatening the hydrological environment due to accumulation of nitrate (NO_3^-) in water sources and hypoxia (O_2 deficiency) (Dinnes et al. 2002; Kladivko et al. 2004); thereby, nonconventional drainage practices, such as controlled drainage and shallow drainage, are being studied (Helmers et al. 2012). These two practices, which reduce NO_3^- loss by reducing drainage volume, have been shown to reduce NO_3^- loss by 18% to 80% across the Midwest and Canada (Sands et al. 2008; Skaggs et al. 2012).

There is little knowledge about how drainage systems affect soybean seedling health. Seedling and root disease have always been significant problems that inhibit soybean yield. Fusarium root rot, for example, was estimated to cause an average yield loss of over 180,000 t (6.6×10^6 bu) y^{-1} in the United States from 1994 to 2010 (Wrather and Koenning 2010; Wrather et al. 1997; Zhang et al. 2010). Several species of *Fusarium* are associated with soybean root rot, including *F. avenaceum, F. graminearum, F. orthoceras, F. oxysporum,* and *F. solani* (French and Kennedy 1963; Killebrew et al. 1993; Leslie et al. 1990; Nyvall 1976; Zhang et al. 2010). *Fusarium* spp. are more active and survive best in dry soil compared to wet soil and, therefore, cause more root disease when soil moisture is not high (Cook and Papendick 1972; Stover 1953; Wong et al. 1984). Although it is

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reasonable to assume that drainage creates a drier soil environment that favors survival of *Fusarium* spp., the link between *Fusarium* spp. abundance and soybean root rot needs to be examined. The objective of this study was to determine the effect of drainage treatments on (1) soybean seedling root rot, (2) seedling root growth, and (3) incidence of *Fusarium* spp. associated with soybean root rot.

Materials and Methods

Field Experiment. Field experiments were conducted within a drainage management research trial at the Iowa State Southeast Research and Demonstration Farm, located near Crawfordsville, Iowa (41°19′38″ N, 91°48′29″ W), in 2012 and 2013. The plots were established in 2007 and became a part of the Cropping Systems Coordinated Agricultural Project in 2011 (sustainablecorn.org). The total research area was 415 × 405 m (1,361 × 1,328 ft) and had an average slope of less than 1%. The site was divided into a northern and southern block; the northern block consisted of Kalona soil (fine, smectitic, mesic Vertic Endoaquolls), and the southern block consisted of Taintor soil (fine, smectitic, mesic Vertic Argiaquolls). Each block consisted of four drainage treatments. These two blocks were analyzed as one experiment considering blocks as replications. Treatments were arranged in a randomized complete block design with two replicates. The four drainage treatments were conventional drainage (CvD), shallow drainage (SD), controlled drainage (CtD), and no drainage (ND). Plots were designed to have a maximum drainage coefficient of 1.9 cm d^{-1} (0.4 in day^{-1}) and ranged in size from 1.2 to 2.4 ha (3 to 5.9 ac). CvD included subsurface drains installed 1.2 m (3.9 ft) deep with 18.0 m (59 ft) spacing; SD had subsurface drains installed 0.76 m (2.5 ft) deep with 12.2 m (40 ft) spacing; CtD consisted of subsurface drains installed 1.2 m (3.9 ft) deep with 18 m (59 ft) spacing, with a water table control structure located at the drainage outlet; and ND had no artificial drainage. The site is under a typical corn (*Zea mays* L.)–soybean rotation, but each plot was split in half so both crops could be grown every year. Two soybean cultivars, Asgrow 1023603 and Pioneer 93Y40, were planted at a rate of 409,453 seeds ha^{-1} (165,700 seeds ac^{-1}) on May 15, 2012, and at the rate of 395,368 seeds ha^{-1} (160,000 seeds ac^{-1}) on June 12, 2013. Tillage operations were done in fall and spring to prepare the seedbed. An automatic on-site meteorological station (IA8688 Washington) as part of the National Climate Data Center located 31 km (19.2 mi) northwest of the research site was used to monitor weather conditions.

Root Analysis. At the V2 growth stage (Fehr et al. 1971), 30 plants were collected from 15 arbitrarily selected sites, two plants from each site, in each plot. Sample size was determined based on a previous research on *Fusarium* species at Iowa State University (Arias 2012). Plants were divided into two groups: group 1, used for root analysis, and group 2, used for isolation of root pathogens. All 15 plants from group 1 were visually assessed for percentage of root rot severity as the percentage of area with root lesions compared to the total root area. An image of each root collected in 2013 was captured using a flatbed scanner (Epson Perfection V700 photo). Images were analyzed using WinRhizo 2008 software (Regent Instrument Inc., Quebec, Canada) to determine root length, root average diameter, and the number of root tips for the whole root. After scanning, each root was dried at 75°C (167°F) for 24 hours, and then weighed. Root imaging, and thus root length, average root diameter, number of tips, and root dry weight were not recorded in 2012.

Fusarium Isolation. Fresh roots from sample group 2 were used for isolating *Fusarium* spp. Four symptomatic root pieces were sectioned from each root, cut into 2 cm (0.8 in) pieces, then surface sterilized in 10% bleach solution for two minutes, rinsed three times in sterilized distilled water, and dried on sterilized paper towels. Root pieces were then placed on water agar media with antibiotics (WA + SM; 20 g [0.70 oz] agar L^{-1} [33.8 fl oz] with 0.3 g [0.01 oz] streptomycin and 14 mg [5×10^{-4} oz] metalaxyl). All plates were incubated for seven days at room temperature (25°C ± 2°C [77°F ± 3.6°F]) under fluorescent light. Fungal colonies from WA + SM were transferred to 1.5 ml (0.05 fl oz) centrifuge tubes containing potato (*Solanum tuberosum* L.) dextrose broth and incubated for seven days at ambient temperature and stored at 4°C (39.2°F) until identification. A total of 100 µl (3.4×10^{-3} fl oz) mycelium suspensions were pipetted from tubes onto carnation (*Dianthus caryophyllus* L.) leaf agar (CLA; 15 g [0.53 oz] agar L^{-1} [33.8 fl oz] with carnation leaves sprinkled) and antibiotic-amended potato dextrose agar (PDA; 39 g [1.4 oz] PDA, 0.15 g [5.3×10^{-3} oz] streptomycin and 0.15 g [5.3×10^{-3} oz] tetrachlorocycline per liter [33.8 fl oz]), and incubated for 5 to 10 days at ambient temperature under fluorescent light. Isolates growing on CLA were microscopically examined for *Fusarium* macroconidia to identify *Fusarium* spp. and determine the incidence. Isolates were grown on PDA to examine the colony morphology. *Fusarium* incidence was estimated using the following formula:

$$\textit{Fusarium} \text{ incidence} = \frac{\text{Number of roots with } \textit{Fusarium} \text{ presence}}{\text{Total root samples per treatment}} \times 100. \quad (1)$$

Greenhouse Experiment. Greenhouse experiments were conducted using soil collected from the Iowa State Southeast Research and Demonstration Farm field experiment plots to indirectly measure levels of root rot pathogens in the long-term drainage plots. Three experimental runs were conducted in 2013: (1) March 13 to April 10, (2) November 7 to December 5, and (3) November 20 to December 18 in the Iowa State University Department of Plant Pathology and Microbiology greenhouse facilities in Ames, Iowa.

Field soil was collected from the ND and CvD plots after harvesting soybean in the 2012 and 2013 growing seasons. Soil collected in 2012 was used in the first run, and soil collected in 2013 was used in the second and third runs. A total of 100 L (26.4 gal) of soil from each drainage system were collected from 15 sites, following a zigzag pattern in each year. A day after collection, soil was shredded into similar sized granules, then sieved through a 5 mm (0.2 in) mesh, and the fine sand granule soil components were stored in 150 L (40 gal) buckets at 4°C (39.2°F) until used for planting.

A three-way factorial, completely randomized design was deployed with 12 total treatment combinations, including 2 soil sources (ND and CvD), 2 soybean cultivars (Ripley and Williams 82), and 3 water regimes (low, moderate, and saturated), with each treatment replicated 10 times in each greenhouse trial. Approximately 380 g (13.4 oz) of 1 cm (0.39 in) sized aggregated soils were placed into a 7.5 cm (3 in) diameter plastic pot with five small holes on the bottom for drainage, then a layer of 1 mm (0.04 in) sized granule soils were added up to a total weight of 450 g (15.8 oz). Four seeds were planted at 2.5 cm (1 in) depth and watered

daily to saturation level until emergence. Plant number in each experimental unit was thinned to two. Water regime treatments were started after plant emergence. Pots were watered using a graduated cylinder with 25 mL (0.84 fl oz), 40 mL (1.35 fl oz), and to saturation every day from emergence until sampling for low, moderate, and saturated water treatments, respectively. Each pot was weighed before and after watering. On average, the difference in weight before and after watering was 25, 35, and 58 g (0.88, 1.23, and 2.04 oz) for the low, moderate, and saturated water treatments, respectively. The greenhouse temperature was ranged from 23°C (73.4°F) to 28°C (82.4°F). Four high-pressure sodium (Na) grow lights, hanging 1.5 m (4.9 ft) above the plants, supplemented natural light for 14 hours a day.

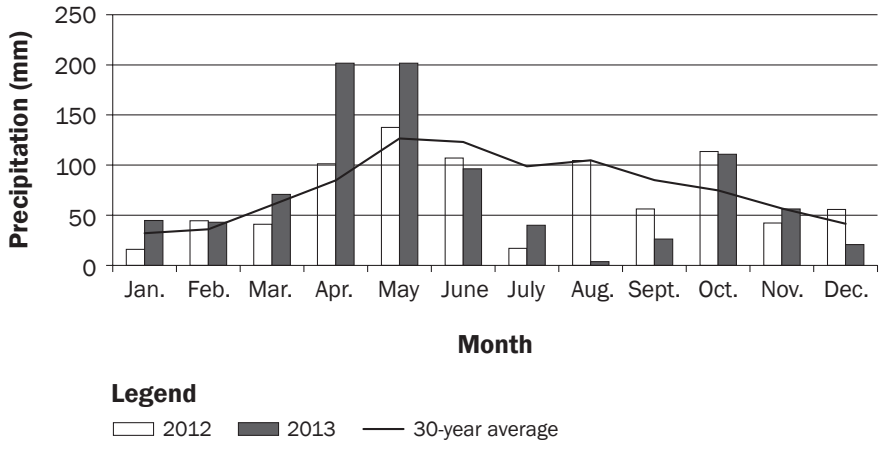
Plants were harvested 28 days after planting at the V2 growth stage (Fehr et al. 1971). The two plants from each pot were arbitrarily assigned to either of the two groups and processed for root analysis and isolation of the pathogen, as described above. For isolation of *Fusarium*, only one piece of each symptomatic root was incubated from the greenhouse experiments where four pieces were used from the field.

Data Analysis. Analysis of variance (ANOVA) was performed in SAS (version 9.4; SAS Institute, Cary, North Carolina) using PROC GLIMMIX for all the parameters. Field and greenhouse tests were analyzed separately. For the field experiment, drainage treatment was used as a fixed factor and replication was considered a random factor in the model. Fisher's protected least square difference (LSD) at $\alpha = 0.05$ was used to separate treatment means. The three runs of the greenhouse experiment were combined because there were no significant interactions between runs and soil source for root rot severity and *Fusarium* incidence. Treatments (soil source, cultivar, watering intensity, and their interactions) were used as fixed factors and replication within greenhouse was used as random factor.

Results and Discussion

Field Experiments. Drainage treatments were significantly different for root rot severity in 2013 ($p < 0.01$), but not in 2012 ($p = 0.10$). Average root rot was over sevenfold greater in 2013 than in 2012 ($p < 0.01$). This might be due, in part, to the difference in precipitation between these two years; the year 2013 was wetter than 2012 (figure 1). Cumulative precipitation from planting to sampling date, roughly a month period, was almost threefold greater in 2013 (88 mm [3.5 in]) than in 2012 (31 mm [1.2 in]). Because of lack of enough precipitation in 2012, the CtD plots were in "free drainage" from April 5 to June 14. In 2012, there were no differences in soil moisture among the treatments, which may be why we did not see differences in root rot percentage as well.

Figure 1
Cumulative monthly precipitation in 2012, 2013, and 30-year average at Crawfordsville, Iowa. Data were obtained from National Weather Service Cooperative Observer Program on Iowa Environmental Mesonet website (http://mesonet.agron.iastate.edu).



In 2013, root rot severity ranged between 22% in CvD plots to 31% in SD plots (table 1). ND and SD treatments had greater root rot compared to the plots with CvD, but there was no difference between CvD and CtD. CtD had less root rot than SD. Fields with ND had greater root rot than CvD. These results suggest that drainage may affect root rot severity. Fields with higher soil moisture from shallower water tables are more prone to root rot because some soybean root rot pathogens need moisture to infect roots (Cook and Papendick 1972). Severe root rot was reported in excessive water conditions for different pathogen-host combinations, including soybean (Kuan and Erwin 1980; Schmitthenner 1985; Tu 1994). Due to the drought at the end of 2012, the water table control boards in the CtD plots were maintained at a depth of 0.76 m (2.5 ft) from the surface for all of 2013. Therefore, the CtD behaved somewhere in between CvD and SD.

Fusarium incidence was significantly different among drainage treatments in both years ($p < 0.01$; table 1). In contrast to root rot severity, *Fusarium* spp. isolation was greater in 2012 than 2013 ($p < 0.01$). This may be due to earlier planting or because the drier soils in 2012 favored *Fusarium* spp. survival (Cook and Papendick 1972; Stover 1953). Across the drainage treatments, *Fusarium* isolation ranged from 35% to 92% of the roots in 2012, and 16% to 59% in 2013. The SD had greater *Fusarium* isolation in both years. Although ND and SD had similar root rot level in 2013, ND had less *Fusarium* isolation than all other drainage treatments in both years. This indicates the root rot in ND was not primarily due to *Fusarium* spp. Other pathogen species, for example *Pythium*, *Phytophthora*, and *Rhizoctonia*, which were not evaluated in this study, might also have contributed to root rot severity (Schmitthenner 1985; Wen 2013). This study also supports that the well-drained soils favor survival and multiplication of *Fusarium* spp. (Cook and Papendick 1972; Stover 1953; Tan et al. 2002; Wong et al. 1984).

Drainage treatments in the field were not significantly different for root dry weight, total root length, average root diameter, and root tips number in 2013 (table 1).

Greenhouse Experiments. Main effects of soil source and cultivars were not significant for root rot severity in the greenhouse ($p = 0.70$; $p = 0.11$), but the soil source × cultivar interaction was significant ($p < 0.01$). On average, Ripley had more root rot in soils from CvD plots than ND plots, while Williams 82 had more root rot on plants grown in ND soil (table 2). For Ripley, CvD had more root rot in the moderate and saturated watering intensities than the ND, which

Table 1
Effect of field drainage treatments on soybean root health at the Iowa State University Southeast Research and Demonstration Farm in 2012 and 2013.

	Least square means†							
	Root rot severity (%)		*Fusarium* incidence (%)		Dry weight (g)	Root length (cm)	Average root diameter (mm)	Root tips number
Treatments*	2012	2013	2012	2013	2013	2013	2013	2013
Conventional drainage	3.7	22.3c	77ab	45b	0.17	48.9	0.98	59
Shallow drainage	4.4	31.0a	92a	53ab	0.16	50.1	0.96	60
Controlled drainage	3.9	26.3bc	55bc	59a	0.15	44.1	1.08	53
No drainage	3.4	30.2ab	35c	16c	0.16	52.1	1.07	63
Mean	3.8	27.4	65	43	0.16	48.8	1.02	59
p value	0.10	<0.01	<0.01	<0.01	0.22	0.11	0.07	0.16

*Conventional drainage = drainage pipes were 1.2 m deep with 18 m spacing. Shallow drainage = drainage pipes were 0.76 m deep with 12.2 m spacing. Controlled drainage = drainage pipes were 1.2 m deep with 18 m spacing, with a valve unit to raise water level if needed. No drainage = no artificial drainage pipes were installed.

†Percentage root rot severity was visually estimated as percentage of area covered by root lesions of the total root area. Root lengths, root diameters, and tips number were obtained by WinRhizo 2008 software (Regent Instrument Inc., Quebec, Canada) analysis of root images produced by Epson Perfection V700 Photo scanner. Root dry weight, length, diameter, and tips were recorded in 2013 only. *Fusarium* genus was identified morphologically. *Fusarium* incidence was estimated using the following formula: (number of roots with *Fusarium* presence ÷ total root per treatment) × 100. Numbers followed by the same letters within a column are not significantly different at $\alpha = 0.05$. Means were separated by protected least significant difference (LSD).

Table 2
Least square means of cultivar, soil source, and watering intensity for soybean root rot severity (%) in greenhouse grown soybean seedlings in 2013*.

Cultivar and soil source†	Watering intensity‡				
	Low	Moderate	Saturate	Mean	*p* value
Ripley					
Conventional drainage	31.7B	45.8A	44.5A	40.7	<0.01
No drainage	33.5B	36.2B	43.5A	37.7	<0.01
Mean	32.6C	41.0B	44.0A	39.2	<0.01
p value	0.29	<0.01	0.63	0.01	—
Williams 82					
Conventional drainage	35.0	38.3	34.3	35.9	0.21
No drainage	42.0	43.4	40.0	41.8	0.36
Mean	38.5	40.8	37.2	38.8	0.10
p value	<0.01	0.03	0.02	<0.01	—

*Percentage root rot severity was visually estimated after plants grown in greenhouse for 28 days as percentage of area covered by root lesions of the total root area. Numbers followed by the same upper case letters within a row are not significantly different at $\alpha < 0.05$. Means were separated by protected least significant difference (LSD).

†Soil was collected from field at Iowa State University Southeast Research Farm at Crawfordsville, Iowa, with different drainage regimes, which were established in 2007. Conventional drainage = drainage pipes 1.2 m deep with 18 m spacing. No drainage = no artificial drainage pipes installed.

‡Low = 25 ml water was applied per pot. Moderate = 35 ml water was applied per pot. Saturated = water was applied until saturation. Each pot had 450 g soil. Pots were watered every day after emergence until sampling.

led to the higher average of root rot overall. This could be due to root rot pathogens that are found in the soil that are more problematic in soils with high moisture. Higher soil moisture in the ND plots may result in more compact soil (Allmaras et al. 1988; Défossez et al. 2003; Hamza and Anderson 2005), and more compact soils favor Fusarium root rot and Phytophthora root rot (Burke et al. 1980; Gray and Pope 1986). There is no clear explanation for the differences in root rot between Ripley and Williams 82 interaction of soil source × cultivar, but the two cultivars differ in root structures and Ripley has moderate resistance to root rots in general (Cooper et al. 1990; Farias-Neto et al. 2007).

Amount of water applied to soil had a significant effect on root rot for Ripley ($p < 0.01$), but not for Williams 82 ($p = 0.10$). For Ripley, low watering intensity caused less root rot compared to moderate and saturated water application, ranging from 32.6% to 44% (table 2).

Fusarium spp. incidence was not different between the two cultivars (table 3). Main effects of soil source and amount of water application were significant, but interactions were not significant. Plants grown in soil from CvD plots had a higher incidence of *Fusarium* isolation from roots than plants grown in soil from ND plots. *Fusarium* incidence decreased as water amount increased. *Fusarium* incidence decreased from 70% to 56% as watering amount increased from 5% to 12%. This result supports our field observations and also confirms previous reports that well-drained and dry soil favor *Fusarium* survival and multiplication (Cook and Papendick 1972; Stover 1953; Tan et al. 2002; Wong et al. 1984).

Root dry weight was not different between soil sources ($p = 0.19$) but increased with increasing watering intensity ($p < 0.01$) (table 3). Root length was different between the two cultivars, and there was a significant cultivar × soil source interaction. Ripley had longer roots in soil from CvD plots than soil

Table 3
Effect of cultivar, soil source, and watering intensity on *Fusarium* spp. incidence and soybean root growth in a greenhouse experiment conducted in 2013.

	Least square means*				
Treatments	***Fusarium* incidence (%)**	**Dry weight (g)**	**Root length (cm)**	**Average root diameter (mm)**	**Root tips number**
Cultivar					
Ripley	65	0.18	404.9	0.46	808
Williams 82	63	0.20	343.7	0.50	646
p value	0.57	<0.01	<0.01	<0.01	<0.01
Soil source†					
Conventional drainage	69	0.19	381.8	0.48	747
No drainage	59	0.20	366.9	0.48	707
p value	0.04	0.19	0.22	0.92	0.15
Watering intensity‡					
Low	70a	0.14c	268.7c	0.44c	581c
Moderate	66ab	0.19b	349.4b	0.47b	695b
Saturate	56b	0.25a	504.8a	0.54a	904a
p value	0.04	<0.01	<0.01	<0.01	<0.01

**Fusarium* genus was identified morphologically. *Fusarium* incidence was estimated using the following formula: (number of roots with *Fusarium* presence ÷ total root per treatment) × 100. Root length, average root diameter, and tips number were given by WinRhizo 2008 software analysis of root images produced by Epson Perfection V700 Photo scanner. Means followed by the same letters within a column are not significantly different at $\alpha = 0.05$. Means were separated by protected least significant difference (LSD).

†Soil was collected from field at Iowa State University Southeast Research Farm at Crawfordsville with different drainage regimes, which were established in 2007. Conventional drainage = drainage pipes were 1.2 m deep with 18 m spacing. No drainage = no artificial drainage pipes were installed.

‡Low = 25 ml water was applied per pot. Moderate = 35 ml water was applied per pot. Saturated = water was applied until saturation. Each pot had 450 g soil. Pots were watered every day after emergence until sampling.

from ND; however Williams 82 had similar root length in both soils. Root length also increased with increasing amount of water. Root diameter was greater in Williams 82, but Ripley had more root tips. Soil source had no significant difference for root diameter and number of tips. Similar to the other parameters, root diameter and number of tips also increased with increasing amount of water. Overall, saturated water treatment had greater root weight, root length, root diameter, and number of root tips suggesting increasing water resulted in greater root growth.

Summary and Conclusions

Root rot was greater in soils with no or shallow drainage while *Fusarium* incidence was least in ND plots in both years. Even with the delayed planting in 2013, average root rot was greater than in 2012 and might be associated with wet soil in 2013.

To indirectly measure if there were different levels of root rot pathogens in the long-term drainage plots, we collected soil from the ND and CvD plots and planted soybeans in these soils under controlled greenhouse conditions. Consistent to the field result, *Fusarium* incidence was less on roots growing in ND soils in the greenhouse experiments. Root rot increased with increasing amount of water applied to the soil while *Fusarium* incidence decreased. In conclusion, root rot is favored by high moisture, but *Fusarium* is isolated more frequently on roots in well-drained soil suggesting that other soil pathogens, which were not evaluated in this study, may have been the cause of root rot. Other root growth measurements (i.e., root weight, root length, root diameter, and number of tips) increased with increasing water suggesting that enough water is required to have better root growth but fields with poor drainage may have a greater risk of root rot. Long-term drainage may affect *Fusarium* population in the field, and under certain conditions it may affect health and growth of soybean roots.

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