EFFICACY OF SEED TREATMENTS AND IN-FURROW FUNGICIDES FOR MANAGEMENT OF DRY BEAN ROOT ROT CAUSED BY *RHIZOCTONIA SOLANI* AND *FUSARIUM SOLANI*, AND FIELD PEA ROOT ROT CAUSED BY *FUSARIUM AVENACEUM* AND *FUSARIUM SOLANI* UNDER FIELD AND GREENHOUSE CONDITIONS

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Chryseis Theresa Tvedt

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Efficacy of seed treatments and in-furrow fungicides for management of dry bean root rot caused by *Rhizoctonia solani* and *Fusarium solani*, and field pea root rot caused by *Fusarium avenaceum* and *Fusarium solani*

By

Chryseis Theresa Tvedt

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Julie Pasche
Chair

Samuel Markell

Michael Wunsch

Thomas DeSutter

Approved:

4/6/2017
Date

Jack Rasmussen
Department Chair

ABSTRACT

Dry bean and field pea root rots have resulted in substantial yield losses in North Dakota. Root rot symptoms range from small lesions to complete root destruction. Traditional management practices such as seed treatment fungicides and crop rotation have proven insufficient under high disease pressure. The objective of this research was to determine the efficacy of in-furrow fungicide applications for management of dry bean and field pea root rot under field and greenhouse conditions. Fungicides were applied in-furrow at planting on dry beans and field peas. In most trials, the inoculated/non-treated control displayed significantly higher levels of root rot than the non-inoculated/non-treated control. In-furrow fungicides generally reduced root rot severity, sometimes significantly over the seed treatment; however, the level of control varied among hosts and pathogens. The results of these studies indicate that the use of in-furrow fungicides, along with cultural practices, may improve the overall management of root rot.

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LITERATURE REVIEW

Legumes

Legumes are part of the Fabaceae family and produce seeds in pods. Over 18,000 legume species exist and may be used for grain, pasture, or agroforestry purposes. Almost all legumes have the ability to fix N through a symbiotic relationship with soil borne or inoculated Rhizobium bacteria; as a result of this process, legumes require fewer N inputs than non-legume crops. Cool season legumes grow best at 18 to 24 C and include clover (*Trifolium* spp.), alfalfa (*Medicago sativa* L.), and field pea (*Pisum sativum* L.); warm season legumes grow best at temperatures greater than 24 C and include soybeans (*Glycine max* L.) and dry beans (*Phaseolus vulgaris* L.) (Graham and Vance, 2003).

Legumes grown in North Dakota include field peas, chickpeas, dry beans, lentils, and soybeans. Dry beans are commonly used in soup chili that have an average seed protein content of 22%. Beans that are not deemed to be food quality are typically used for livestock feed (Myers, 1999). Field peas are low in fat, contain 21-25% protein, and are comprised of 86-87% total digestible nutrients (McKay et al., 2003).

Dry Bean

Dry beans originated over 7,000 years ago in Central and South America and were transported through Mexico and the United States where Native Americans grew them with corn and squash. Today, dry beans are still an important food crop in the United States (Myers, 1999). The United States produces approximately 6 percent of the world's dry beans and ranks 6th in production behind Brazil, India, China, Myanmar, and Mexico (Minor and Bond, 2016). In total, 696,000 dry bean hectares (ha) were planted in the United States in 2014, 712,000 ha in 2015, and 692,000 ha in 2016 with North Dakota, Michigan, Nebraska, and Minnesota as top

producers (USDA-NASS). United States dry bean production has remained relatively stable with a yearly average of 607,000 ha planted since 2009 (Zahniser and Wells, 2014). Dry bean market classes grown in the United States include pinto, navy, black, great northern, light red kidney, dark red kidney, pink, small red, cranberry, and small white beans. Pinto beans are grown on the most hectarage in the United States (39% of total United States hectarage) followed by navy beans (15% of total United States hectarage) (USDA-NASS; Zahniser and Wells, 2014).

North Dakota has been a dry bean producing state since 1970 and has been the number one producer in the United states since 1991 (Glogoza et al., 2000; USDA-NASS). North Dakota produced 37% of total United States dry bean production in 2012, and though only 178,000 ha were planted in 2013 (29% of total United States ha planted), the 2014, 2015, and 2016 growing seasons saw a rebound with 255,000, 265,000, and 253,000 ha planted, respectively (30%, 29.5%, and 29.5% of total United States ha planted) (USDA-NASS). Dry beans are grown in all regions of North Dakota, though the eastern region of the state leads production. Pinto beans are the most commonly planted market class in North Dakota with 150,000 ha planted in 2015 (USDA-NASS). Walsh County led North Dakota in ha of dry beans in 2013, 2014, and 2015 with 26,500, 38,100, and 41,000 ha planted respectively. Grand Forks County followed Walsh County those years with 24,000, 32,500, and 34,600 ha planted, respectively (USDA-NASS).

Production of dry beans in Minnesota has been occurring since the early 1960s. Minnestoa ranked third in United States production in 2015 and 2016 behind North Dakota and Michigan. Growers in Minnesota produced 9.7% of total United States dry beans in 2012, 9.6% in 2013, 10% in 2014, 13% in 2015, and 11.4% in 2016. Kidney beans are most commonly

grown in Minnesota with over 4,000 ha reported in 2015. Polk and Otter Tail counties have led Minnesota in dry bean ha planted 2013 through 2015 (USDA-NASS).

'Avalanche' is a navy bean variety released by the North Dakota Agricultural Experiment Station in 2008. The variety was bred to combine several desirable bean traits such as early maturity, good yield and seed quality, and resistance to multiple diseases. It is a type II, upright vine variety that typically matures in about 102 days, making it well adapted to the North Dakota climate (Osorno et al., 2011).

'Montcalm' is a dark red kidney bean variety released by Michigan State University in 1974 and has grown to be one of the most commonly grown kidney bean varieties (Miklas et al., 2002). It is a full season bush type variety that typically matures in 95 to 105 days, making it well adapted to the growing season of the Midwest (Osorno et al., 2013). Montcalm kidney beans are primarily grown in Minnesota with 1,268 and 1,669 reported ha planted in 2013 and 2015, making it the most planted dry bean variety in Minnesota at 13.6% and 17.4% of total dry bean ha planted, respectively (Knodel et al., 2014; Knodel et al., 2016).

Field Pea

The field pea was one of the first crops grown agriculturally around 10,000 years ago and originated in southwest Asia. It is an important food crop that is used for human consumption and livestock feed (Sell, 1993). The field pea is a vegetable, pulse crop, and legume that germinates and emerges best at 12 to 18 C in cool, semi-arid climates. The crop generally grows to be 61 to 122 cm tall and is separated into two growing types – bush or vine. Most vine-type cultivated peas are semi-leafless, with modified leaflets that are clusters of tendrils instead of true leaves. In North Dakota, peas are typically planted in late April and May in 15 to 30 cm rows at about 122,000 seeds per ha (McKay et al., 2003).

Over 10 million ha of field peas are grown worldwide with Russia, China, Canada, Europe, Australia, and the United States as the top producers (McKay et al., 2003). About 364,000 to 526,000 ha of field peas were grown from 2013 to 2016, respectively in the United States, a considerable increase from the 121,000 and 243,000 ha planted in 2011 and 2012, respectively. From 2005 to 2010, 283,000 to 364,000 ha were planted in the United States. Montana, North Dakota, Idaho, Oregon, and Washington lead United States field pea production (USDA-NASS). While both green and yellow cotyledon field peas are grown in the United States, the yellow type is more common and produces higher yield than the green type (McVay et al., 2013).

North Dakota is the second-largest producer of field peas, following Montana (USDA-NASS). In 2012 through 2016, 95,000 to 202,000 ha of field peas were planted in North Dakota, accounting for from 28%, to 39% of total United States field pea ha planted, respectively (USDA-NASS). North Dakota field pea production is most heavily concentrated in the northwestern region of the state. Divide County led North Dakota in pea planted ha in 2013 and 2014 with 15,600 and 13,600 ha planted, respectively. In 2015, McLean and Divide counties led with 15,600 and 15,500 ha planted, respectively (USDA-NASS).

'DS Admiral' is a field pea variety that was developed by the Danisco Seed Company in Denmark and released in June of 2000 by the Canadian Food Inspection Agency, Variety Registration Office. The variety has good yield, is early maturing (96 days), and has good lodging resistance. It is a medium-sized, yellow cotyledon, semi-leafless variety that has a round seeds and white flowers (Andersen et al., 2002).

Root Rot

Root rot is a term used to describe discoloration and decay of plant roots caused by a pathogen. Root rot of dry beans and field peas has caused damping off and yield loss in North Dakota for several years. Above ground, root rot may appear in circular or irregular patches in a field and produce stunting, yellowing, premature leaf drop, and poor pod fill. However, the absence of above-ground symptoms does not necessarily indicate lack of disease, as a plant may appear healthy until removed from the soil. Below ground, root rot symptoms include irregular-shaped, dark, necrotic lesions on the roots and lower stem that grow with age (Schwartz, 2011). In response to root rot pathogens, dry bean and field pea plants may compensate for root loss by forming adventitious roots - lateral roots that grow from the main stem above the root rot infection (Gossen et al., 2016; Snapp et al., 2003).

Root rot was among the top five worst disease problems in dry beans in 2013 and 2015 in North Dakota and continues to be a concern today (Knodel et al., 2014; Knodel et al., 2016). *Fusarium solani* (Martius) Appel & Wollenweber emend. Snyder & Hansen is the leading cause of dry bean root rot in North Dakota and Minnesota followed by *Rhizoctonia solani* Kühn (Goswami and Rasmussen, 2009). Fusarium and Rhizoctonia root rots of dry bean are capable of causing over 80% yield loss (Gossen et al., 2016). Symptoms of root rot in dry bean include red-brown lesions on the hypocotyl and primary root that expand and darken with age. Longitudinal cracks may also form in older lesions, and root death may occur (Schwartz, 2011).

Field pea root rot in North Dakota is caused by a disease complex that includes *Fusarium* spp., *Pythium* spp., *Aphanomyces euteiches* Drechs, and *Rhizoctonia solani* Kühn. Root rot is currently the most damaging disease in North Dakota field pea production and can cause 60 to 75% yield loss (Endres et al., 2009; Gossen et al., 2016; Sharma-Poudyal et al., 2015). *Fusarium*

solani (Martius) Appel & Wollenweber emend. Snyder & Hansen is among the most common pathogens to infect peas, and *Fusarium avenaceum* (Fries) Saccardo has also become a major root rot concern in peas in North Dakota as well as other pea production areas in the United States and Canada within the past decade (Chittem et al., 2015; Mathew et al., 2008). Conducive infection conditions for Fusarium root rot of field pea include warm, moist soil, short crop rotations that allow primary inoculum to build up, tillage systems that allow infected crop residue to remain near the soil surface, and plants that are stressed by drought, flooding, soil compaction, or extreme soil temperatures (Gossen et al., 2016). In peas, root rot symptoms are typically most prominent on the taproot near the seed. Red-brown lesions may appear on root surfaces and in vascular tissue of the root causing reduced root growth or death (Malvick and Babadoost, 2002). Severe infection may sever the root.

The resting structures – sclerotia, hardened mycelia, or chlamydospores – are the primary inoculum of the root rot pathogens, overwinter in soil or host debris, and germinate in the presence of root exudates. Once primary infection is caused by mycelium, macroconidia, or microconidia, the pathogen spreads within the host root system and to neighboring plants with secondary spores or mycelial growth. At the end of the growing season, resting structures form in the host debris and soil (Gossen et al., 2016).

Rhizoctonia solani

Rhizoctonia solani (teleomorph *Thanatephorus cucumeris* (Frank) Donk) is a phytopathogenic basidiomycete fungus first described in 1858 on potato by Julius Kühn (Ogoshi, 1987). The fungus does not produce conidia and rarely produces basidiospores. Its primary method of reproduction is as vegetative mycelium and sclerotia. Hardened mycelium can also act as a survival structure. This fungus typically lives in soil and infects the roots and shoots of a

wide variety of crops including dry bean, sugar beet, corn, rice, and potato (Ceresini, 1999; Gossen et al., 2016; Pena et al., 2013). *R. solani* infection is favorable under wet conditions and an average temperature of 18 C (Muyolo et al., 1993). Though infection occurs at temperatures above 17.5 C, hyphal growth is most rapid at 24 to 30 C (Gossen et al., 2016). On PDA growth medium, *R. solani* produces mycelium densely bound to the growth medium and hyaline though it may turn brown with age. Microscopically, *R. solani* can be identified by its characteristic hyphal branching at a 90-degree angle and lack of conidia.

R. solani is classified by anastomosis groups (AG) (Hanson, 2005). Isolates with hyphae that successfully fuse (anastomose) with each other are considered genetically related and part of the same AG (Ceresini, 1999). Even when sexual structures are formed, it is not possible to differentiate AGs morphologically (with the exception of AG4, which produces three sterigmata instead of four) (Ogoshi, 1987). There are currently 14 AG with some groups containing subdivisions. Anastomosis groups 1, 1-IB, 2-2-IIIB, 2-2-IV, 4, and 5 are pathogenic on dry beans, and AG4 most commonly causes Rhizoctonia root rot on dry bean worldwide (Eken and Demirci, 2004; Mathew et al., 2012; Yang and Li, 2012).

Among others, AG2-2 and AG4 are found in North Dakota, and both cause high disease severity. Although AG2-2 is more aggressive on dry beans than AG4, AG4 remains most important on dry beans worldwide due to a wider geographic distribution than AG2-2 (Muyolo et al., 1993; Eken and Demirci, 2004). AG2-2-IIIB is capable of growing at 35 C while AG2-2-IV prefers cooler temperatures; both are prevalent in North Dakota (Muyolo et al., 1993; Brantner and Windels, 2007). AG2-2-IIIB is more aggressive on dry bean and is found in higher frequencies in dry bean fields than AG2-2-IV (Engelkes and Windels, 1996; Brantner and Windels, 2007). *R. solani* is also a pathogen of field peas, but is not considered among the most

prevalent and damaging root rotting pathogens (Chittem et al., 2015; Mathew et al., 2008). AG 2-1, 3, 4, 8, 5, 9, and 10 infect field peas. Of those, AG4 and AG2-1 are most commonly associated with field peas and cause the most severe infection (Sharma-Poudyal et al., 2015; Yang and Li, 2012).

Fusarium solani

Fusarium solani (teleomorph *Nectria haematococca* ((Berkeley & Broome) Samuels & Nirenberg) is a phytopathogenic fungus that typically survives in soil as chlamydospores and causes several significant tuber, root, and stem rot diseases on crops (Agrios, 2005). Dr. Carl Friedrich Philipp von Martius first described the fungus in 1842 as *Fusisporium solani* on rotted potatoes. The genus name was then altered to *Fusarium* in 1881 by mycologist Dr. Pier Saccardo (Luginbuhl, 2010).

On potato dextrose agar (PDA) growth medium, *F. solani* exhibits white-cream or colored mycelium that grows quickly and appears fluffy (Luginbuhl, 2010). *F. solani* produces two types of microscopic asexual reproductive structures; macroconidia and microconidia. The most obvious distinction between these spore types is size and shape. Macroconidia of *F. solani* formed in cream, blue, or green sporodochia are straight or slightly curved (canoe-shaped) and relatively wide with 3 to 7 septa and a distinctive basal cell with a notched or rounded end. Microconidia are smaller than macroconidia, form on long monophialides in aerial mycelia, and are ellipsoid with 0 to 1 septa. Chlamydospores are the thick-walled survival structures formed by *F. solani* that may form intercalary or terminally on the hyphae. Chlamydospores are globose with smooth or rough walls and may form singly or in pairs. Sexual reproductive structures, ascospores, are produced in red or orange perithecia readily in wet, tropical environments;

however, the sexual stage of *F. solani* is rarely observed in more temperate climates (Leslie and Summerell, 2006).

Fusarium avenaceum

Fusarium avenaceum (teleomorph *Gibberella avenacea* (Cook)) is a soil borne, necrotrophic pathogen that is widely distributed throughout the world. It has a wide host range and causes root rot symptoms that are most severe at 25 to 30 C (Gossen et al., 2016). Its morphology in culture is highly variable, producing mycelium that may grow slowly, appear dense, and can be pink, brown, gray, or burgundy (Leslie and Summerell, 2006; Sangalang et al., 1995). Of the two types of conidia formed by *F. avenaceum*, macroconidia are produced more commonly than microconidia. Macroconidia are formed in brown or orange sporodochia and are straight or slightly curved (canoe-shaped), long and slender tapering to a point, and have 3 to 5 septa with a notched or foot-shaped basal cell. Microconidia may be formed on monphialides or polyphialides in aerial mycelia and are fusoid – wide center with tapering ends – with 1 or 2 septa. Unlike most *Fusarium* species, *F. avenaceum* does not produce chlamydospores which makes the presence of host residue in the upper layer of soil important for survival of the pathogen. No sexual state has been identified for this species (Leslie and Summerell, 2006).

Root Rot Management

Root rot of dry beans and field peas can be managed with crop rotation to reduce initial inoculum in the soil. A three or four year rotation with alfalfa, barley, oats, wheat, or corn will reduce Rhizoctonia root rot severity. Fusarium root rot management via crop rotation is difficult due to the expansive host range of *Fusarium* spp. that encompasses sugar beets, potatoes, cereals, and legumes, all grown in North Dakota in rotation with dry beans and field peas (Gossen et al., 2016).

Tillage also decreases soil inoculum because it buries crop residue in which the pathogen survives, which exposes the residue to soil-borne organisms that decay plant material (Schwartz, 2011). Deep tillage is especially effective for managing *F. avenaceum* inoculum since the pathogen does not produce chlamydospores and, therefore, must survive on host residue. *R. solani* and *F. solani* survive in the soil as sclerotia and chlamydospores, respectively; therefore, tillage is not as effective in controlling these pathogens (Gossen et al., 2016). Shallow planting in warm, moist soil aids in rapid emergence and growth, thereby helping the plant escape infection by growing beyond the plant's most vulnerable seed and seedling stage (Gossen et al., 2016). Planting seed that is high-quality and certified also maximizes growth and vigor (Schwartz, 2011). Reducing soil compaction with cultivation and managing irrigation to minimize excess moisture are also useful management practices for root rot. Minnesota and North Dakota have few irrigated dry bean and field pea ha; Minnesota has more irrigated dry bean ha than North Dakota (Knodel et al., 2016). However, managing irrigation runoff of those ha will help control the spread of the pathogen (Schwartz, 2011). Growers may also promote the growth of adventitious roots by cultivating in a way that increases soil-to-stem contact. Integrating the various disease management practices mentioned above will help to reduce root rot incidence. However, under severe disease pressure, these management strategies do not provide adequate management (Snapp et al., 2003).

Integrating host resistance to root rot into new varieties is the most environmentally friendly, and economically feasible management strategy. In addition to reducing disease severity in the current crop, host resistance reduces the accumulation of primary inoculum for future planting seasons (Agrios, 2005). No complete resistance to Rhizoctonia or Fusarium root rot in dry bean, or to Fusarium root rot in field pea has been identified; however, partial

resistance and tolerance have been identified in some cultivars (Gossen et al., 2016; Feng et al., 2010). Partial resistance to dry bean root rot caused by *R. solani* is more prevalent in Mesoamerican than Andean gene pools (Goswami and Rasmussen, 2009; Pena et al., 2013). Fusarium root rot resistance in field pea is likely linked to seed color, as darker-pigmented seed show higher partial resistance to root rot (Porter, 2010).

Chemical Root Rot Management

In addition to other management techniques described above, root rot is commonly managed through chemical control with seed treatment fungicides. Fungicides are used as curatives and protectants against fungal plant diseases by directly affecting and inhibiting a fungal pathogen. Fungicidal seed treatments are used for three primary reasons: (1) to manage a fungal disease during the early stages of plant growth, (2) to reduce fungal disease during the life of the plant so that it may be more productive, and (3) to reduce fungal rots of stored crops. Fungicides are classified and grouped by the Fungicide Resistance Action Committee (FRAC). Fungicides within the same FRAC group have similar chemical composition and mode of action (McGrath, 2004).

Seed treatments are a commonly utilized option to manage root rot in field pea and dry bean. The two prominent seed treatments used in North Dakota are mefenoxam/fludioxonil (Apron MAXX, 11.5 g mefenoxam/L, 7.7 g fludioxonil/L; Syngenta Crop Protection, Greensboro, NC) and fludioxonil (Maxim, 25.2 g active ingredient (AI)/L; Syngenta Crop Protection, Greensboro, NC). Mefenoxam/fludioxonil is the most commonly used seed treatment in North Dakota (Knodel et al., 2014; Knodel et al., 2016).

Fludioxonil and mefenoxam belong to the PhenylPyrrole (PP) and PhenylAmide (PA) groups, respectively. PP fungicides interfere with the transportation of sugars and amino acids in

the fungal membrane and have a low to moderate resistance risk. PA fungicides inhibit rRNA biosynthesis and have a high risk of resistance development (FRAC, 2014). Fludioxonil has been shown to significantly reduce the severity of Fusarium tuber rot in caladium caused by *F. solani* (Vea and Palmer, 2013). However, the active ingredient fludioxonil has shown only moderate suppression of disease caused by *Rhizoctonia* species on soybean (Meyer et al., 2005). Mefenoxam and fludioxonil applied separately as a drench significantly reduced disease incidence caused by *R. solani* and *F. solani* on cowpea (Ramusi et al., 2017). Mefenoxam/fludioxonil seed treatment improved yield and plant emergence of faba beans infected with root rot caused by *F. avenaceum* and *R. solani* (Chang et al., 2014). Though seed treatment fungicides are a commonly utilized option for root rot management, they do not provide satisfactory management when disease pressure is high (Gossen et al., 2016).

In-furrow Fungicides

A less common method of chemical management is the in-furrow application of fungicides, which involves spraying a fungicide directly into the furrow as planting occurs. Like seed treatments, in-furrow applications help to suppress disease incidence and severity while the plant is at its most vulnerable seed and seedling stage. The fungicide will not provide protection from soil-borne diseases through the entire growing season, but it will help to improve seedling health and stand establishment so that the plant may reach an age where it is less affected by soil pathogens (Rideout, 2002). In-furrow fungicide applications have shown to improve stand and yield in peanuts, sugar beets, potatoes, wheat, and corn (Cotterill, 1991; Keyes, 2015; Rideout, 2002).

Fungicides from numerous classes such as quinone outside inhibitors (QoI), triazoles, and succinate dehydrogenase inhibitors (SDHI) have been utilized for in-furrow applications. QoI

fungicides act at the Quinol outer binding site of the cytochrome bc1 complex, inhibiting the mitochondrial respiration process and disrupting membrane synthesis by blocking demethylation; they have a high risk of resistance development. DMI fungicides disrupt membrane synthesis by inhibiting demethylation of sterol biosynthesis and have a moderate risk of resistance development. SDHI fungicides target the mitochondrial respiration chain thereby disrupting the tricarboxylic cycle and mitochondrial electron transport chain; they have a medium to high risk of resistance development (FRAC, 2014).

QoI fungicides are more effective than triazole fungicides in managing root rot caused by *R. solani* in sugar beet when band applied (Windels and Brantner, 2008). Azoxystrobin (Quadris, 249.3 g AI/L; Syngenta Crop Protection, Greensboro, NC) provides significant efficacy on crown and stem rot of lisianthus caused by *F. solani* and *F. avenaceum* and *R. solani* on sugar beet (Vea and Palmer, 2013; Windels and Brantner, 2005). Pyraclostrobin (Headline, 249.3 g AI/L; BASF, Research Triangle Park, NC), when applied in-furrow, significantly reduced root rot caused by *F. solani* on snap beans (Vea and Palmer, 2013). Though there has been little research into the impact of picoxystrobin (Aproach, 249.3 g AI/L; DuPont, Wilmington, DE) on Fusarium root rot, it provided adequate protection against *R. solani* on sugar beets (Khan and Carlson, 2012).

Triazole fungicides are a subgroup of the FRAC group DeMethylation Inhibitors (DMI). Prothioconazole (Proline, 479.4 g AI/L; Bayer CropScience, Research Triangle Park, NC) is effective against numerous *Fusarium* species in watermelon when applied as a soil drench (Vea and Palmer, 2013). It is also effective against *R. solani* in sugar beets when applied after planting (Bolton et al., 2010). Metconazole (Caramba, 89.9 g AI/L; BASF, Research Triangle Park, NC) is effective against root rot caused by *F. solani* on various crops, though no significant

reduction in root rot caused by *R. solani* was observed when metconazole was applied in sugar beets (Vea and Palmer, 2013; Windels and Brantner, 2008).

Boscalid (Endura, 674.9 g AI/L; BASF, Research Triangle Park, NC) is an SDHI that has shown promising results against damping off and root rot caused by *Fusarium* species on various trees when mixed with pyraclostrobin (Vea and Palmer, 2013). The boscalid-pyraclostrobin mixture has also proven very effective against *R. solani* on soybean (Meyer et al., 2005). Fluxapyroxad/pyraclostrobin (Priaxor, 166.6 g fluxapyroxad/L, 333.2 g pyraclostrobin/L; BASF, Research Triangle Park, NC) is a relatively new fungicide. Fluxapyroxad, the SDHI component, has been effective against rice sheath blight caused by *R. solani*, though there has been limited research on its effects on root rots (Chen et al., 2014). The active ingredients fluopyram (Velum Prime, 498.5 g AI/L; Bayer CropScience, Research Triangle Park, NC), penthiopyrad (Vertisan, 200.1 g AI/L, DuPont, Wilmington, DE), and fluxapyroxad are more recently developed SDHI fungicides selected to work well on both basidiomycetes and ascomycetes (Avenot and Michailides, 2010).

The fungicides described above are commonly used on numerous crops throughout agriculture, including dry beans and field peas. Boscalid, pyraclostrobin, fluxapyroxad/pyraclostrobin, prothioconazole, picoxystrobin, and azoxystrobin were listed among the top 15 foliar fungicides applied in North Dakota in 2013 and 2015 (Knodel et al., 2014; Knodel et al., 2016). Though these fungicides are commonly used, they are not typically applied in-furrow on field peas and dry beans. However, a small percentage of dry bean hectarage was treated in-furrow with pyraclostrobin, fluxapyroxad/pyraclostrobin, and boscalid in North Dakota and Minnesota in 2015 (Knodel et al., 2016). With research and development

of procedures, however, in-furrow fungicide applications in dry beans and field peas may become more common in the future.

Chemical Behavior in Soil

Soil is a medium for plant growth and is composed of sand, silt, and clay. Nearly all of Earth's inhabitants rely on soil for sustenance since all food chains begin with plant growth. From soil, plants collect nutrients, air, water, and physical support (Brady and Weil, 2008). Many types of soils are used in agriculture including field soil and greenhouse potting mix. Once a chemical makes contact with soil, it can move in a variety of ways. It may be volatilized into the atmosphere, leach through the soil, be decomposed by microorganisms, be taken up by plants, or be adsorbed to the soil and be immobile (Brady and Weil, 2008). When a chemical is immobile, it is said to have been adsorbed and is unavailable to the chemical's plant or pathogen target (Strek and Weber, 1982). This interaction is of importance for in-furrow fungicide applications. The degree to which a chemical is adsorbed by the soil depends upon the characteristics of both the chemical compound and the soil. Soil that has high organic matter and clay with large surface areas tend to be the strongest adsorbents. Adsorption to silicate clays is dependent upon pH, with lower pH compounds more readily adsorbed; whereas adsorption to organic matter is based on chemical structure (Brady and Weil, 2008). Chemical compounds with functional groups such as –OH, $-NH_2$, -NHR, $-CONH_2$, -COOR, and $-^{+}NH_2$ adsorb strongly to soil humus (Albers et al., 2009). Large organic molecules with many charged sites also are more strongly adsorbed to soil than smaller molecules (Brady and Weil, 2008). An experiment conducted using the chemical pollutant polychlorinated biphenyl showed that soils with organic matter removed with hydrogen peroxide (H_2O_2) lost almost all chemical adsorption capability (Strek and Weber, 1982).

Soil Distribution Coefficients

The tendency of an organic compound, such as a fungicide, to remain within a soil is termed the soil distribution coefficient (K_d). This coefficient is the ratio of the amount of chemical adsorbed by the soil to the amount of chemical remaining in solution (Brady and Weil, 2008).

$$K_d = \frac{\text{mg chemical sorbed per kg soil}}{\text{mg chemical per L solution}}$$

The K_d for chemicals tends to vary widely depending upon the organic matter level of the soil in which it is distributed. Therefore, soil scientists use a similar distribution ratio that focuses on adsorption by organic matter; it is termed the organic carbon distribution coefficient (K_{oc}) and is the ratio of the amount of chemical adsorbed in organic carbon to the amount of chemical remaining in solution.

$$K_{oc} = \frac{\text{mg chemical sorbed per kg organic carbon}}{\text{mg chemical per L solution}}$$

Chemicals with higher K_{oc} values are more tightly adsorbed by the soil and are therefore less available for movement or uptake by plants and microorganisms (Brady and Weil, 2008). Therefore, fungicide efficacy, either in the form of seed treatment or in-furrow application, depend upon the interaction with differing soil types.

Soil Moisture

Another major determinant of fungicide fate is soil moisture. Fungicides move within soil the same way water does. Water or chemical percolates downward within a soil profile due to gravity. Excess water that cannot be held by the soil will leach away and is termed gravitational water. Once gravitational water has finished draining away, matric forces hold the water that remains; this soil is said to be at field capacity (Brady and Weil, 2008). The amount

of available water in a soil depends on texture and organic matter content. Sand contains the least and clay contains the most plant available water. Increased organic matter content also increases plant available water (Shaxson and Barber, 2003).

Additionally, fungicides are more mobile in wet soil than dry soil, and increasing soil moisture will displace adsorbed fungicides, making them more abundant in the soil solution to volatilize, leach away, or be active against their intended target (Munnecke, 1972).

Summary

The production of dry beans and field peas is extremely important for North Dakota growers. Root rot of dry bean caused by *R. solani* and *F. solani*, and root rot of field pea caused by *F. avenaceum* and *F. solani* are significant problems in regions of North Dakota that are major producers of those crops. Under severe disease pressure, traditional methods of root rot management including, host resistance, tillage and seed treatment fungicides do not provide adequate management; therefore, other management practices need to be developed. In-furrow fungicide applications have proven effective in other crops such as sugar beet and potato; therefore it is prudent to evaluate this application method for dry beans and field peas though their efficacy may partially depend on adsorption in soil.

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CHAPTER 1: EFFICACY OF SEED TREATMENTS AND IN-FURROW FUNGICIDES FOR MANAGEMENT OF DRY BEAN ROOT ROT CAUSED BY *RHIZOCTONIA SOLANI* AND *FUSARIUM SOLANI* UNDER FIELD AND GREENHOUSE CONDITIONS

Introduction

North Dakota has been the top producer of dry beans in the United States since 1991, accounting for 29% to 37% of total United States dry bean production from 2012 to 2016 (USDA-NASS). Pinto, black, and navy beans are the most commonly grown market class in North Dakota with Walsh and Grand Forks counties leading production. Kidney, navy, and black beans are most commonly grown in Minnesota (Knodel et al., 2016).

Dry bean root rot is an important yield limiting disease in North Dakota that causes restriction of water and nutrient uptake by the plant. This disease was considered among the top three dry bean diseases in North Dakota in 2013 through 2015 by growers, and it is capable of causing 84% to 88% yield loss (Gossen et al., 2016; Knodel et al., 2014; 2015; 2016). The two pathogens that most commonly cause dry bean root rot in North Dakota are *Rhizoctonia solani* Kühn and *Fusarium solani* (Martius) Appel & Wollenweber emend. Snyder & Hansen (Goswami and Rasmussen, 2009).

Above ground, root rot symptoms appear as chlorotic, stunted patches in the field and may lead to premature leaf drop and poor pod fill. However, above-ground symptoms may not always be evident in infected fields; therefore, plant roots must be examined to effectively identify root rot. Below ground, general root rot symptoms include red or brown, necrotic lesions on the hypocotyl and primary root that grow and darken with age. In older lesions,

longitudinal cracks may form, and roots may die or be severed by pathogen destruction (Schwartz, 2011).

Traditionally, dry bean root rot has been managed with fungicide seed treatments, crop rotation, more aggressive tillage, and timely, shallow planting of certified seed in warm, moist soil (Gossen et al., 2016; Schwartz, 2011). The level of host resistance to root rot and the above management tactics do not provide satisfactory management under severe disease pressure (Gossen et al., 2016). In-furrow fungicides are sprayed directly into the furrow at planting with the seed and allow the plant to grow beyond its most vulnerable seed and seedling stage without infection (Rideout, 2002). In-furrow fungicides have improved stand and yield in crops such as potatoes, sugar beets, peanuts, wheat, and corn, and therefore, may be a viable option to manage root rot of dry beans (Cotterill, 1991; Keyes, 2015; Rideout, 2002). This project is targeted at identifying fungicides shown to be, or that have the potential to be, efficacious against the root rot pathogens most damaging in the field pea and dry bean growing regions of North Dakota. Also, results will provide the relative efficacy of the fungicides applied in-furrow and compare that efficacy against standard seed treatment fungicides. The objective of this research was to determine the efficacy of the application of in-furrow fungicides for management of dry bean root rot caused by *R. solani* and *F. solani*.

Materials and Methods

Inoculum Preparation

For each field and greenhouse trial, pathogen-infested grain was added to the soil. Each pathogen isolate was grown at 20 C, with a 12-hour photoperiod, for 14 days on potato dextrose agar (PDA) (Becton, Dickinson and Company, Sparks, MD; 4 grams potato starch, 20 grams dextrose, and 15 grams agar per liter) amended with 1 mL of 5% streptomycin sulfate and

neomycin sulfate per 500 mL PDA media. In greenhouse trials, the pathogen was grown on sterilized wheat kernels. In field trials, the pathogen was grown on either wheat or millet kernels. For small quantities used for greenhouse trials, the inoculum was made in Erlenmeyer flasks containing 100 mg of grain. For large quantities used for field trials, the inoculum was made in metal trays containing 1.5 kg of grain. Grain was soaked in water overnight, the water was drained, and sterilized via autoclaving at 121 C to remove contamination and to prevent germination of the grain. Flasks were autoclaved for one hour; trays were autoclaved for two hours. The following day, the trays/flasks were autoclaved a second time. After cooling, the grain was inoculated with the pathogen and allowed to grow for approximately 14 days (Table 1.2). The grain was mixed every three days to ensure uniform infestation. The trays/flasks were emptied onto butcher's paper where the grain was spread to dry. Finally, the dry inoculum was collected, sieved, and bagged or packaged for planting. Inoculum was stored in a freezer at 4 C and remained highly aggressive for approximately six months based on greenhouse trials conducted.

Greenhouse Trials

Phytotoxicity Trial

To determine if the application of in-furrow fungicides is phytotoxic to plant development, fungicides were applied in-furrow in non-inoculated Pro-mix LP15 (Premier Tech Horticulture, Quakertown, PA) potting soil. Pots measuring 27 cm x 13.5 cm x 13 cm deep were filled with potting soil. A furrow was created in the soil and four pots were placed end to end in a spray chamber with the soil surface was approximately 7.5 cm below the spray nozzle. The fungicides were sprayed using a calibrated chain-driven chamber sprayer (DeVries Manufacturing, Hollandale, MN) calibrated to deliver 65 L/ha by compressed air at 137 kPa and

1.8 m/s through a 4001E even fan nozzle (TeeJet Technologies, Springfield, IL). The three FRAC 11 fungicides were applied in-furrow at three rates (Table 1.1).

Table 1.1. In-furrow fungicide active ingredients, trade names, companies, fungicide resistance action committee (FRAC) groups, and formulated product rates for the greenhouse trials.

Fungicide active ingredient	Trade name	Active ingredient concentration (%)	Company	FRAC	Rate 1 (L/ha)	Rate 2 (L/ha)	Rate 3 (L/ha)
Azoxystrobin	Quadris	22.9	Syngenta	11	.45	.66	.88
Pyraclostrobin	Headline	23.6	BASF	11	.45	.66	.88
Picoxystrobin	Aproach	22.5	DuPont	11	.45	.66	.88
Prothioconazole	Proline	41.0	Bayer	3	.31	.42	
Fluopyram	Velum Prime	41.5	Bayer	7	.40	.50	
Penthiopyrad	Vertisan	20.6	DuPont	7	.80	1.02	1.46

Seeds were planted 4 cm deep into the furrow either before spraying so that the fungicide was in direct contact with the seed, or after spraying so that there was limited contact between the fungicide and seed. Five root rot susceptible ‘Montcalm’ dark red kidney bean (Michigan Agricultural Experiment Station; Michigan State University) seeds were planted per pot based on 76 cm rows and a population of 161,000 seeds/ha. The furrows were covered with soil and watered. After 14 days, emergence and plant height were recorded. The trial was conducted as a three-factor (fungicide x rate x application timing) randomized complete block design (RCBD) with 18 treatments and four replicates, totaling 72 experimental units.

Isolate Pathogenicity/Aggressiveness Trial

The pathogenicity and aggressiveness of three *R. solani* isolates were tested in the greenhouse to determine which isolate, placement of the kernel inoculum, and length of plant development provides adequate disease severity to effectively evaluate in-furrow fungicide

efficacy in the field and greenhouse. Five *F. solani* isolates were tested in the greenhouse for pathogenicity and aggressiveness to be used in field and greenhouse trials (Table 1.2).

Table 1.2. *Rhizoctonia solani* and *Fusarium solani* isolates used in the isolate pathogenicity and aggressiveness trials.

Isolate name	Pathogen	AG†
DB Rhizoc 6	*R. solani*	2-2
SB Rhizoc 3	*R. solani*	2-2
07RGBR1	*R. solani*	4
Fsp NDSU	*F. solani*	NA
91.113.3	*F. solani*	NA
101-5	*F. solani*	NA
F. solani 1	*F. solani*	NA
F. solani 2	*F. solani*	NA

† Anastomosis group

Pots were filled with Pro-mix LP15 potting soil and inoculated with wheat seeds infested with a single *R. solani* isolate. Three 'Montcalm' bean seeds were planted 4 cm deep per pot and one infested kernel was placed either next to, or 1.5 cm below the seed. The furrows were covered with soil and watered. After 14 or 30 days, plants were removed and roots were washed. Root rot severity was measured using a linear scale of 1 to 9 (Figure 1.1; Van Schoonhoven and Pastor-Corrales, 1987). For *R. solani*, the experimental design was a three factor (isolate x inoculum placement x timing) factorial RCBD with 13 treatments and three replicates, totaling 39 experimental units. For *F. solani*, a single infested kernel was placed next to the seed and plants were removed and rated 14 days after planting. The experimental design was a RCBD with 6 treatments and three replicates, totaling 18 experimental units.

Figure 1.1. Dry bean root rot scale. 1 = no visible symptoms, 3 = lesion(s) covering approximately 10% of hypocotyl and root tissue, 5 = lesion(s) covering approximately 25% of the hypocotyl and root tissue, 7 = lesion(s) covering approximately 50% of the hypocotyl and root tissue, 9 = 75% or more of the hypocotyl and root tissue are covered in lesions, or the taproot is severed (Van Schoonhoven and Pastor-Corrales, 1987).

In-furrow Efficacy Trials

R. solani Inoculated Trial. Once an isolate, inoculum placement, incubation time were determined to have the desired aggressiveness and the level of phytotoxicity was determined, an in-furrow fungicide trial was performed to evaluate the efficacy of the fungicides for managing Rhizoctonia root rot. Ulen series field soil was collected from the middle of a catena at the Ekre Grassland Preserve near Kindred, North Dakota and analyzed by the North Dakota State University soil testing laboratory (Table 1.3). Ulen series soil is classified as sandy, mixed, frigid Aeric Calciaquolls which indicates a Mollisol order (base-rich with thick, dark A horizon, formed under grassland), aquic suborder (moisture regime of periodically saturated), calcic great group (contains a calcic horizon), aeric subgroup (aeration), and family that is sandy (texture), mixed (both 1:1 and 2:1 clays present), frigid (mean annual soil temperature < 8 C with seasonality).

Pots were filled with equal masses of dried, homogenized, sieved field soil. The soil was watered to 80% field capacity, determined by saturating three test pots and recording 80% of that pot's weight once all gravitational water had leached away. A 4 cm deep furrow was made down the center of the pot, and the soil was inoculated by placing a single wheat kernel infested with *R. solani* 1.5 cm below the furrow. Five 'Montcalm' bean seeds were placed into the furrow made in each pot.

Table 1.3. Average nutrient content (nitrate, phosphorus, potassium), pH, electrical conductivity (EC), percent organic matter (OM), and texture - of soil collected from the Ekre Grassland Preserve for in-furrow trial in the greenhouse.

Collection Site	NO_3-N† (kg/ha)	P‡ (kg/ha)	K§ (kg/ha)	pH¶	EC# (mmhos/cm)	OM†† (%)	Texture‡‡
Midland	3.4	6.7	143.5	7.10	0.13	1.60	Sand

† Nitrate kg/ha was determined by the water extraction method
‡ Phosphorus kg/ha was determined by the Olson procedure
§ Potassium kg/ha was determined by the 1N ammonium acetate method
¶ pH was determined with a 1:1 soil to water ratio
# Electrical conductivity was determined with a 1:1 soil to water ratio
†† Percent organic matter was determined by loss on ignition
‡‡ Texture was determined by the hydrometer method

The furrow was left uncovered and the each fungicide was applied directly onto the seeds and furrow. The pots were sprayed as described above with either two or three rates of six fungicides (Table 1.1). The furrows were closed by pushing soil over the seed and each pot was weighed and watered daily to maintain 80% field capacity moisture. After 14 days, plant emergence was recorded, plants were removed, roots were washed, and plants were evaluated for plant height, shoot weight, and root weight. Root rot severity was measured using a 1 to 9 linear scale (Figure 1.1). The experiment was conducted twice in an RCBD with 18 treatments and six replicates, totaling 108 experimental units.

Field Trials

A total of nine fungicides were evaluated for efficacy in-furrow against dry bean root rot over three growing seasons. In 2014, all nine fungicides were evaluated alone and in conjunction with a seed treatment fungicide, mefenoxam/fludioxonil (Apron Maxx RTA; Syngenta Crop Protection) and a non-treated control in Fargo, North Dakota for a total of 20 treatments (Table 1.4). Eight fungicides were evaluated in 11 treatments in 2015, and five fungicides in eight treatments in 2016 in Fargo and Carrington, North Dakota (Table 1.4). Each trial was performed in a RCBD with four replicates in 2014, and six replicates in 2015 and 2016. An inoculated control, a non-inoculated control, and a mefenoxam/fludioxonil seed treatment (Apron Maxx 5 fl oz/cwt) were included in all trials. In 2016, all seed except for the mefenoxam/fludioxonil seed treatment was treated with mefenoxam (Apron XL 0.16 fl oz/cwt) to manage resident *Pythium* spp. in the soil.

Table 1.4. In-furrow fungicide active ingredients, trade names, companies, fungicide resistance action committee (FRAC) groups, and formulated product rates for the field trials conducted over three growing seasons.

Fungicide active ingredient	Trade name	Company	FRAC Group	Rate (L/ha)	2014	2015	2016
Azoxystrobin	Quadris	Syngenta	11	.66	X	X	X
Pyraclostrobin	Headline	BASF	11	.66	X	X	X
Picoxystrobin	Aproach	DuPont	11	.66	X	X	
Prothioconazole	Proline	Bayer	3	.42	X	X	X
Metconazole	Caramba	BASF	3	.66	X		
Boscalid	Endura	BASF	7	.58	X	X	
Fluxapyroxad/ pyraclostrobin	Priaxor	BASF	7/11	.49	X	X	X
Fluopyram	Velum Prime	Bayer	7	.50	X	X	X
Penthiopyrad	Vertisan	DuPont	7	1.46	X	X	X

In each growing season and at each location, two side-by-side trials were planted with 'Avalanche' navy beans (North Dakota Agricultural Experiment Station; North Dakota State University). Each trial tested the treatments on either *F. solani* or *R. solani*. In Fargo, each plot within each trial measured 27.5 square meters with four-5.5 meter long rows spaced 38 cm apart. The target population was 360,000 plants per ha. In Carrington, each plot within each trial measured 33.5 square meters with four-8 meter long rows spaced 38 cm apart. The target population for these trials was 290,000 plants per ha.

Plots were inoculated before planting in Fargo with sterilized wheat seeds infested with *F. solani* or *R. solani*. Infested wheat was delivered through the planter prior to the seeds about 1.5 cm deeper than seed planting depth. In trials conducted in Carrington, inoculum was delivered with the seed. In all trials, in-furrow fungicides were delivered to the soil directly in front of where the seed dropped at planting. In 2016, trials conducted in Carrington were irrigated during the early growing season. All other dry bean trials relied on rain events for moisture.

Plant population, vigor, and phytotoxicity notes were collected at approximately two and four weeks after planting in 2015 and 2016; no phytotoxicity notes were recorded in 2014. Plant population was determined by counting the plants in a marked six-meter section of two-rows in each plot and extrapolating that into plants per ha. Vigor was recorded as a percent and was determined by assigning 100% to the most vigorous-appearing plot in each replicate, then assigning ratings within the replicate compared to that plot. Phytotoxicity was recorded as percent plants affected in each plot.

Plots were sampled three times in 2014 (25, 37, and 51 days after planting), and twice in 2015 (22 and 43 days after planting) by removing five plants from the middle two rows of each

plot. In 2016, plots were sampled once (27 days after planting) by removing 30 plants from the middle two rows of each plot. Disease severity was measured based on a 1 to 9 scale where 1 indicates disease-free roots and 9 indicates complete infection (Figure 1.1; Van Schoonhoven and Pastor-Corrales, 1987). Yield and test weight were assessed at plant maturity. Roots from the inoculated and non-inoculated controls were cultured on PDA to determine causal pathogens of the visible root rot. Pathogens were identified to species using morphologic characteristics.

Weather data for planting dates was collected from the North Dakota Agricultural Weather Network (NDAWN). Soil samples were collected with a soil probe in a "W" pattern from each field trial and analyzed by the North Dakota State University soil testing laboratory (Table 1.5). Five samples were analyzed per trial location.

Table 1.5. Average nutrient content (nitrate, phosphorus, potassium), pH, electrical conductivity (EC), percent organic matter (OM), and texture of soil sampled from dry bean field trials 2014 through 2016.

Field Site	NO_3-N† (kg/ha)	P‡ (kg/ha)	K§ (kg/ha)	pH¶	EC# mmhos/cm	OM†† %	Texture‡‡
Carrington Rhizoctonia 2015	51.6	61.9	728.1	6.2	0.23	3.78	Loam
Carrington Rhizoctonia 2016	40.6	51.6	826.3	7.6	0.29	3.34	Silt Loam
Carrington Fusarium 2015	53.8	85.6	1027.6	6.4	0.24	3.86	Silt Loam
Carrington Fusarium 2016	24.7	25.1	722.7	7.9	0.30	3.62	Loam
Fargo Rhizoctonia 2014, 2015, 2016	34.5	26.9	907.9	8.1	0.74	6.48	Clay
Fargo Fusarium 2014, 2015, 2016	34.3	25.1	847.8	8.1	0.72	6.94	Silty Clay

† Nitrate kg/ha was determined by the water extraction method
‡ Phosphorus kg/ha was determined by the Olson procedure
§ Potassium kg/ha was determined by the 1N ammonium acetate method
¶ pH was determined with a 1:1 soil to water ratio
# Electrical conductivity was determined with a 1:1 soil to water ratio
†† Percent organic matter was determined by loss on ignition
‡‡ Texture was determined by the hydrometer method

Statistical Analysis

Categorical root rot severity data was converted to a percent root disease index (%RDI) using the formula:

$$\%\text{DI} = \left[\frac{(a * 1) + (b * 2) + (c * 3) + (d * 4) + (e * 5) + (f * 6) + (g * 7) + (h * 8) + (i * 9)}{(a + b + c + d + e + f + g + h + i) * j}\right] * 100$$

where *a, b, c, d, e, f, g, h,* and *i* represent the number of plants with the disease severity ratings of 1, 2, 3, 4, 5, 6, 7, 8, and 9, respectively, and *j* represents the highest root rot severity rating (Li et al., 2014).

Levene's test for homogeneity of variance was used to ensure variance equality between the first and second performance of the greenhouse trials before further analyses were performed. One-way analysis of variance (ANOVA) was conducted for both field and greenhouse studies using the PROC GLM procedure in SAS 9.4 (SAS Institute, Cary, NC). Fisher's protected LSD was used to determine differences among treatment means ($\alpha = 0.05$). The dry bean *R. solani* greenhouse inoculum trial was analyzed as a three-factor (isolate x inoculum placement x timing) factorial, and the 2014 field trials were analyzed as two-factor (in-furrow fungicide x seed treatment) factorials ($\alpha = 0.05$).

Results

Greenhouse Trials

Phytotoxicity Trial

There was no sign of phytotoxicity in the absence of pathogen inoculum for any of the fungicides evaluated for in-furrow application. No significant difference were observed in emergence or plant height among the fungicides, rates, or timing of application (Appendix A; Table A.1).

Isolate Pathogenicity/Aggressiveness Trial

Inoculum placement and timing of plant removal did not significantly affect disease severity (Appendix A; Table A.2, A.3). No significant interactions were observed among the main effects of isolate, inoculum placement, and plant removal timing (Appendix C; Table C.1). All three *R. solani* isolates were pathogenic, producing significantly higher disease severity than the non-inoculated control. The AG2-2 isolates DB Rhizoc 6 and SB Rhizoc 3, caused significantly higher levels of disease severity than the AG4 isolate 07RGBR1 (Figure 1.2A). SB Rhizoc 3 was used in the greenhouse in-furrow trial, and all three isolates were mixed and used to produce inoculum for the field trials.

Of the *F. solani* isolates, 101-5, *F. solani* 1, and *F. solani* 2 were pathogenic, producing significantly higher levels of root rot severity than the non-inoculated control (Figure 1.2B). However, a combination of isolate, inoculum placement and rating time which consistently produced ample disease severity was not obtained, therefore, *F. solani* in-furrow greenhouse trials were not conducted. A mixture of 101-5 and *F. solani* 1 was used to produce inoculum in the field trials.

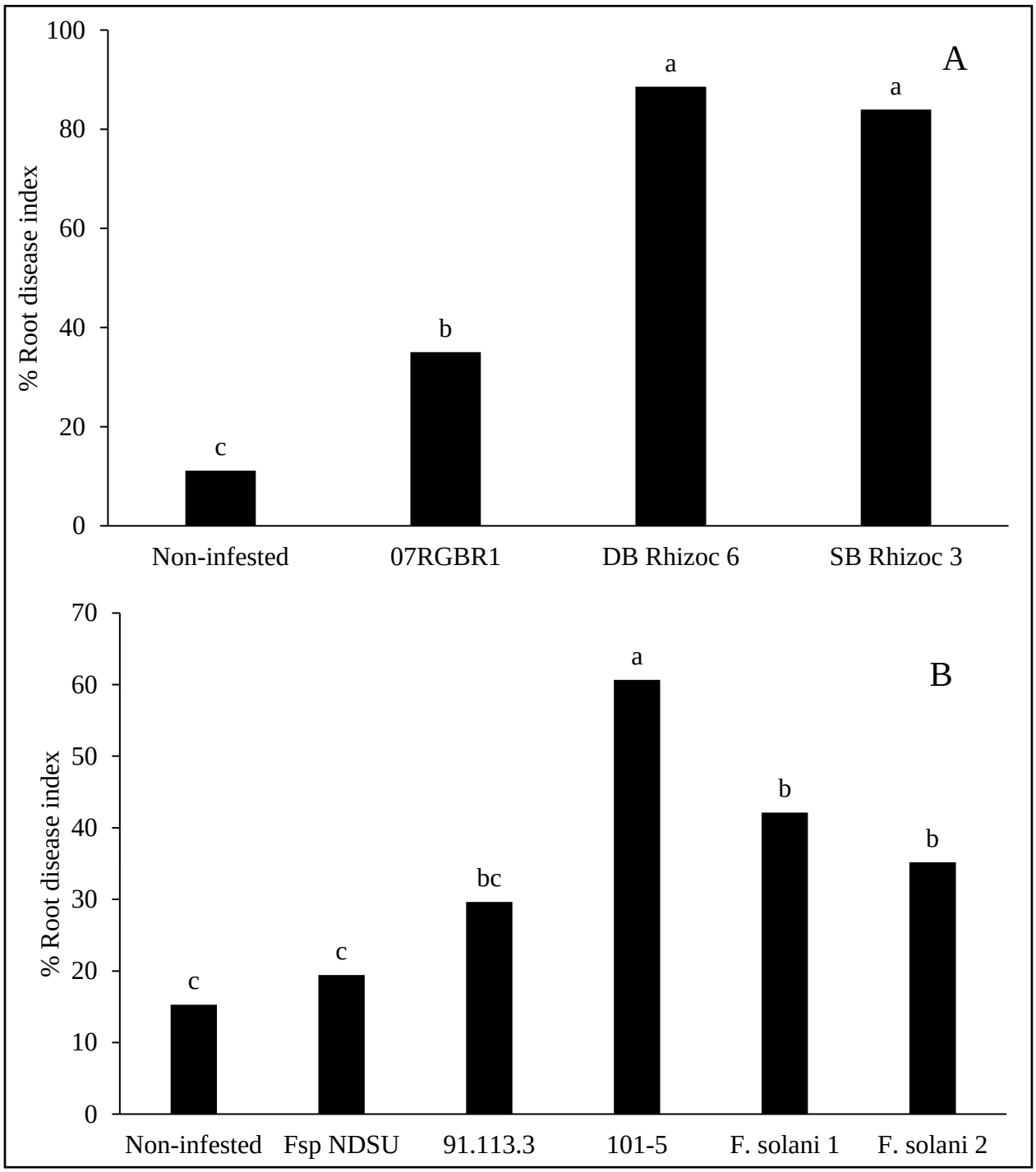

Figure 1.2. Root rot severity (percent root disease index; %RDI) of three *Rhizoctonia solani* (A) and five *Fusarium solani* (B) isolates under greenhouse conditions. Bars within the same sample day with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

In-furrow Efficacy Trials

R. solani Inoculated Trials. Variances were homogeneous; therefore, data from trial one and two were combined for further analyses. The inoculated control had a %RDI of 52%, significantly higher than %RDI observed in the non-inoculated control of 17%. No significant differences were observed among treatments for shoot weight and emergence (Appendix A; Table A.4). All in-furrow treatments significantly reduced root rot severity and increased plant height and root length compared to the inoculated control; however, there were few differences among in-furrow treatments and rates (Appendix A; Table A.4, Figure 1.3). All rates of azoxystrobin, picoxystrobin, and penthiopyrad showed significantly increased root weight compared to the inoculated control (Figure 1.4). Preliminary data for this trial in high and low organic matter soils has been generated but further trials are needed to complete the results (Appendix E).

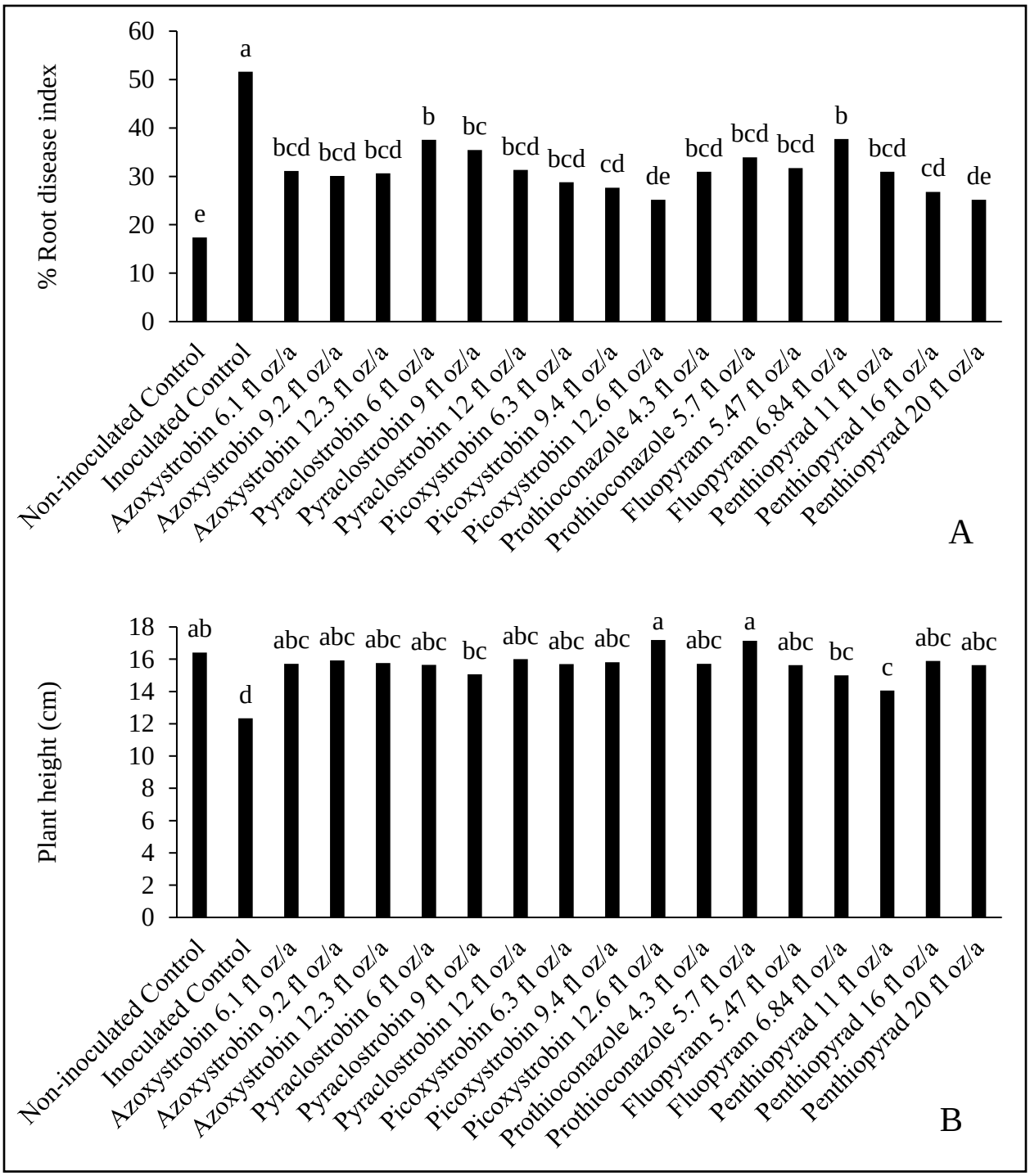

Figure 1.3. Rhizoctonia root rot severity (percent root disease index; %RDI) (A) and plant height (B) of the in-furrow trial under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

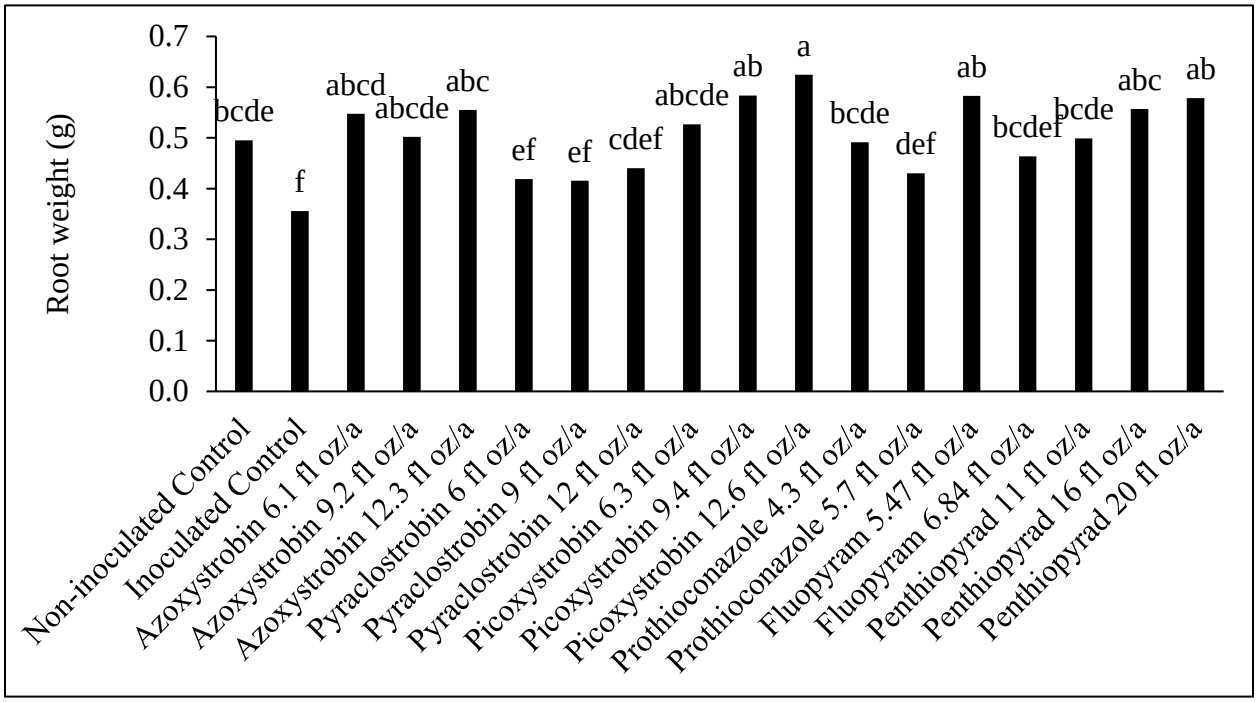

Figure 1.4. Root weight of the Rhizoctonia root rot in-furrow trial under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Field Trials

The efficacy of in-furrow fungicides for managing root rot in dry beans caused by *R. solani* and *F. solani* varied across years and locations. Phytotoxicity was not significant in any of the trials (Appendix A). Significant differences were observed among all other data parameters in at least one trial, but due to the vast amount of data, only statistically significant results will be reported. Some fungicides caused significantly increased vigor, plant and root biomass and decreased root rot severity; however, plant emergence and seed yield were generally not significantly increased. Fungicide efficacy varied across trial-years based on location, the environment (soil-type and moisture), and pathogen infestation. When significant differences were observed, multiple fungicides from different FRAC groups were often found to be effective but no one fungicide proved to consistently be the most effective. Environmental data from

NDAWN indicated that planting in Fargo occurred under the warmest soil temperature in 2016 and the wettest soil in 2015. In Carrington, the warmest and driest soil at planting was in 2015 (Table 1.6).

Table 1.6. Environmental conditions at planting of dry bean in-furrow trials in Fargo and Carrington in 2014, 2015, and 2016 with corresponding disease severity rating.

Trial location	Planting date	Soil temperature before planting† (°C)	Soil temperature after planting† (°C)	Rainfall before planting‡ (cm)	Rainfall after planting‡ (cm)	%RDI§ *R. solani*	%RDI *F. solani*
Fargo 2014	5/29	14.6	19.0	0.11	0.29	32.8	13.9
Fargo 2015	6/19	19.5	22.4	0.31	0.14	32.2	35.2
Fargo 2016	6/13	20.0	23.1	0.16	0.24	32.1	32.5
Carrington 2015	6/1	14.6	20.6	0.05	0.02	52.6	40.0
Carrington 2016¶	5/31	18.5	21.2	0.17	0.16	67.3	35.6

† Average over the two weeks before planting
‡ Average over the two weeks after planting
§ Average percent root disease index; %RDI of inoculated control from sampling closest to 25 days after planting
¶ Trial was irrigated during early growing season

2014 Field Trials

In the 2014 Rhizoctonia and Fusarium root rot trials in Fargo %RDI at the three sampling dates for the no in-furrow treatment were 32.8%, 38.9%, and 30.6%; the %RDI for the *F. solani* trial were 17.4%, 22.8%, and 15%. Generally, significant differences were observed among many of the parameters evaluated, however, in nearly every instance, there was no statistical improvement over the standard seed treatment fungicide. *R. solani* and *F. solani* were isolated from roots in their respective trials.

In the *R. solani* trial in Fargo in 2014, significant differences among treatments were observed in plant height at all three sampling dates and root rot severity, but only at the third sampling date, though no treatment significantly improved plant height or reduced root rot severity compared to the mefenoxam/fludioxonil seed treatment (Appendix A; Table A.6). All treatments except azoxystrobin alone and pyraclostrobin applied in combination with the seed treatment showed significantly improved root weight compared to the mefenoxam/fludioxonil seed treatment alone at the first sampling (Figure 1.5). Pyraclostrobin alone and with the seed treatment and fluxapyroxad/pyraclostrobin showed significantly improved shoot weight at the first sampling compared to the no in-furrow treatment and the mefenoxam/fludioxonil seed treatment. Although shoot weight showed significant differences among treatments in the second and third sampling dates, no treatment significantly improved shoot weight compared to the mefenoxam/fludioxonil seed treatment (Appendix A; Table A.7).

In the *F. solani* trial in Fargo in 2014, significant root rot severity differences were observed among treatments at all sampling dates; however, none of the treatments significantly reduced root rot severity compared to the mefenoxam/fludioxonil seed treatment (Appendix A; Table A.9). There were also significant differences in plant height at the second and third sampling dates, root weight at the third sampling date, and shoot weight at all three sampling dates; however, none of the treatments were significantly better than the mefenoxam/fludioxonil seed treatment (Appendix A; Table A.9, A.10).

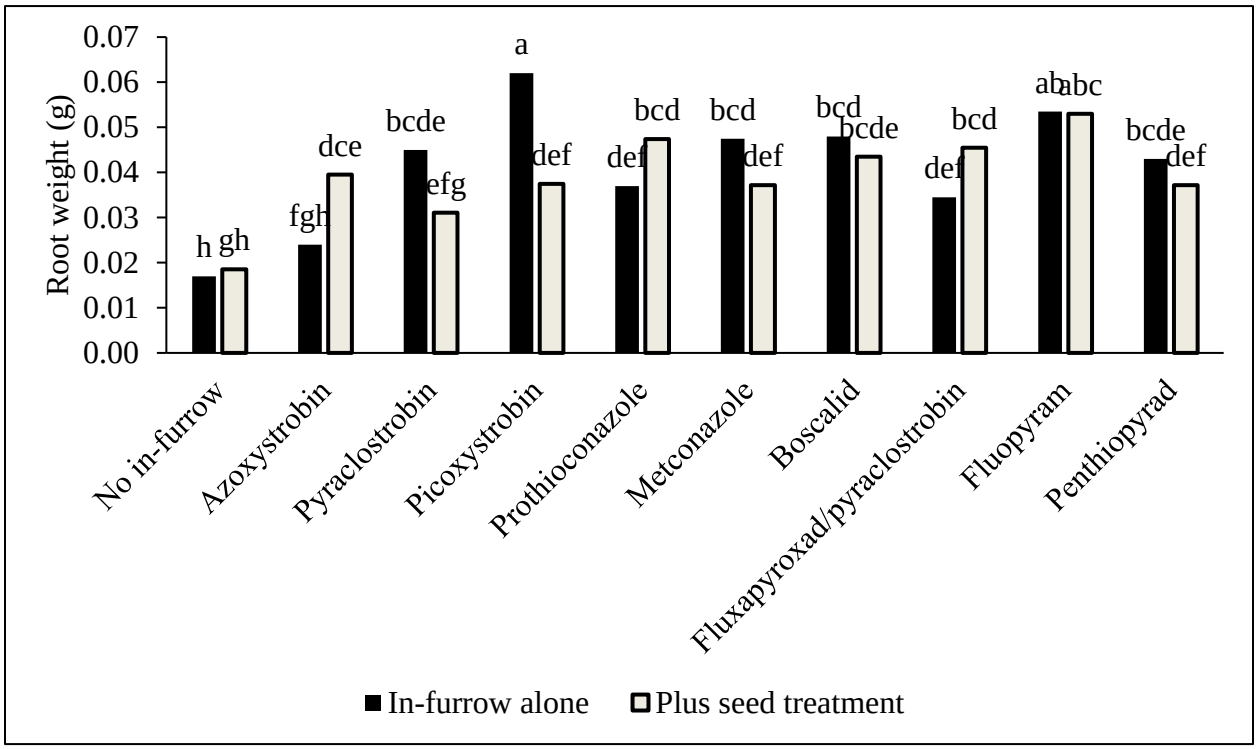

Figure 1.5. Root weight at the first sampling of the Rhizoctonia root rot trial in 2014 in Fargo under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

2015 Field Trials

In the 2015 Rhizoctonia and Fusarium root rot trials in Fargo and Carrington, relatively low levels of root rot severity were observed, although significant increases over the non-inoculated control were observed. In the *R. solani* trials, %RDI in the inoculated control were 32.2% and 31.9% at the first and second sample dates in Fargo; the non-inoculated control %RDI were 17.4% and 24.4%. In the Carrington *R. solani* trial, the inoculated control root rot severity ratings were 52.6% and 32.6% at the first and second sample dates; the non-inoculated control ratings were 30% and 16.7%. *R. solani* and *F. solani* were not isolated from roots in the 2015 trials.

In the Fargo *F. solani* trial, the inoculated control %RDI were 33.6% and 38.9% at the first and second sampling dates; the non-inoculated control %RDI were 18% and 24.8%. In the Carrington *F. solani* trial, the inoculated control root rot severity ratings were 40% and 32.6% at the first and second sampling dates; the non-inoculated control ratings were 21.9% and 13.3%.

In the *R. solani* trial in Fargo in 2015 Picoxystrobin, boscalid, fluxapyroxad/pyraclostrobin, fluopyram, and penthiopyrad showed significantly reduced root rot severity compared to the mefenoxam/fludioxonil seed treatment (Table 1.7). At the second sampling date, picoxystrobin and fluxapyroxad/pyraclostrobin showed significantly reduced root rot severity compared to the inoculated control and the mefenoxam/fludioxonil seed treatment. All treatments except fluxapyroxad/pyraclostrobin and penthiopyrad showed significantly improved vigor over the inoculated control at the first sampling date, though none of the in-furrow treatments performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 1.6). No significant differences were observed among other data parameters.

Table 1.7. Root rot severity (percent root disease index; %RDI) for dry beans where soil was inoculated with *Rhizoctonia solani*. Seeds were treated with a standard seed treatment or fungicides were applied in-furrow at planting on 6/19/2015 in Fargo, ND.

	7/6/2015	7/29/2015
Treatment†	% Root disease index	% Root disease index
Nontreated/non-infested	17.4 e‡	24.4 d
Nontreated/infested	32.2 a	31.9 ab
Mefenoxam/Fludioxonil§	30.1 ab	33.0 a
Azoxystrobin	25.9 bcd	29.3 abcd
Pyraclostrobin	30.2 ab	29.3 abcd
Picoxystrobin	23.3 cd	27.8 bcd
Prothioconazole	27.4 abc	28.9 abcd
Boscalid	21.1 de	30.7 abc
Fluxapyroxad/Pyraclostrobin	22.3 cde	26.3 cd
Fluopyram	24.3 cd	30.4 abc
Penthiopyrad	21.9 de	29.6 abc
P value (0.05)	0.0055	0.0089
CV	25.73	29.12

† Soil for all treatments, except the non-infested, was infested with *Rhizoctonia solani*.
‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).
§ Applied as a seed treatment

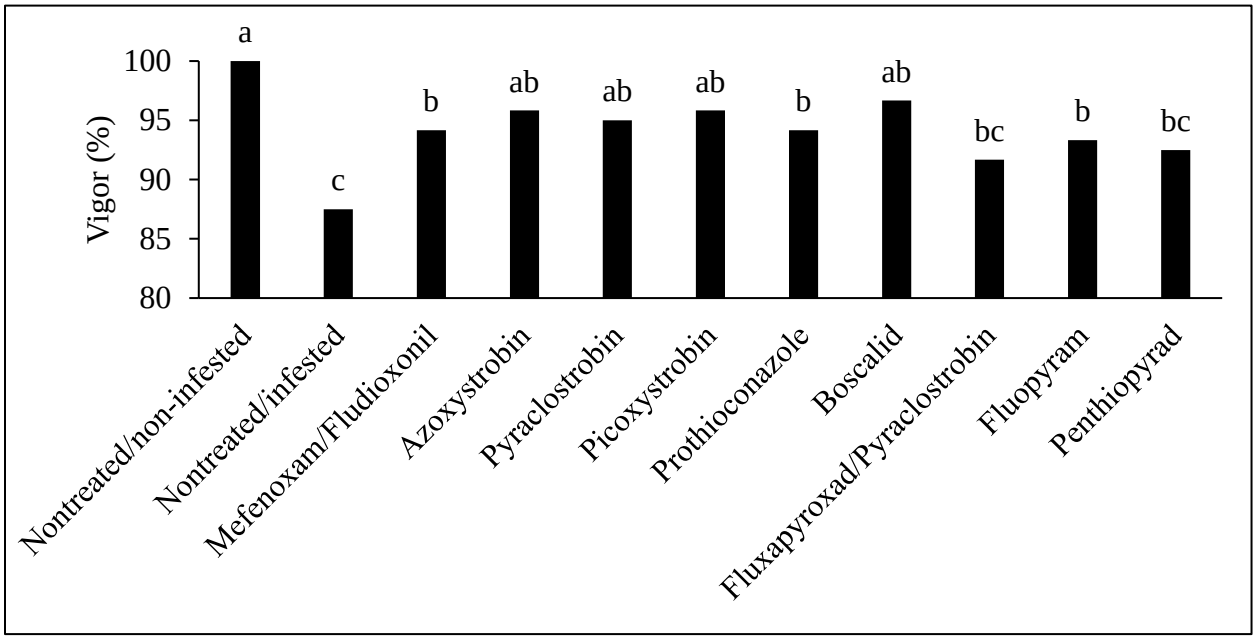

Figure 1.6. Percent vigor at the first sampling of the Fargo *R. solani* root rot trial in 2015. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference (α = 0.05).

At the first sampling date of the 2015 *R. solani* root rot trial in Carrington, root rot severity was not significant among the treatments (Table 1.8). At the second sampling date, all treatments except picoxystrobin showed significantly reduced root rot severity compared to the inoculated control, though none of the in-furrow treatments performed better than the mefenoxam/fludioxonil seed treatment. At the first sampling date, all treatments significantly increased vigor compared to the inoculated control, though none of the in-furrow treatments performed better than the mefenoxam/fludioxonil seed treatment (Figure 1.7).

Table 1.8. Root rot severity (percent root disease index; %RDI) for dry beans where soil was inoculated with *Rhizoctonia solani*. Seeds were treated with a standard seed treatment or fungicides were applied in-furrow at planting on 6/1/2015 in Carrington, ND.

	6/23/2015	7/14/2015
Treatment†	% Root disease index	% Root disease index
Nontreated/non-infested	30.0 a‡	16.7 c
Nontreated/infested	52.6 a	32.6 a
Mefenoxam/Fludioxonil§	47.8 a	25.2 b
Azoxystrobin	37.8 a	21.9 bc
Pyraclostrobin	37.3 a	24.1 b
Picoxystrobin	36.7 a	26.3 ab
Prothioconazole	44.4 a	24.1 b
Boscalid	35.9 a	24.1 b
Fluxapyroxad/Pyraclostrobin	39.6 a	22.2 bc
Fluopyram	37.0 a	24.8 b
Penthiopyrad	37.8 a	24.1 b
P value (0.05)	0.3092	0.0098
CV	35.12	23.29

† Soil for treatments 2-11 was infested with *Rhizoctonia solani*.
‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).
§ Applied as a seed treatment

While there were significant differences among treatments for plant height and shoot weight at the first sampling, the non-inoculated and inoculated controls were not significantly

different (Appendix A; Table A.13, A.14). No significant differences were observed among other data parameters.

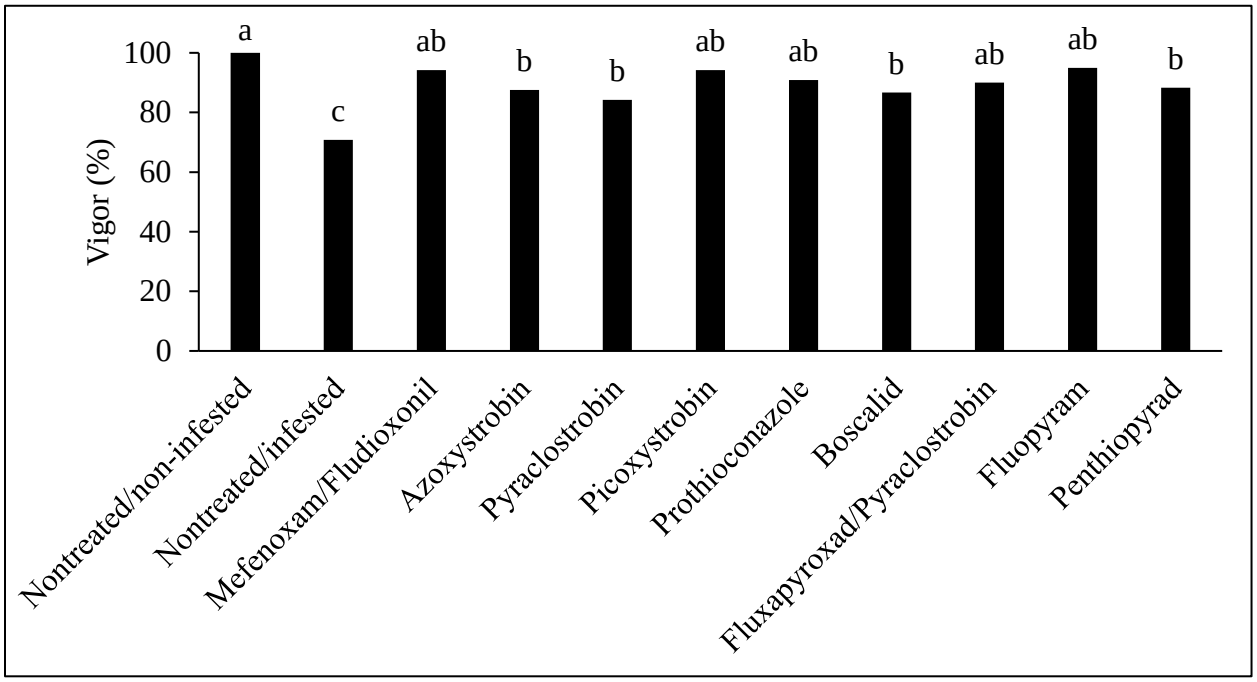

Figure 1.7. Percent vigor at the first sampling of the Carrington *Rhizoctonia solani* root rot trial in 2015. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

In the 2015 *F. solani* root rot trial in Fargo, all treatments at the first sampling date, and all treatments except boscalid and fluxapyroxad/pyraclostrobin at the second sampling date showed significantly improved vigor compared to the inoculated control, though no in-furrow treatments performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 1.8). The mefenoxam/fludioxonil seed treatment, azoxystrobin, picoxystrobin, and prothioconazole showed significantly reduced root rot severity compared to the inoculated control at the first sampling date; however, no in-furrow treatments performed significantly better than the mefenoxam/fludioxonil seed treatment. At the second sampling date, all

treatments significantly reduced root rot severity compared to the inoculated control, though no in-furrow treatment performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 1.9A).

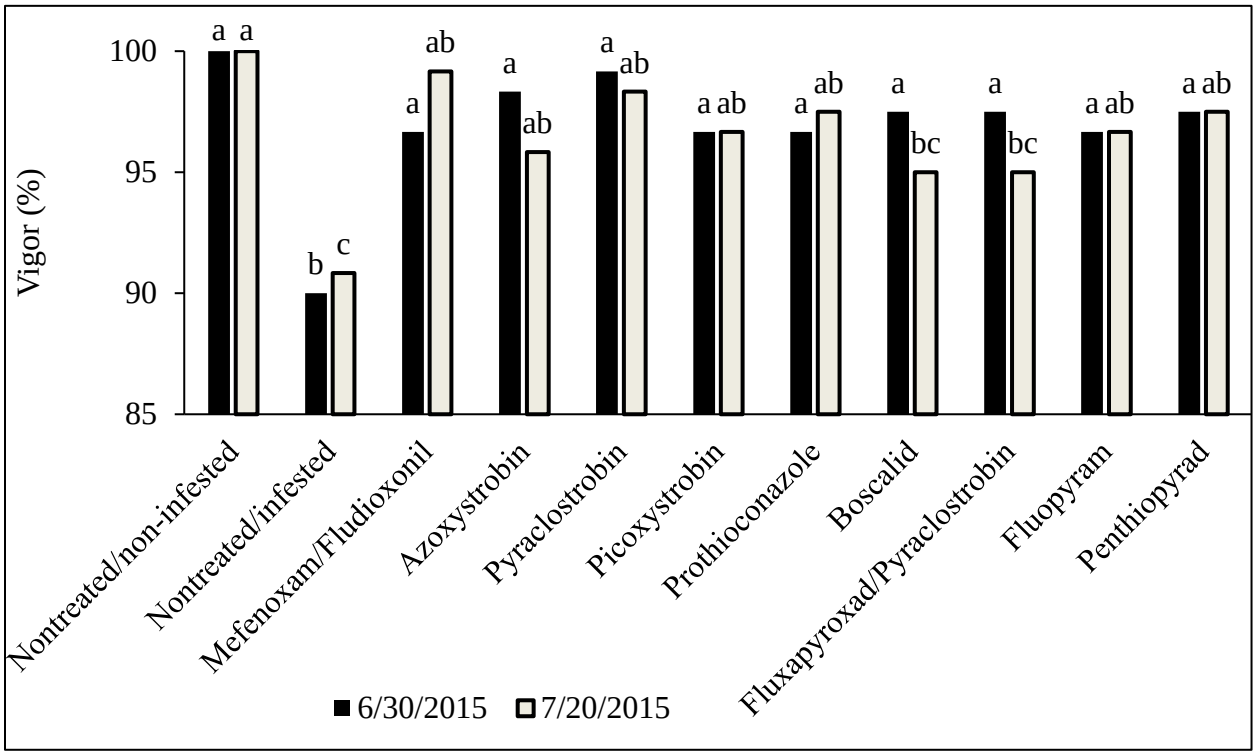

Figure 1.8. Percent vigor of the Fargo *Fusarium solani* root rot trial in 2015. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

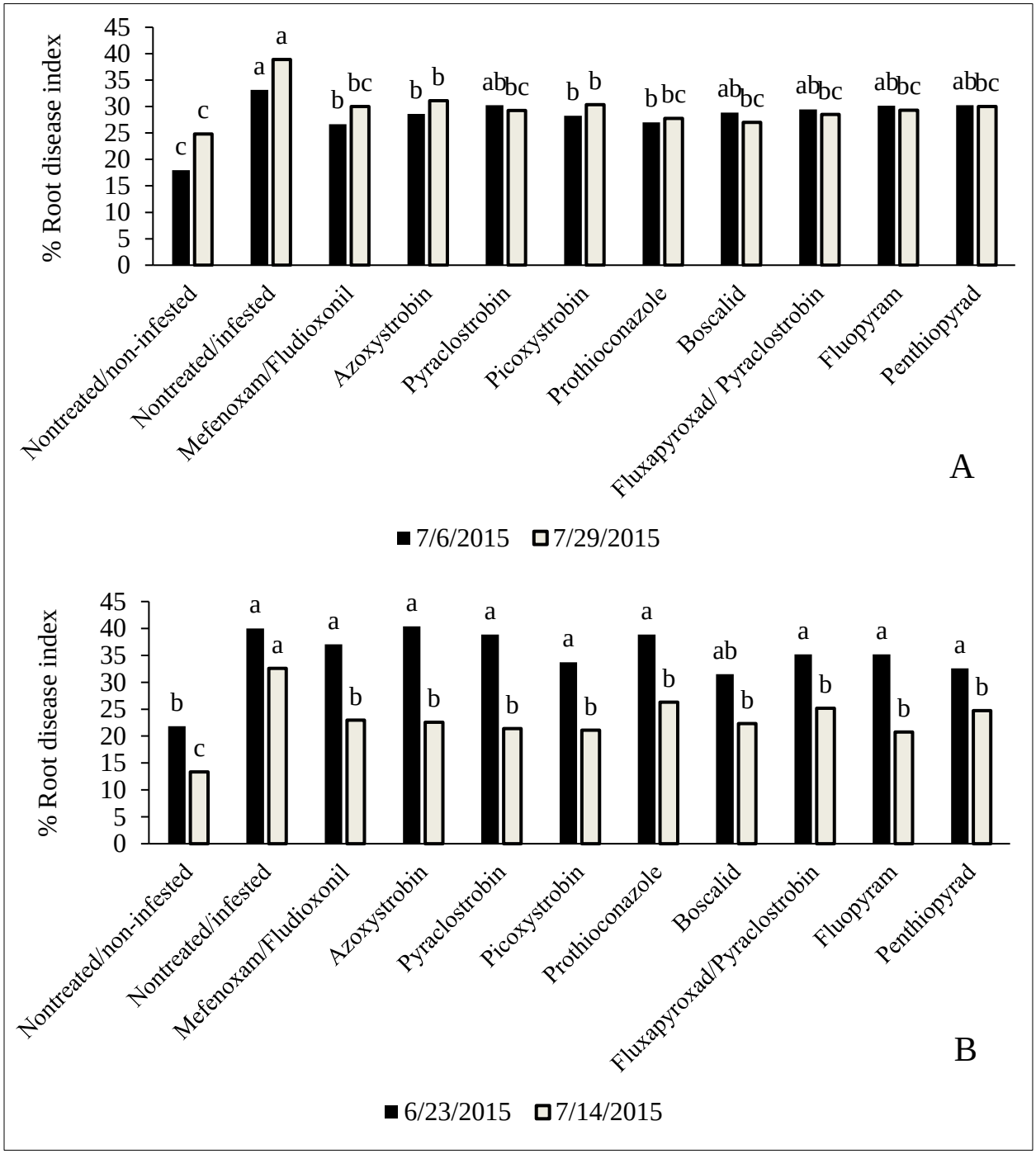

Figure 1.9. Fusarium root rot severity (percent root disease index; %RDI) of the Fargo (A) and Carrington (B) root rot trial in 2015 under field conditions Bars within the same sampling date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

In the 2015 *F. solani* root rot trial in Carrington, although significant differences were observed in root rot severity, no in-furrow fungicide applications provided significantly better control of root rot than did the seed treatment (Figure 1.9B). All treatments at the first sampling date, and all treatments except picoxystrobin, prothioconazole, and fluopyram at the second sampling date showed significantly improved vigor compared to the inoculated control; though none of the in-furrow treatments performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 1.10).

Though there were significant differences among treatments for root weight at the first sampling, and plant height and root weight at the second sampling, in-furrow treatments were not significantly better than the seed treatment (Appendix A; Table A.18).

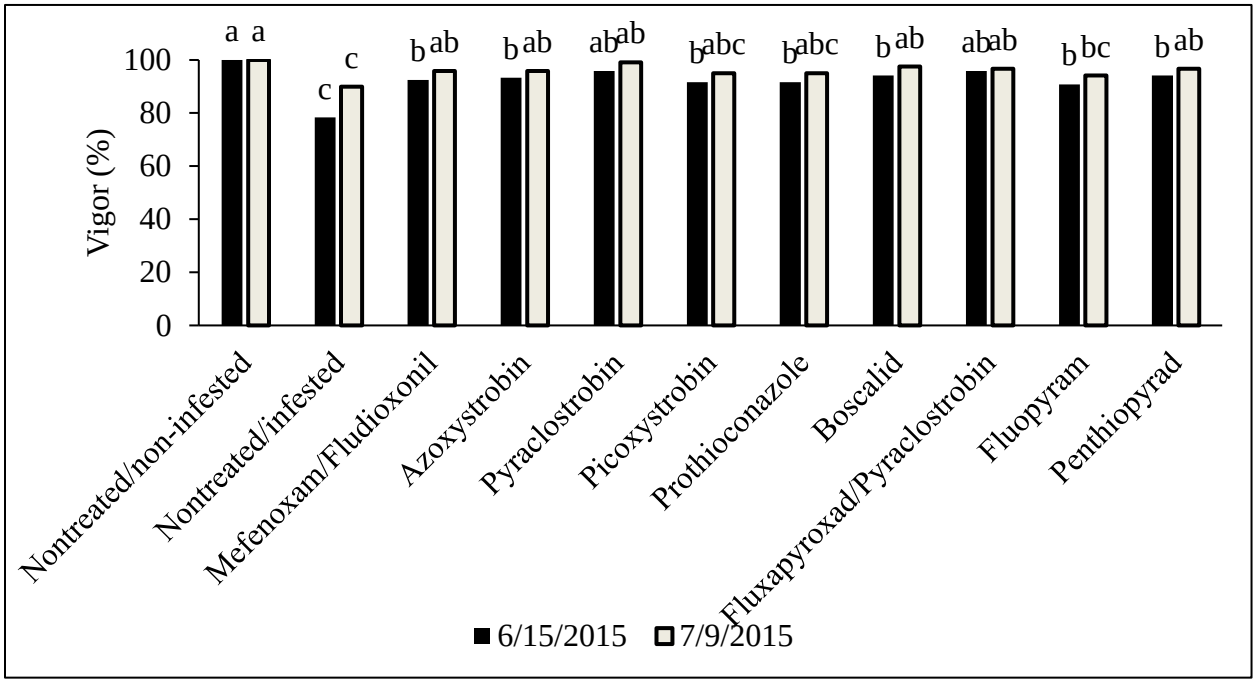

Figure 1.10. Percent vigor of the Carrington *F. solani* root rot trial in 2015. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

2016 Field Trials

In the 2016 Rhizoctonia and Fusarium root rot trials in Fargo and Carrington, significant increases in root rot severity were observed with all inoculations except the *F. solani* trial in Fargo. In the Fargo *R. solani* trial, the inoculated control %RDI was 32.1%; the non-inoculated control %RDI was 26.9%. In the Carrington *R. solani* trial, the inoculated control %RDI was 67.3%; the non-inoculated control was 19.2%. In the Fargo *F. solani* trial, the inoculated control %RDI was 32.5%; the non-inoculated control was 30.5%. In the Carrington *F. solani* trial, the inoculated control %RDI was 35.6%; the non-inoculated control was 17.2%. Supplemental irrigation was provided to the trials in Carrington prior to emergence, resulting in severe reductions in plant populations and increases in root rot in all inoculated treatments. No *R. solani* or *F. solani* was isolated from roots in 2016.

In the 2016 *R. solani* root rot trial in Fargo, pyraclostrobin and penthiopyrad showed significantly reduced root rot severity compared to the mefenoxam/fludioxonil seed treatment (Figure 1.11A). No significant differences were observed among other data parameters at this site.

In the 2016 *R. solani* root rot trial in Carrington, azoxystrobin, pyraclostrobin, prothioconazole, and penthiopyrad showed significantly reduced root rot severity compared to the mefenoxam/fludioxonil seed treatment (Figure 1.11B). At the both observation dates, all treatments except fluopyram showed significantly increased plant populations and vigor over the mefenoxam/fludioxonil seed treatment (Figure 1.12). All treatments except fluopyram performed significantly increased yield compared to the mefenoxam/fludioxonil seed treatment (Figure 1.13).

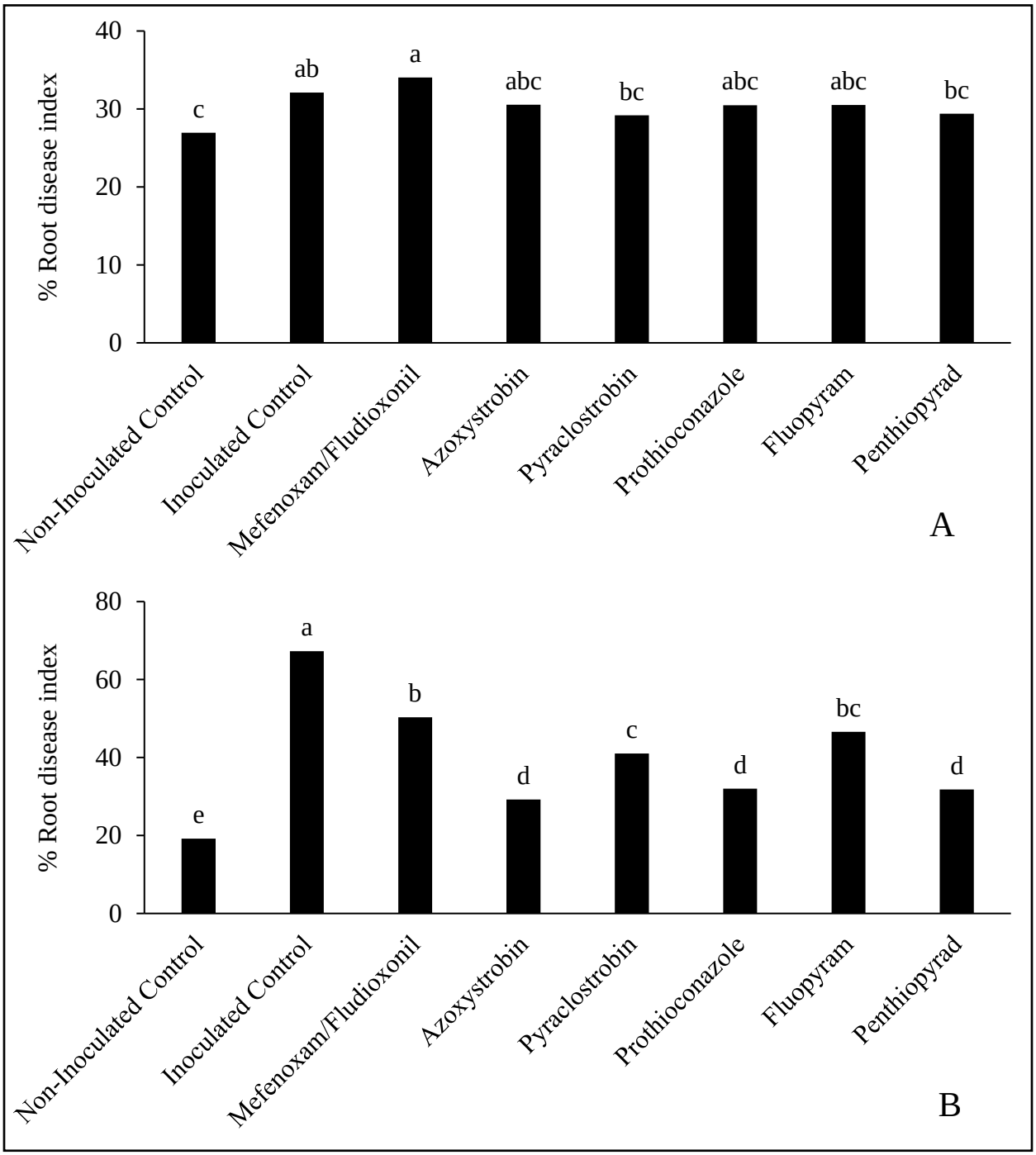

Figure 1.11. Rhizoctonia root rot severity (percent root disease index; %RDI) in Fargo (A) and Carrington (B) in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

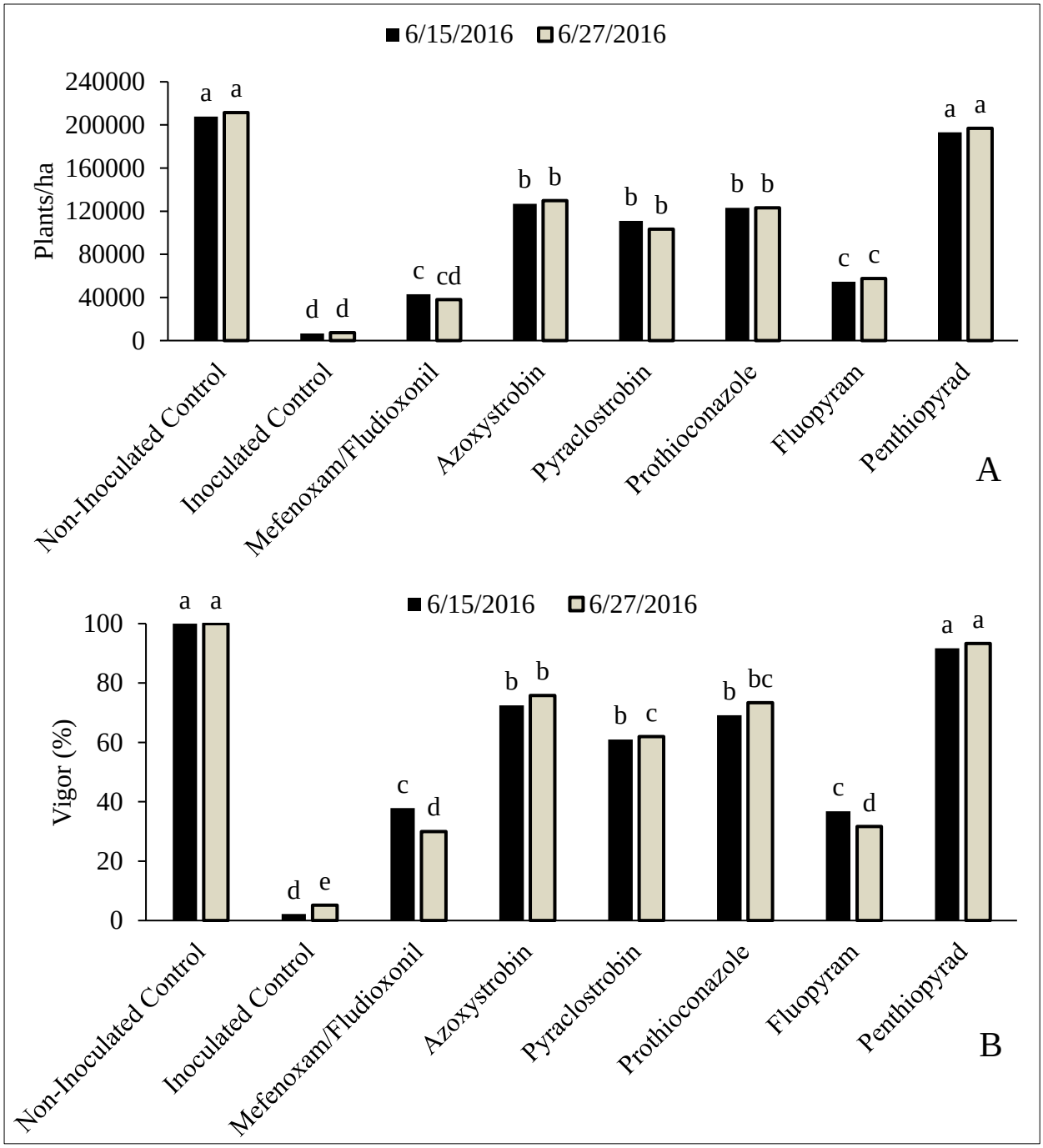

Figure 1.12. Plant population (A) and vigor (B) of the Rhizoctonia root rot trial in Carrington in 2016 under field conditions. Bars within the same observation date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

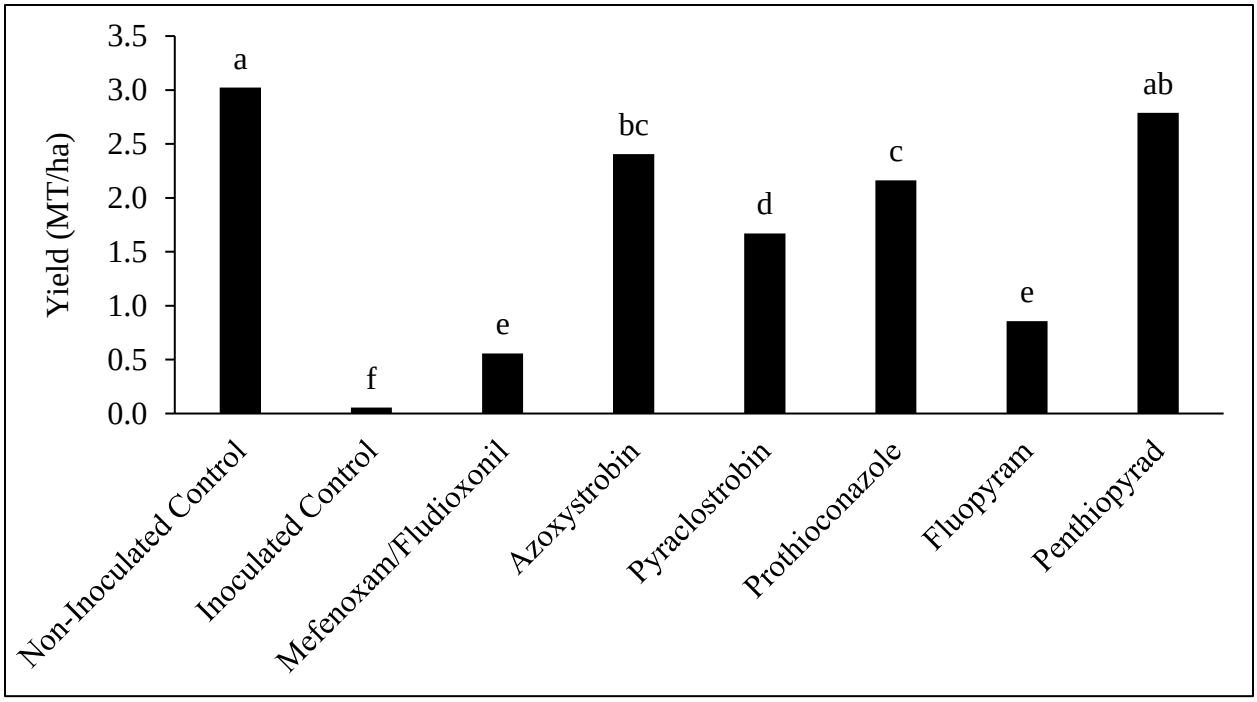

Figure 1.13. Yield of the Rhizoctonia root rot trial in Carrington in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

In the 2016 *F. solani* root rot trial in Fargo, the only parameter where in-furrow treatment outperformed seed treatment was at the second sampling date where prothioconazole showed significantly improved vigor (Figure 1.14).

In the 2016 *F. solani* root rot trial in Carrington, none of the in-furrow treatments significantly improved vigor over the mefenoxam/fludioxonil seed treatment at either sampling date (Figure 1.15). Pyraclostrobin, prothioconazole, and penthiopyrad showed significantly reduced root rot severity compared to the inoculated control; no in-furrow treatment performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 1.16A). Only penthiopyrad showed significantly improved yield compared to the mefenoxam/fludioxonil seed treatment (Figure 1.16B).

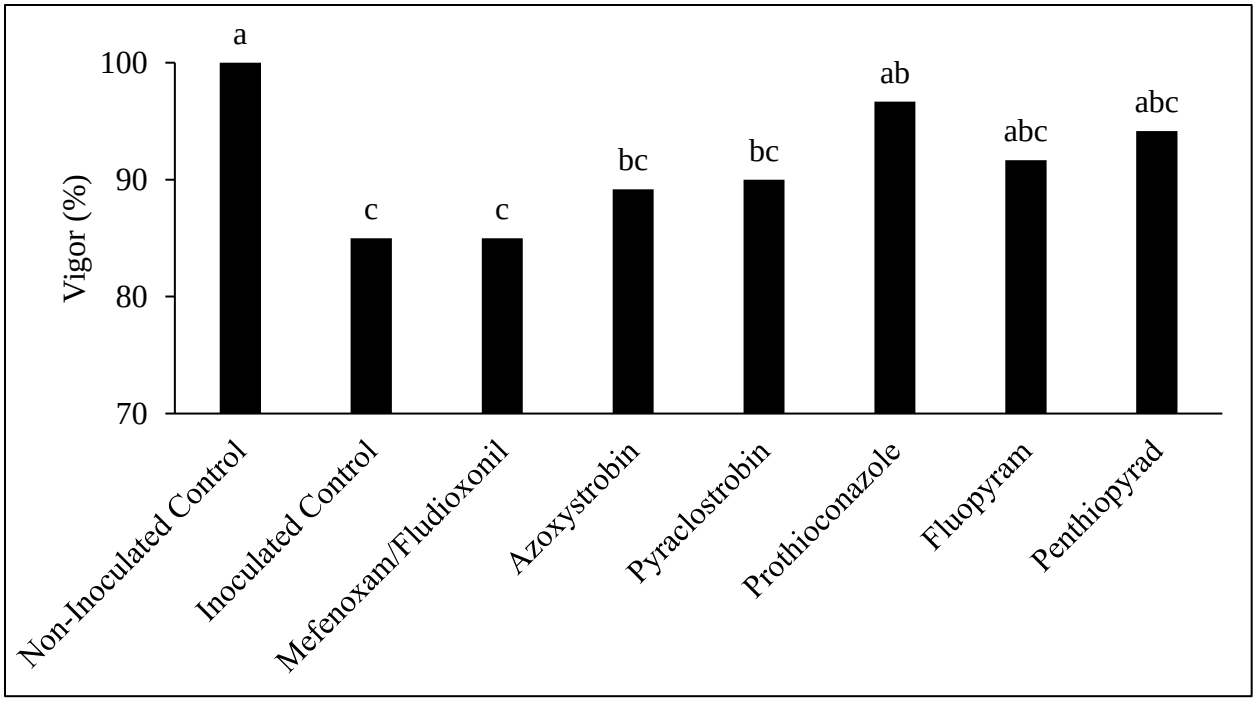

Figure 1.14. Percent vigor at the second observation date of the Fargo *F. solani* root rot trial in 2016. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference (α = 0.05).

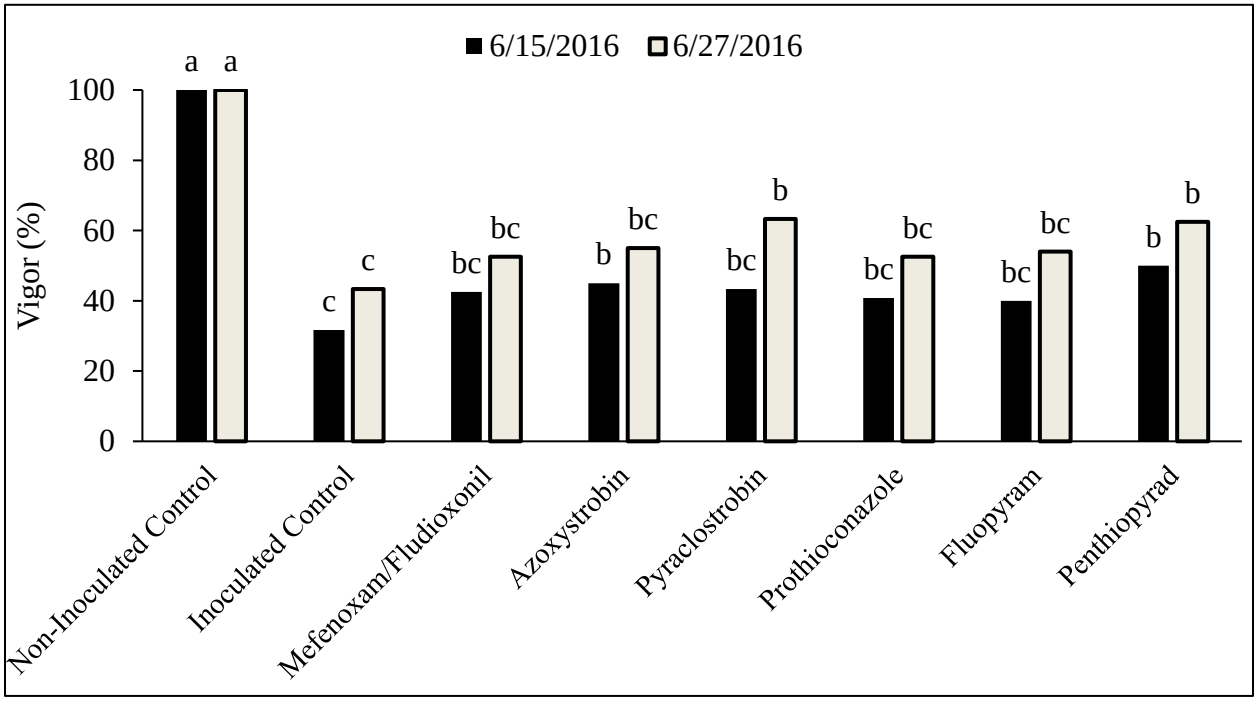

Figure 1.15. Vigor of the Fusarium root rot trial in Carrington in 2016 under field conditions. Bars within the same observation date with the same letter above are not significantly different based on Fisher's protected least significant difference (α = 0.05).

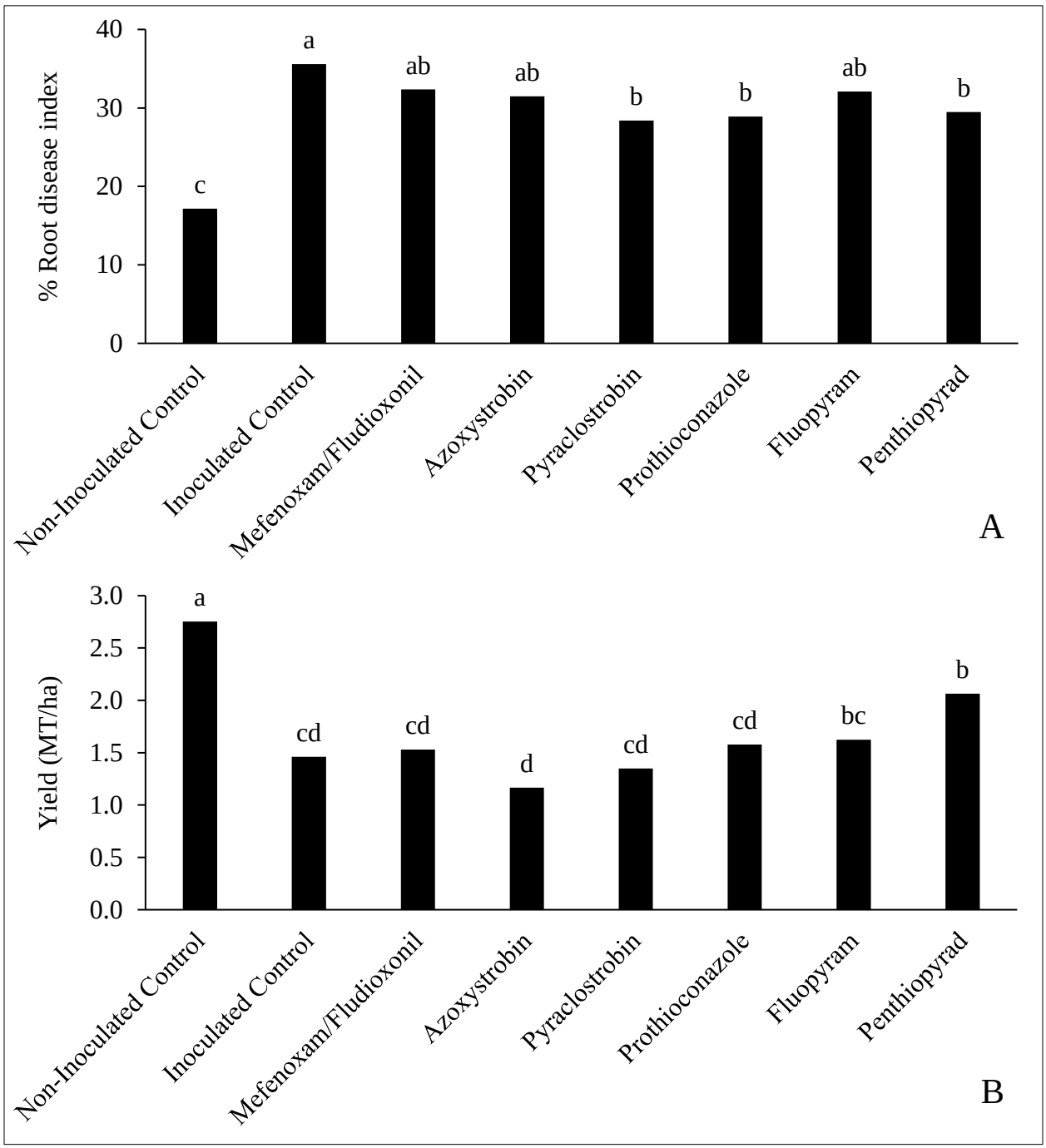

Figure 1.16. Root rot severity (percent root disease index; %RDI) (A) and yield (B) of the Fusarium root rot trial in Carrington in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Discussion

In 2015, the economic value of dry bean production in North Dakota was over $210 million USD (USDA-NASS 2016). Production fell just slightly from 2015 to 2016, but North Dakota remains the US leader in dry bean production with 253,000 ha planted with Michigan ranking 2nd with 85,000 ha. Over the past several years, growers have indicated that root rot is among the three most damaging diseases in dry bean production (Knodel et al. 2013-2016). Root rot affects all classes of dry beans and, while the level of root rot resistance in currently grown cultivars has improved over recent years, it is not sufficient under high disease pressure. The use of seed treatment fungicides is the best available option to manage root rot, and although seed treatments are still recommended, some growers suffer substantial losses, even when using seed treatment fungicides. Numerous pathogens, most notably *F. solani* and *R. solani*, have been implicated in the root rotting complex of dry beans in North Dakota (Goswami and Rasmussen, 2009), further complicating disease management. Currently no dry bean cultivars with resistance to withstand high disease pressure are available. The management of root rot is mainly through the use of seed treatment fungicides. While seed treatment fungicides have shown some efficacy against root rot, this too does not provide satisfactory management under high disease pressure. It is possible that the lack of efficacy is due to the late onset of the root rot and any control provided by seed treatments may have diminished as soon as 4 weeks after planting.

Management of root, crown and stem rots caused by *F. avenaceum* and *F. solani*, using in-furrow fungicide applications has been evaluated on numerous hosts with varying success (Vea and Palmer, 2013). In field evaluations for the management of *F. solani* on snap beans, the use of in-furrow fungicide applications (chlorothalonil, pyraclostrobin, azoxystrobin and trifloxystrobin) resulted in a significant decrease in root rot 72 days after planting. An increase in

yield was observed with all fungicides except chlorothalonil when compared to the non-treated control. Much of the other research conducted in this area has focused on Fusarium root rots of common houseplants. Root rots caused by both *F. aveneaceum* and *F. solani* were successfully managed by numerous fungicides.

In-furrow fungicide applications have resulted in significant decreases in root rot caused by *R. solani* and increases in yield in wheat (Cotterill, 1991) and barley (Cotterill, 1993; Paulitz and Reinerstsen, 2005). In-furrow applications also protected against both pre- and post-emergence seedling death in cotton (Hillocks et al., 1988; Lawrence et al., 2004) and reduced stem and stolon cankers in potatoes, although not always significantly (Miller and Miller, 2009). Additionally, early season foliar applications have proven effective in managing root and crown rot caused by *R. solani* in sugar beet under field conditions (Bolton et al., 2010; Jacobson et al., 2004; Khan et al., 2004; Stump et al., 2004; Windels and Brantner, 2005).

Information generated from research on these unrelated hosts may not be applicable to field peas and dry beans due to differences in production practices, however, it is important to note that the pathogens are similar and the fungicide applications are targeted at controlling the pathogens, here, *R. solani*, *F. avenaceum* and *F. solani*. The application of in-furrow fungicides for the management of root rot is still in the experimental stage, however, given that few alternatives exist, it is prudent to explore this possible management tactic. While there are no guarantees that in-furrow fungicide applications will be effective in controlling root rot in dry beans, the lines of evidence provided above lead to the belief that there is a reasonable chance for success and that this is worth pursuing further by conducting greenhouse and field experiments.

Significant reductions in root rot have been observed with in-furrow fungicide applications in field and greenhouse trials conducted to date. Root rot reductions are not always

observed with the application of in-furrow fungicides, but this is also true for the use of seed treatment fungicides. There are many factors that may contribute to the variable results in these trials, including; soil type, soil moisture, the pathogen used to infest the soil, and the levels and diversity of natural soil pathogens. However, given the data presented here and that few alternatives exist; we believe this is a viable management tool in some circumstances. What is not clear is, which fungicides and rates will provide the best control across dry bean growing regions. Additionally, the expense of some of these products may limit the economic feasibility of the application of in-furrow fungicides.

Dry bean growers in the region have experimented with in-furrow fungicide applications for root rot control and are seeing positive results. Accurate and timely recommendations for growers may increase the likelihood of success by determining which, if any, fungicides are effective and the application rate resulting in the best disease management, or save them expense by deterring applications based on lack of economic return. Changes in 2016 trial protocols were made to increase the likelihood of detecting differences among the in-furrow fungicides.

To our knowledge, these are the first in-furrow fungicide efficacy trials conducted on dry beans in field or greenhouse settings. In-furrow fungicide applications are currently not commonly used in dry beans, though some growers have begun to apply pyraclostrobin, fluxapyroxad/pyraclostrobin, and boscalid in-furrow on a small percentage of hectarage in North Dakota and Minnesota (Knodel et al., 2016).

In the greenhouse, plants were assessed for root rot severity at 14 days after planting. This time interval was chosen over 30 days after planting because adequate disease severity had developed by 14 days after planting (Figure 1.2A) which makes the trial more efficient by reducing total time and working with smaller plants. In addition, although there was no

significant difference in disease severity between inoculum placement, inoculum was chosen to be placed below the seed for two reasons. First, *R. solani* inoculum caused a significant reduction in emergence when placed next to the seed. Second, placing the inoculum kernel below the seed minimizes direct contact between the in-furrow fungicide and the inoculum.

Penthiopyrad was the only in-furrow fungicide to significantly reduce Rhizoctonia root rot severity in greenhouse trials and all five field trials. Pyraclostrobin, prothioconazole, and penthiopyrad showed significantly reduced Fusarium root rot severity in three of five field trials. The other two trials were in 2014 and 2016 in Fargo where root rot severity was not significantly reduced compared to the inoculated control. Low disease levels may have contributed to non-significance in these trials. The inoculated control in the 2016 Fargo *F. solani* trial had a similar disease severity as Carrington in 2015, which had significant root rot severity differences. The difference in non-inoculated control ratings between Fargo and Carrington may be due to differing underlying natural disease pressure, weather, or other factors.

Efficacy of the other in-furrow fungicides in this research varied across year and location which may be due to environmental differences in the field and the variability of the natural soil pathogen populations. In Carrington in both 2015 and 2016, Rhizoctonia root rot severity was higher than that of Fusarium root rot, which may be explained by the average soil temperature before and after planting. *R. solani* causes infection at lower temperatures than *F. solani*, so the low temperatures at planting and following in 2015 and 2016, respectively would favor *R. solani* infection at the plants' most vulnerable seed and seedling stage. Perhaps the plants were able to grow past their most vulnerable stages before a temperature was reached for *F. solani* to cause as much damage as *R. solani* (Gossen et al., 2016).

R. solani also causes most severe infection under wet conditions, and the overall highest disease severity was observed in Carrington in 2016 when the trials were under irrigation for the early growing season. *F. solani* produces infection best when its host is under stress. Perhaps Fusarium root rot severity would have been higher in Carrington in 2016 if irrigation and lack of drainage had combined to cause flood stress to the plants. Drought stress may have also increased Fusarium root rot severity, though that would have been logistically unfeasible under field conditions (Gossen et al., 2016).

In both the Rhizoctonia and Fusarium root rot field trials in Carrington in 2015, disease severity was better managed at the second sampling date than the first compared to the inoculated control. Even if root rot severity was not significantly decreased at the first sampling, reductions were observed in some trials later in the growing season. Therefore, applying in-furrow fungicides may indirectly reduce root rot severity throughout the growing season by providing seedlings with a healthy start, which leads to more robust adult plants.

No treatments significantly reduced Fusarium or Rhizoctonia root rot severity at all three sampling dates in Fargo in 2014. Fusarium root rot severity was also not significantly reduced in Fargo in 2016. Perhaps this is also due to the fungicides being adsorbed more readily in Fargo soil due to its higher organic matter content than Carrington soil. Rhizoctonia root rot severity was significantly reduced in Fargo at the second sampling date in 2014 and in 2016, possibly because higher levels of *R. solani* disease were observed than *F. solani*.

This research indicates that in-furrow fungicides may be a viable option for management of root rot in dry beans caused by *Rhizoctonia solani* and *Fusarium solani*. Since the in-furrow fungicides showed no significant phytotoxic effects in either the field or greenhouse, they all

would be good candidates for commercial use with pyraclostrobin, prothioconazole, and penthiopyrad appearing to be the most promising.

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CHAPTER 2: EFFICACY OF SEED TREATMENTS AND IN-FURROW FUNGICIDES FOR MANAGEMENT OF FIELD PEA ROOT ROT CAUSED BY *FUSARIUM AVENACEUM* AND *FUSARIUM SOLANI* UNDER GREENHOUSE AND FIELD CONDITIONS

Introduction

Field pea is an important crop in North Dakota, and North Dakota is the second largest producer of field peas in the United States behind Montana, accounting for between 23% and 39% of total United States field pea production from 2012 to 2016. The northwestern region of the state produces most of North Dakota's field peas, with McLean and Divide counties leading production (USDA-NASS).

Root rot is the most important yield limiting disease of field pea in North Dakota and may cause 60 to 75% yield loss. It is caused by a disease complex that includes *Fusarium* spp., *Pythium* spp., *Aphanomyces euteiches* Drechs, and *Rhizoctonia solani* Kühn (Endres et al., 2009; Gossen et al., 2016; Sharma-Poudyal et al., 2015). Among these, Fusarium root rot is likely the most important, and numerous *Fusarium* spp. have been associated with this disease (Gossen et al., 2016). Two pathogens commonly associated with Fusarium root rot in field pea in North Dakota and elsewhere in the US are *Fusarium avenaceum* (Fries) Saccardo and *Fusarium solani* (Martius) Appel & Wollenweber emend. Snyder & Hansen (Chapara, 2014). *F. solani* is among the most common pathogens to infect peas, and *F. avenaceum* also has become a major root rot concern in peas in North Dakota as well as other pea production areas in the United States and Canada within the past decade (Chittem et al., 2015; Mathew et al., 2008).

Root rot symptoms may appear above ground as yellowed, stunted, irregular patches in the field with premature defoliation and poorly filled pods. These symptoms may not always be

present, and plants may need to be removed from the soil to identify root rot. Below ground, root rot symptoms are typically most prominent on the taproot near the seed. Red-brown lesions may appear on root surfaces and in vascular tissue of the root causing reduced root growth or death (Malvick and Babadoost, 2002). Severe infection may damage and sever the root.

No complete resistance to Fusarium root rot exists in commercial field pea cultivars, and attempts to manage field pea root rot have been made with crop rotation, timely planting, increased tillage, and seed treatment fungicides. However, under high levels of disease pressure these management practices do not provide satisfactory management (Gossen et al., 2016). In-furrow fungicide applications may be a viable option for the management of root rot in field peas that involves spraying a fungicide directly into the furrow at planting with the seed to create a zone of protection around the seed and seedling. This has been effective in other crops such as sugar beets, potatoes, peanuts, wheat, and corn by allowing the plant to grow past the seed and seedling stages when it is most vulnerable. When applied to these crops, the in-furrow fungicides reduced disease severity, improved early season vigor, and increased yield in crop pathosystems such as *R. solani* on wheat, corn, and cotton, and Aspergillus crown rot and Southern stem rot in peanut (Cotterill 1991; Keyes, 2015; Rideout, 2002). The objective of this research was to determine the efficacy of in-furrow fungicides for management of field pea root rot caused by *F. avenaceum* and *F. solani*. To complete this objective, trials were conducted under field and greenhouse conditions.

Materials and Methods

Inoculum Preparation

For each field and greenhouse trial, pathogen-infested grain was added to the soil. Each pathogen isolate was grown at 20 C, with a 12-hour photoperiod, for 14 days on potato dextrose

agar (PDA) (Becton, Dickinson and Company, Sparks, MD; 4 grams potato starch, 20 grams dextrose, and 15 grams agar per liter) amended with 1 mL of 5% streptomycin sulfate and neomycin sulfate per 500 mL PDA media. In greenhouse trials, the pathogen was grown on sterilized wheat kernels. In field trials, the pathogen was grown on either wheat or millet kernels. For small quantities used for greenhouse trials, the inoculum was made in Erlenmeyer flasks containing 100 mg of grain. For large quantities used for field trials, the inoculum was made in metal trays, each containing 1.5 kg of grain.

Grain was soaked in water overnight, the water was drained and the trays/flasks were sterilized at 121 C with an autoclave (Consolidated Sterilizer Systems, Boston, Massachusetts) to remove contamination and to prevent germination of the grain. Flasks were autoclaved for one hour; trays were autoclaved for two hours. The following day, the trays/flasks were autoclaved a second time. After cooling, the grain was inoculated with the pathogen (Table 2.2). The pathogen was allowed to colonize the grain for 12 to 14 days. The grain was mixed every three days to ensure uniform infestation. Once the pathogen had sufficiently colonized the grain, the trays/flasks were spread onto butcher's paper to dry. Finally, the dry inoculum was sieved, mixed, and bagged or packaged for planting. Inoculum was stored in a freezer at 4 C and remained highly aggressive for approximately six months as determined by use in greenhouse trials.

Greenhouse Trials

Phytotoxicity Trial

To determine if the application of QoI fungicides in-furrow is phytotoxic to plant development, in-furrow fungicides were applied to seeds in non-inoculated soil. Pots measuring 27 cm x 13.5 cm x 13 cm deep were filled with Pro-mix LP15 (Premier Tech Horticulture,

Quakertown, PA) potting soil. The furrow was left uncovered so that each rate of fungicide was applied directly to the furrow. Four pots were placed end to end so that the soil surface was approximately 7.5 cm below the spray nozzle. The fungicides were sprayed using a calibrated chain-driven chamber sprayer (DeVries Manufacturing, Hollandale, MN) calibrated to deliver 140 L/ha by compressed air at 137 kPa and 1.8 m/skp through a 4001E even fan nozzle (TeeJet Technologies, Springfield, IL). The three FRAC 11 fungicides were applied in-furrow at three rates (Table 2.1).

Table 2.1. In-furrow fungicide active ingredients, trade names, companies, fungicide resistance action committee (FRAC) groups, and formulated product rates for the greenhouse and in-furrow trials.

Fungicide active ingredient	Trade name	Active ingredient concentration (%)	Company	FRAC	Rate 1 (L/ha)	Rate 2 (L/ha)	Rate 3 (L/ha)
Azoxystrobin	Quadris	22.9	Syngenta	11	.45	.66	.88
Pyraclostrobin	Headline	23.6	BASF	11	.45	.66	.88
Picoxystrobin	Aproach	22.5	DuPont	11	.45	.66	.88
Prothioconazole	Proline	41.0	Bayer	3	.31	.42	
Fluopyram	Velum Prime	41.5	Bayer	7	.40	.50	
Penthiopyrad	Vertisan	20.6	DuPont	7	.80	1.02	1.46

Seeds were planted at 4 cm deep into the furrow either before spraying so that the fungicide was in direct contact with the seed, or after spraying to limit contact between the fungicide and seed. Five pea seeds were planted per pot. The furrows were covered with soil and watered. After 14 days, emergence and plant height were recorded. The experimental was conducted as a three-factor (fungicide x rate x application timing) factorial randomized complete block design (RCBD) with 18 treatments and four replicates, totaling 72 experimental units.

Isolate Pathogenicity/Aggressiveness Trial

The pathogenicity and aggressiveness of three *F. avenaceum* and three *F. solani* isolates were tested in the greenhouse to determine which isolate and placement of the kernel inoculum provides adequate disease severity to effectively evaluate in-furrow fungicide efficacy (Table 2.2). 'DS Admiral' field pea was used for all greenhouse trials (Danisco Seed; Holeby, Denmark).

Table 2.2. Isolates of *Fusarium avenaceum* and *Fusarium solani* used in the isolate pathogenicity, field, and greenhouse trials (Chittem et al., 2015; Porter, 2010).

Isolate name	Species	Host	Collection location
Pea 41	*F. avenaceum*	Field pea	North Dakota
FPS M 60	*F. avenaceum*	Field pea	North Dakota
FA 0601	*F. avenaceum*	Field pea	North Dakota
Fs pisi 215g	*F. solani*	Field pea	Washington
Fsp-01-B18	*F. solani*	Field pea	Washington
Fsp F54B	*F. solani*	Field pea	Washington

Pots were filled with Pro-mix LP15 potting soil and inoculated with sterile wheat seeds infested with a single *F. avenaceum* or *F. solani* isolate. Seeds were planted into a 4 cm deep furrow. Five pea seeds were planted per pot, and one infested kernel was placed either next to the seed or 1.5 cm below the seed. The furrows were covered with soil and the soil was watered. After 14 days, plants were removed and roots were washed and evaluated for plant height, root length, shoot weight, and root weight. Root rot severity was measured using a linear scale of 0 to 5 (Figure 2.1; adapted from Ondrej et al., 2008). The experimental design was a RCBD with 14 treatments and six replicates, totaling 84 experimental units.

Figure 2.1. Field pea root rot scale. 0 = no visible symptoms, 5 = tap root severed (adapted from Ondrej et al., 2008).

In-furrow Efficacy Trials

Once an isolate and inoculum placement was optimized for disease severity and the level of phytotoxicity determined, two in-furrow fungicide trials were performed to test the efficacy of the fungicides for managing root rot caused by *F. avenaceum* and *F. solani*. Ulen series field soil was collected from the middle of a catena at the Ekre Grassland Preserve near Kindred, North Dakota. The soil was analyzed by the North Dakota State University soil testing laboratory (Table 2.3). Ulen series soil is classified as sandy, mixed, frigid Aeric Calciaquolls which indicates a Mollisol order (base-rich with thick, dark A horizon, formed under grassland), aquic suborder (moisture regime of periodically saturated), calcic great group (contains a calcic horizon), aeric subgroup (aeration), and family that is sandy (texture), mixed (both 1:1 and 2:1 clays present), frigid (mean annual soil temperature < 8 C with seasonality).

Table 2.3. Average properties (nitrate, phosphorus, potassium, pH, electrical conductivity (EC), percent organic matter (%OM), and texture) of soil collected from the Ekre Grassland Preserve for in-furrow greenhouse trials.

Collection Site	NO_3-N† (kg/ha)	P‡ (kg/ha)	K§ (kg/ha)	pH¶	EC# mmhos/cm	OM†† %	Texture‡‡
Midland	3.4	6.7	143.5	7.10	0.13	1.60	Sand

† Nitrate kg/ha was determined by the water extraction method
‡ Phosphorus kg/ha was determined by the Olson procedure
§ Potassium kg/ha was determined by the 1N ammonium acetate method
¶ pH was determined with a 1:1 soil to water ratio
# Electrical conductivity (EC) was determined with a 1:1 soil to water ratio
†† Percent organic matter (OM)was determined by loss on ignition
‡‡ Texture was determined by the hydrometer method

Pots were filled with equal masses of the dried, homogenized, sieved field soil. The soil was watered to 80% field capacity, which was determined by saturating a test pot and recording 80% of that pot's weight once all gravitational water had leached away. A 4 cm deep furrow was made down the center of the pot, and the soil was inoculated by placing a single wheat kernel infested with *F. avenaceum* or *F. solani* next to each of five seeds placed in the furrow per pot.

The furrow was left uncovered so that the fungicide was applied directly onto the seeds and furrow. The pots were sprayed as described above with either two or three rates of six fungicides from three FRAC groups (Table 2.1). The furrows were covered with soil and each pot was weighed and watered daily to maintain 80% field capacity moisture. After 14 days, plants were removed and roots were washed and evaluated for plant height, root length, shoot weight, and root weight. Root rot severity was measured using a 0 to 5 linear scale (Figure 2.1) (Ondrej et al., 2008). The experiments were conducted twice as a RCBD with 18 treatments and six replicates, totaling 108 experimental units for each pathogen.

Field Trials

A total of eight fungicides were evaluated for efficacy in-furrow against field pea root rot over two growing seasons. All eight fungicides were evaluated in 11 treatments in 2015 in Carrington and Leonard, North Dakota; five fungicides were evaluated in eight treatments in 2016 in Oakes and Carrington, North Dakota (Table 2.4). Each trial was performed in a RCBD with six replicates. An inoculated control, a non-inoculated control, and a mefenoxam/fludioxonil seed treatment (Apron Maxx 5 fl oz/cwt) were included in all trials. In 2016, all seed except for the mefenoxam/fludioxonil seed treatment was treated with mefenoxam (Apron XL 0.16 fl oz/cwt) to manage *Pythium* spp. in the soil.

Table 2.4. In-furrow fungicide active ingredients, trade names, companies, fungicide resistance action committee (FRAC) groups, and formulated product rates for the field trials conducted over two growing seasons.

Fungicide active ingredient	Trade name	Active ingredient concentration (%)	Company	FRAC Group	Rate (L/ha)	2015	2016
Azoxystrobin	Quadris	22.9	Syngenta	11	.66	X	X
Pyraclostrobin	Headline	23.6	BASF	11	.66	X	X
Picoxystrobin	Aproach	22.5	DuPont	11	.66	X	
Prothioconazole	Proline	41.0	Bayer	3	.42	X	X
Boscalid	Endura	70.0	BASF	7	.58	X	
Fluxapyroxad/ pyraclostrobin	Priaxor	14.3/28.6	BASF	7/11	.49	X	X
Fluopyram	Velum Prime	41.5	Bayer	7	.50	X	X
Penthiopyrad	Vertisan	20.6	DuPont	7	1.46	X	X

In each growing season and at each location, two side-by-side trials were planted with ‘DS Admiral’ or Abarth (Carrington) field pea seed. The objective of each trial was to evaluate in-furrow treatments for the management of Fusarium root rot caused by either *F. avenaceum* or *F. solani*. In Carrington in 2015, only one trial inoculated with *F. solani* was performed. The

plots were inoculated with sterilized millet seeds that were infested with a mixture of three isolates of *F. avenaceum* or *F. solani* by inserting them into the ground with the seed (Table 2.2).

In Leonard in 2015 each plot within each trial measured 30.5 square meters with seven, 6-meter long rows spaced 18 cm apart. In Carrington in 2015, each plot within each trial measured 61 square meters with seven, 12-meter rows spaced 18 cm apart. In Carrington and Oakes in 2016, each plot within each trial measured 33.5 square meters with seven, 8-meter rows spaced 18 cm apart. The target population for each trial was 740,000 plants per ha. The Oakes location was irrigated; all other trials relied on rain events for moisture.

Plant population, vigor, and phytotoxicity were collected at approximately two and four weeks after planting. Plant population was determined by counting the plants in a marked six-meter section of two rows in each plot and extrapolating that into plants per ha. Vigor was recorded as a percent and was determined by assigning 100% to the most vigorous-appearing plot in each replicate, then assigning ratings within the replicate compared to that plot. Phytotoxicity was recorded as percent plants affected in each plot.

Plots were sampled twice in 2015 (18 and 39 days after planting) by removing five plants total from the second and sixth rows of each plot. In 2016, plots were sampled once (30 days after planting) by removing a total of 45 plants from the second and sixth rows of each plot. Disease severity was measured based on a 0 to 5 scale (Figure 2.1) (Ondrej et al., 2008). Yield was determined at harvest and test weight was assessed thereafter. Roots from the inoculated and non-inoculated controls were cultured on PDA to determine causal pathogens of the visible root rot. Pathogens were identified to species using morphological characteristics.

Soil samples were collected with a soil probe in a "W" pattern from each field trial and analyzed by the North Dakota State University soil testing laboratory in the same way as the

greenhouse trials field soil (Table 2.5). Five samples were analyzed per trial separately, values were averaged.

Table 2.5. Average properties (nitrate, phosphorus, potassium, pH, electrical conductivity (EC), percent organic matter (%OM), and texture) of soil sampled from field pea field trials in 2015 and 2016.

Field Site	NO_3-N† (kg/ha)	P‡ (kg/ha)	K§ (kg/ha)	pH¶	EC# mmhos/cm	OM†† %	Texture‡‡
Carrington *F. solani* 2015	58.1	58.3	736.2	6.7	0.26	4.02	Loam
Carrington *F. solani* 2016	34.7	28.2	310.3	7.9	0.71	4.08	Loam
Carrington *F. avenaceum* 2016	22.4	18.4	272.6	7.7	1.19	4.06	Loam
Leonard *F. solani* 2015	42.6	57.8	738.9	7.8	0.24	3.46	Sandy Loam
Leonard *F. avenaceum* 2015	38.1	56.5	964.8	7.7	0.25	3.88	Sandy Loam
Oakes *F. solani* 2016	15.0	95.0	432.2	7.2	0.12	2.94	Sandy Loam
Oakes *F. avenaceum* 2016	25.6	93.7	474.3	7.4	0.15	2.48	Sandy Loam

† Nitrate kg/ha was determined by the water extraction method
‡ Phosphorus kg/ha was determined by the Olson procedure
§ Potassium kg/ha was determined by the 1N ammonium acetate method
¶ pH was determined with a 1:1 soil to water ratio
# Electrical conductivity was determined with a 1:1 soil to water ratio
†† Percent organic matter was determined by loss on ignition
‡‡ Texture was determined by the hydrometer method

Statistical Analysis

Categorical root rot severity data was converted to a percent root disease index (%RDI) using the following formula:

$$\%\text{DI} = \left[\frac{(a * 1) + (b * 2) + (c * 3) + (d * 4) + (e * 5) + (f * 6)}{(a + b + c + d + e + f) * g}\right] * 100$$

where *a*, *b*, *c*, *d*, *e*, and *f* represent the number of plants with the disease severity ratings of 0, 1, 2, 3, 4, and 5, respectively, and *g* represents the highest root rot severity rating (Li et al., 2014).

Levene's test for homogeneity of variance was used to ensure variance equality between the first and second performance of the greenhouse trials so that the data could be combined and analyzed. One-way analysis of variance (ANOVA) was conducted for field and combined greenhouse trials using the PROC GLM procedure in SAS 9.4 (SAS Institute, Cary, NC). Fisher's protected LSD was used to determine differences among treatment means ($\alpha = 0.05$).

Results

Greenhouse Trials

Phytotoxicity Trial

There was no sign of phytotoxicity in the absence of pathogen inoculum for any of the QoI fungicides evaluated for in-furrow application. There were no significant differences in emergence or plant height among the fungicides, rates, or timing of application (Appendix B; Table B.1).

Isolate Pathogenicity/Aggressiveness Trial

All six *F. avenaceum* and *F. solani* isolates produced significantly higher disease severity than the non-inoculated control, and therefore were determined to be pathogenic (Fugire 2.2). The *F. solani* isolate aggressiveness did not vary significantly among the isolates or inoculum placement. Only Pea 41 displayed significantly higher levels of root rot severity when placed next to the seed compared to under the seed in the *F. avenaceum* trial (Figure 2.2A). The *F. avenaceum* isolates Pea 41 and FA 0601, and all three of the *F. solani* isolates produced high levels of disease (Figure 2.2). *F. avenaceum* isolate FA 0601 and *F. solani* isolate Fsp F54B

were used in further in-furrow efficacy greenhouse trials, and a mixture of all three isolates for each pathogen would be used in the field trials.

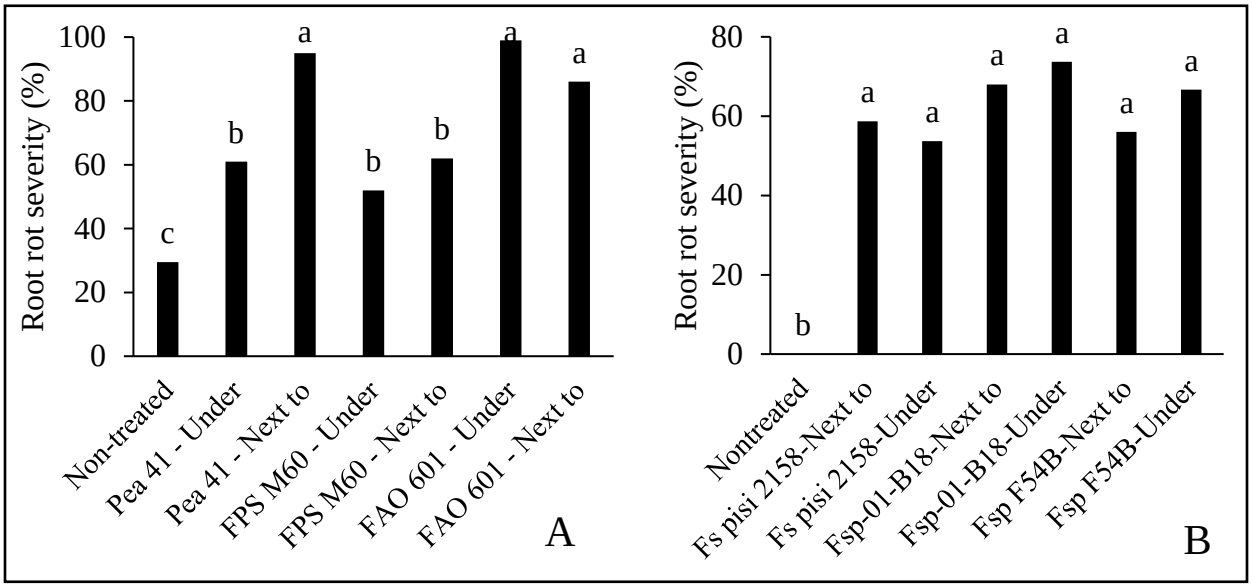

Figure 2.2. Root rot severity (percent root disease index; %RDI) of three *F. avenaceum* (A) and *F. solani* (B) isolates under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

In-furrow Efficacy Trials

Inoculated controls in both the *F. avenaceum* and *F. solani* trials the had significantly higher levels of disease than did the non-inoculated controls, with %RDI 60% and 50%, higher than that of the non-inoculated control, respectively.

F. avenaceum Inoculated Trials. Across most data parameters measured, fluopyram performed best in reducing root rot and increasing plant vigor in *F. avenaceum* root rot greenhouse trials while penthiopyrad generally also performed well (Figures 2.3, 2.4, 2.5). All rates of fluopyram and penthiopyrad displayed significantly reduced root rot severity and improved emergence and shoot weight (Figure 2.3, 2.5A). In addition to fluopyram and

penthiopyrad, azoxystrobin at 6.1 and 9.2 fl oz/a, pyraclostrobin at 6 fl oz/a, and prothioconazole at 5.7 fl oz/a showed significantly improved emergence compared to the inoculated control (Figure 2.3A). Azoxystrobin at 9.2 and 12.3 fl oz/a and both rates of prothioconazole also showed significantly reduced root rot severity (Figure 2.3B). Both rates of fluopyram, and penthiopyrad at 11 and 16 fl oz/a were the only treatments to significantly increase plant height (Figure 2.4A) and only fluopyram at 6.84 fl oz/a showed significantly increased root length (Figure 2.4B). Pyraclostrobin at 12 fl oz/a, both rates of fluopyram, and penthiopyrad at 16 fl oz/a showed significantly increased root weight (Figure 2.5B).

F. solani Inoculated Trials. Contrasting results were observed in the *F. solani* inoculated root rot greenhouse trial. Here, all in-furrow fungicides at all rates except fluopyram and penthiopyrad showed significantly reduced root rot severity, with the application of prothioconazole resulting in the most dramatic disease reduction (Figure 2.6). Though the inoculated and non-inoculated controls were significantly different for plant height, root length, and shoot weight, none of the in-furrow fungicide treatments displayed significant improvements (Appendix B; Table B.2). There was no significant difference in root weight between the inoculated and non-inoculated control, and there were no significant differences in emergence among the treatments.

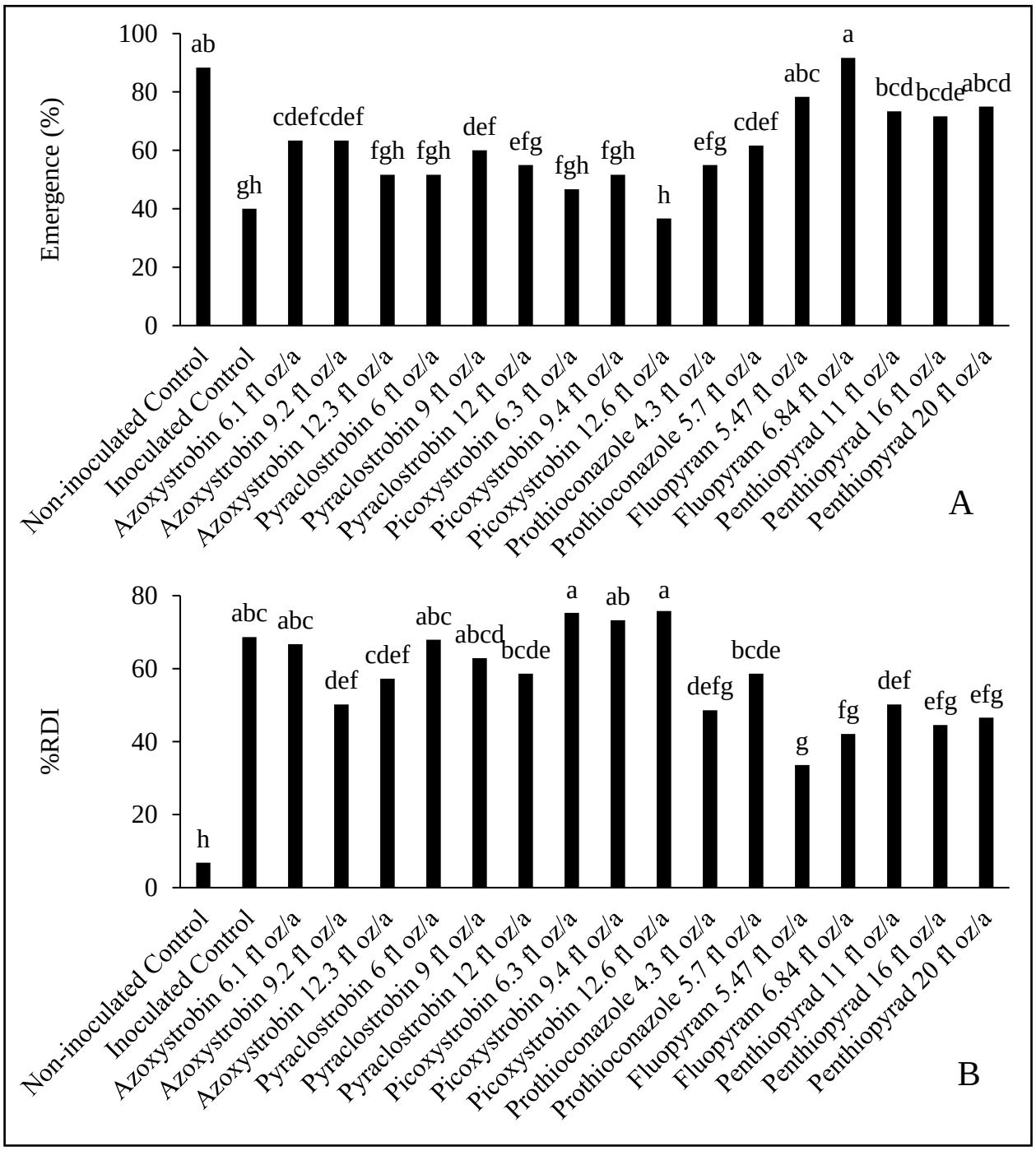

Figure 2.3. Emergence (A) and root rot severity (percent root disease index; %RDI) (B) of the *F. avenaceum* root rot trial under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

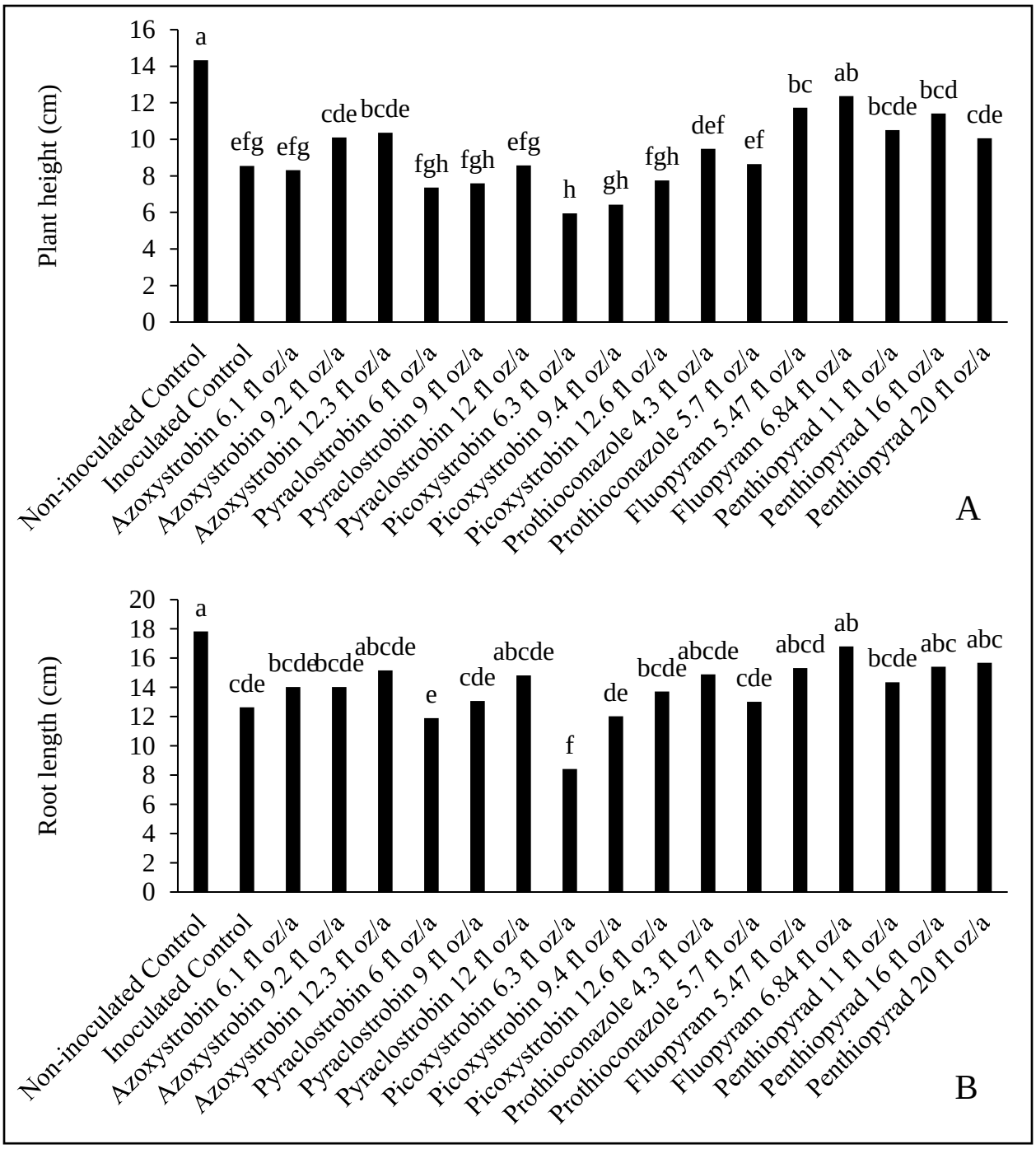

Figure 2.4. Plant height (A) and root length (B) of the *F. avenaceum* in-furrow trial under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

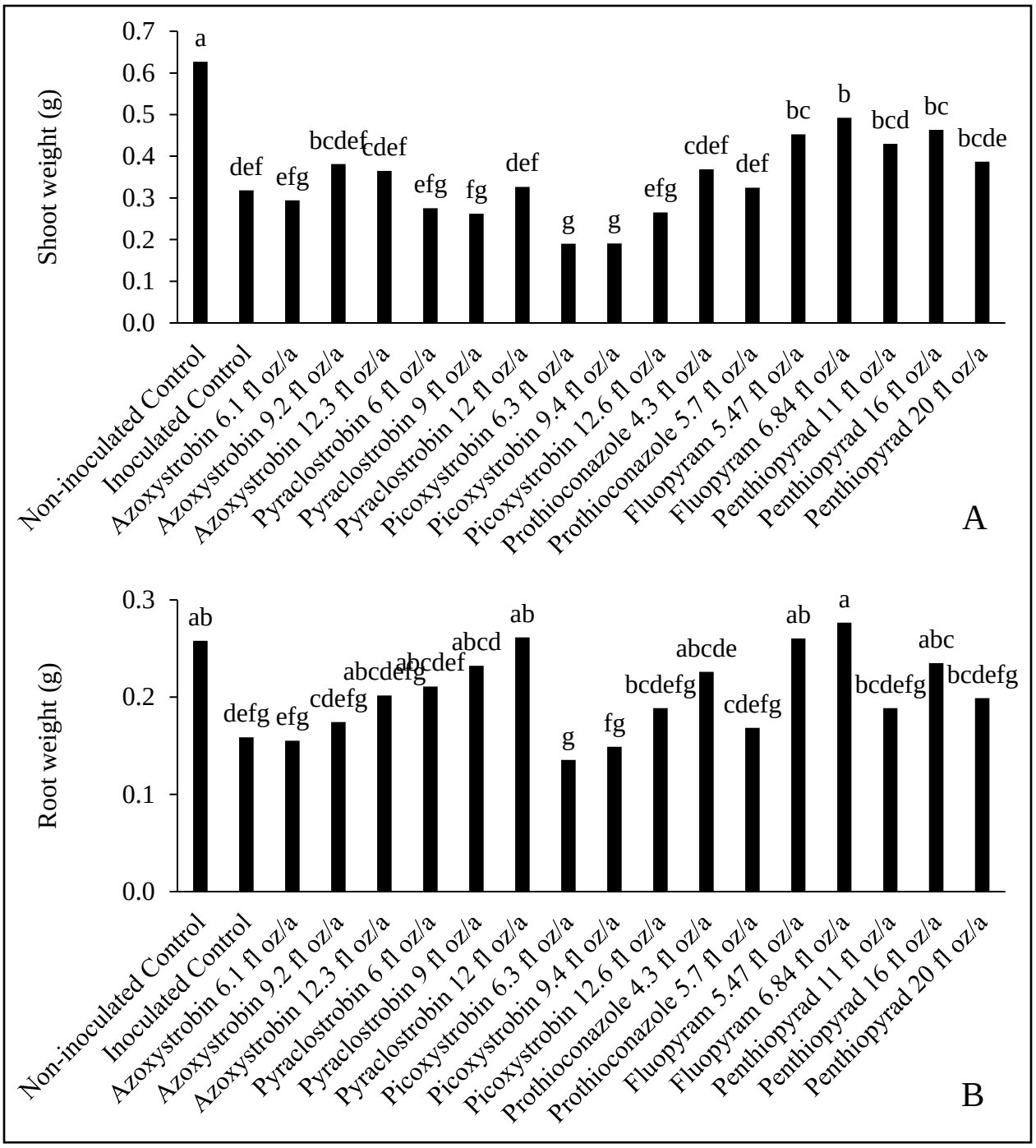

Figure 2.5. Shoot weight (A) and root weight (B) of the *F. avenaceum* trial under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

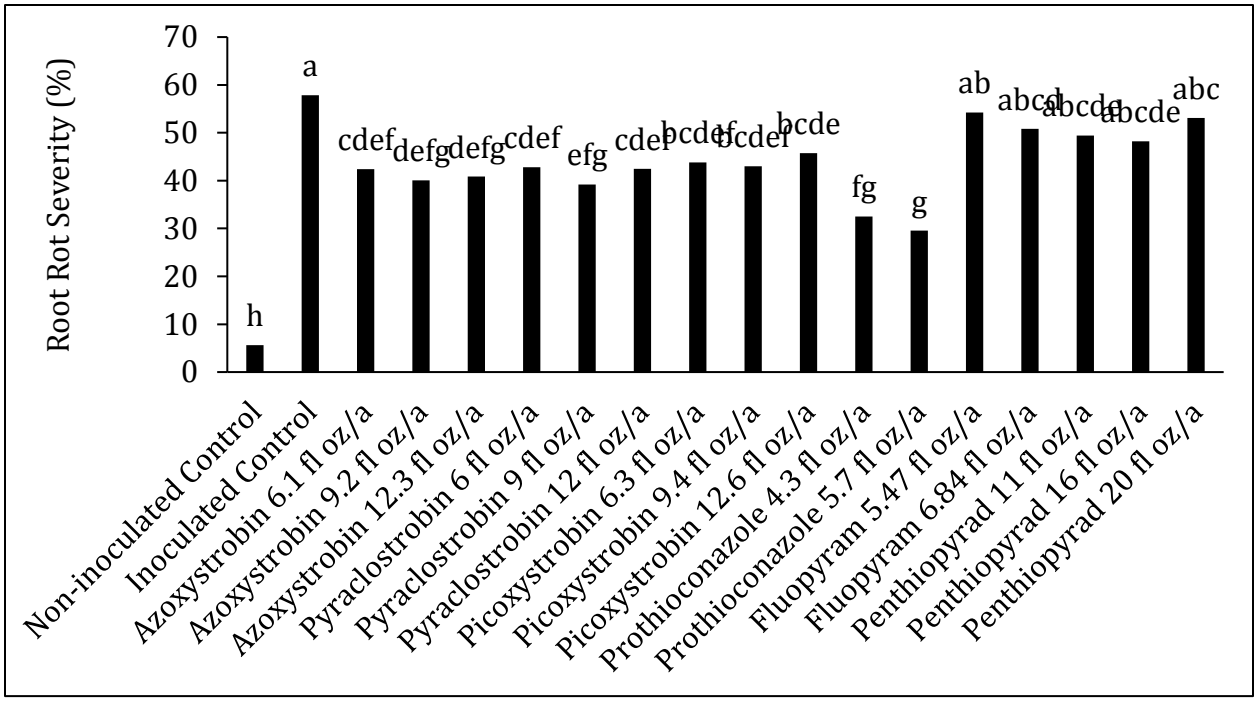

Figure 2.6. *F. solani* root rot severity (percent root disease index; %RDI) under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Field Trials

The efficacy of in-furrow fungicides for managing root rot in field peas caused by *F. avenaceum* and *F. solani* varied across years and locations. Phytotoxicity was not significant in any of the trials (Appendix B). Significant differences were observed among all other data parameters in at least one trial, but due to the vast amount of data, only statistically significant results will be reported. Some fungicides caused significantly increased vigor, plant and root biomass and decreased root rot severity; however, plant emergence and seed yield were generally not significantly increased. Fungicide efficacy was inconsistent across trial-years, and results varied based on location, the environment (soil-type and moisture), and pathogen infestation. When significant differences were observed, multiple fungicides from different FRAC groups were often found to be effective but no one fungicide proved to consistently be the most

effective. Environmental data from NDAWN indicated that the trials were planted under the warmest conditions in Oakes in 2016, and the wettest conditions in Carrington in 2015 (Table 2.6).

Table 2.6. Environmental conditions at planting of field pea in-furrow trials in Carrington, Leonard, and Oakes in 2015 and 2016 with their corresponding disease severity rating.

Trial location	Planting date	Soil temperature before planting† (°C)	Soil temperature after planting† (°C)	Rainfall before planting‡ (cm)	Rainfall after planting‡ (cm)	ARRS§ *F. avenaceum* (%RDI)	ARRS *F. solani* (%RDI)
Carrington 2015	5/12	12.2	12.3	.22	.56	NA	30
Carrington 2016	5/5	10.1	14.0	.24	.03	34.9	48.8
Leonard 2015	5/21	10.4	16.5	.62	.24	48.6	44.8
Oakes 2016¶	5/16	14.7	19.6	.08	.29	60.7	83.0

† Average over the two weeks before planting
‡ Average over the two weeks after planting
§ Average root rot severity (percent root disease index; %RDI) of inoculated control from sampling closest to 25 days after planting
¶ Trial was irrigated during early growing season

2015 Field Trials

Relatively low levels of root rot severity were observed in the 2015 *F. avenaceum* and *F. solani* root rot trials in Carrington and Leonard, although significant increases were observed with all inoculations. In the Carrington *F. solani* trial, the inoculated control %RDI was 30% and 54% at the first and second sampling dates, which were not significantly higher than the non-inoculated control %RDI of 23% and 46%, respectively (Figure 2.7). In the Leonard *F. avenaceum* trial, the inoculated control %RDI was 48.6% and 81.4% at the first and second samplings; significantly higher than the non-inoculated control ratings of 16.7% and 39.9%. In

the Leonard *F. solani* trial, the inoculated control %RDI was 45% and 74% at the first and second sampling dates; both inoculated control ratings were significantly higher than the non-inoculated %RDI of 20% and 41%. *F. avenaceum* and *F. solani* were present in their respective trials in Leonard, though no *F. solani* was isolated in the Carrington *F. solani* trial (Table 2.7).

Table 2.7. *Fusarium* species identified in 2015 field trials from the inoculated and non-inoculated control plots

Leonard *F. avenaceum*	Leonard *F. solani*	Carrington *F. solani*
F. avenaceum	*F. solani*	*F. oxysporum*
F. oxysporum	*F. oxysporum*	*F. graminearum*
F. culmorum	*F. graminearum*	
F. graminearum		
F. redolens		
F. acuminatum		

In the *F. avenaceum* trial in Leonard, significant differences were observed in root rot only at the second sampling date; however, none of the in-furrow treatments performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 2.7). The mefenoxam/fludioxonil seed treatment had the highest plant population, significantly higher than any other treatment at the first data collection date (Figure 2.8A). None of the in-furrow treatments improved vigor significantly over the mefenoxam/fludioxonil seed treatment (Figure 2.8B).

The mefenoxam/fludioxonil seed treatment, azoxystrobin, and prothioconazole showed significantly increased plant height at the second sampling date and root length at the first sampling date compared to the inoculated control, though no in-furrow treatment performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 2.9). Only the mefenoxam/fludioxonil seed treatment and azoxystrobin in-furrow showed significantly

increased shoot weight at the first sampling date compared to the inoculated control, though azoxystrobin did not perform significantly better than the seed treatment (Appendix B; Table B.3).

Root rot severity, plant height, and root weight at the first sampling, and root length and shoot weight at the second sampling showed no significant differences among treatments. Though root weight at the second sampling date and yield showed significant differences among treatments, the inoculated and non-inoculated controls were not significantly different (Appendix B; Table B.3, B.4).

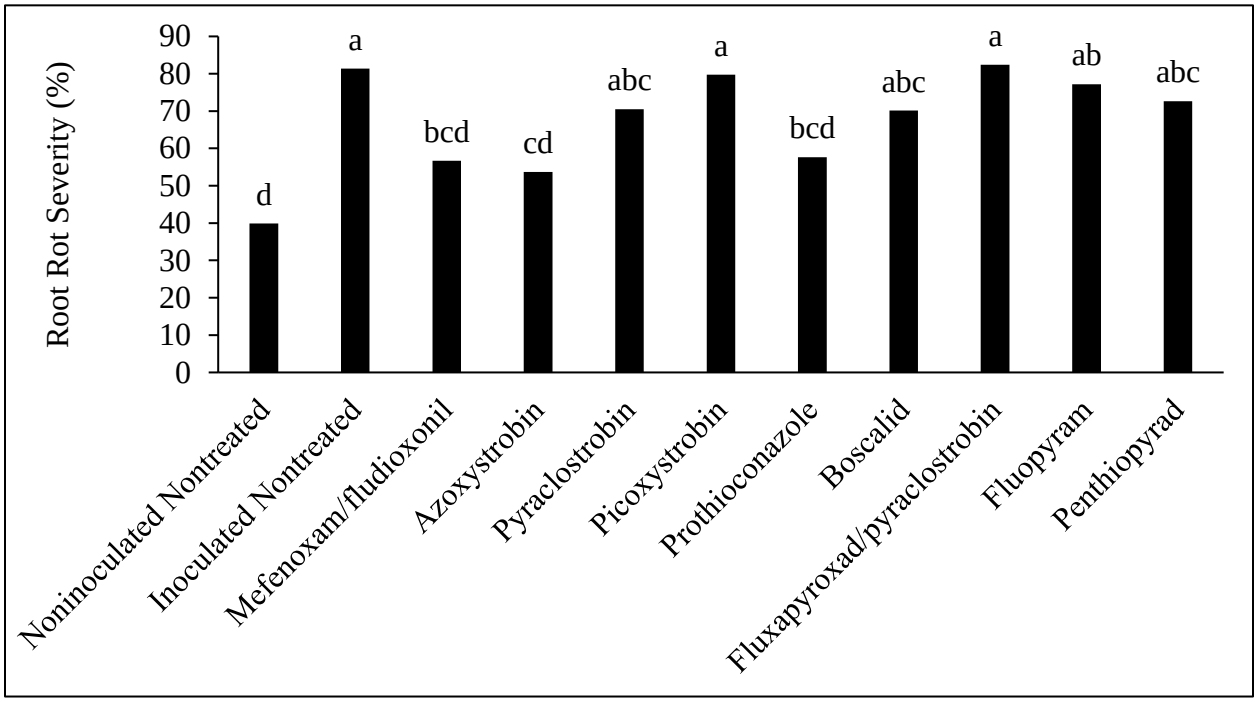

Figure 2.7. *F. avenaceum* root rot severity (percent root disease index; %RDI) at the second sampling date in Leonard in 2015 under field conditions. Bars within the same sample date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

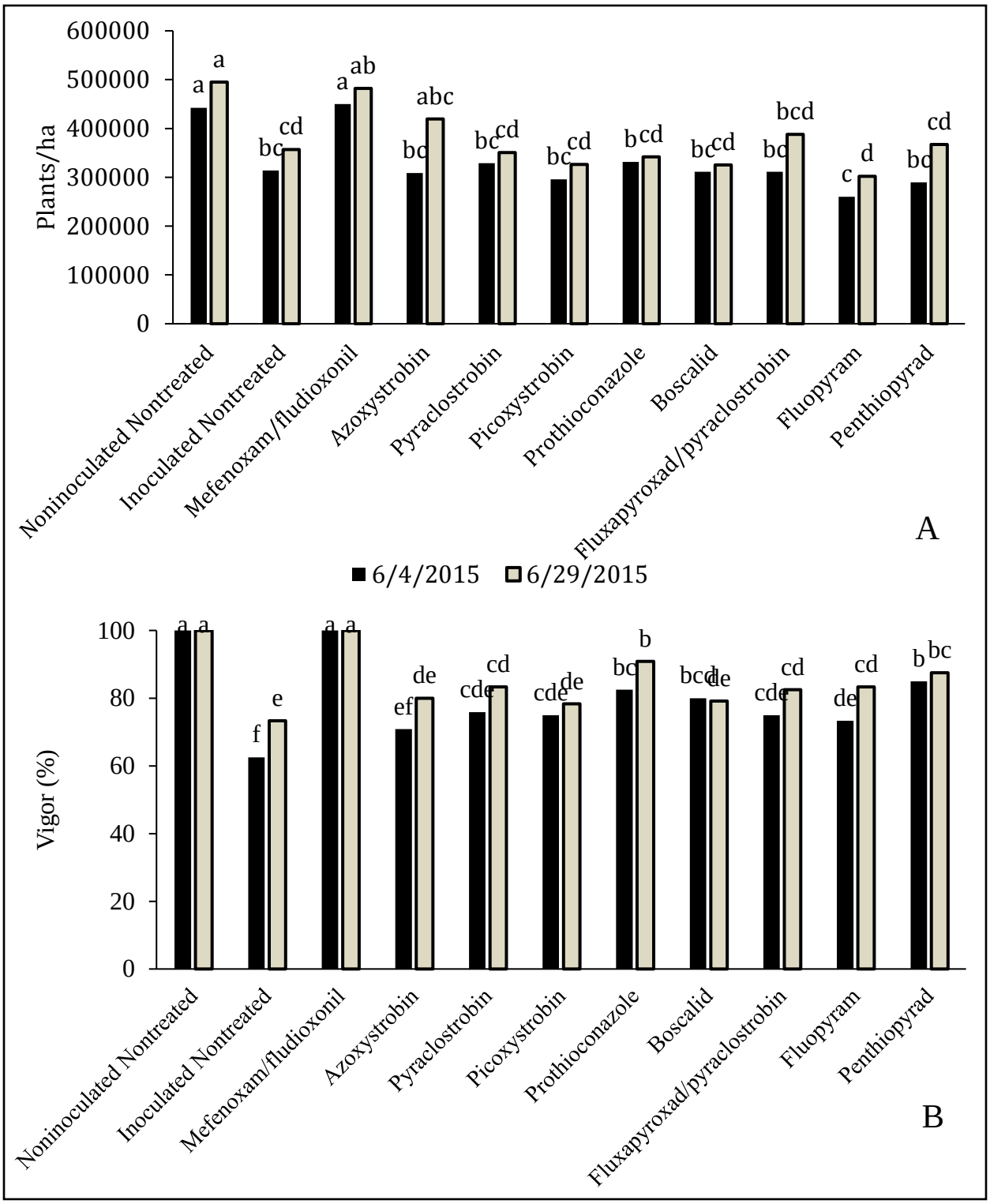

Figure 2.8. Plant population (A) and vigor (B) of the *F. avenaceum* trial in Leonard, ND in 2015 under field conditions. Bars within the same sampling date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

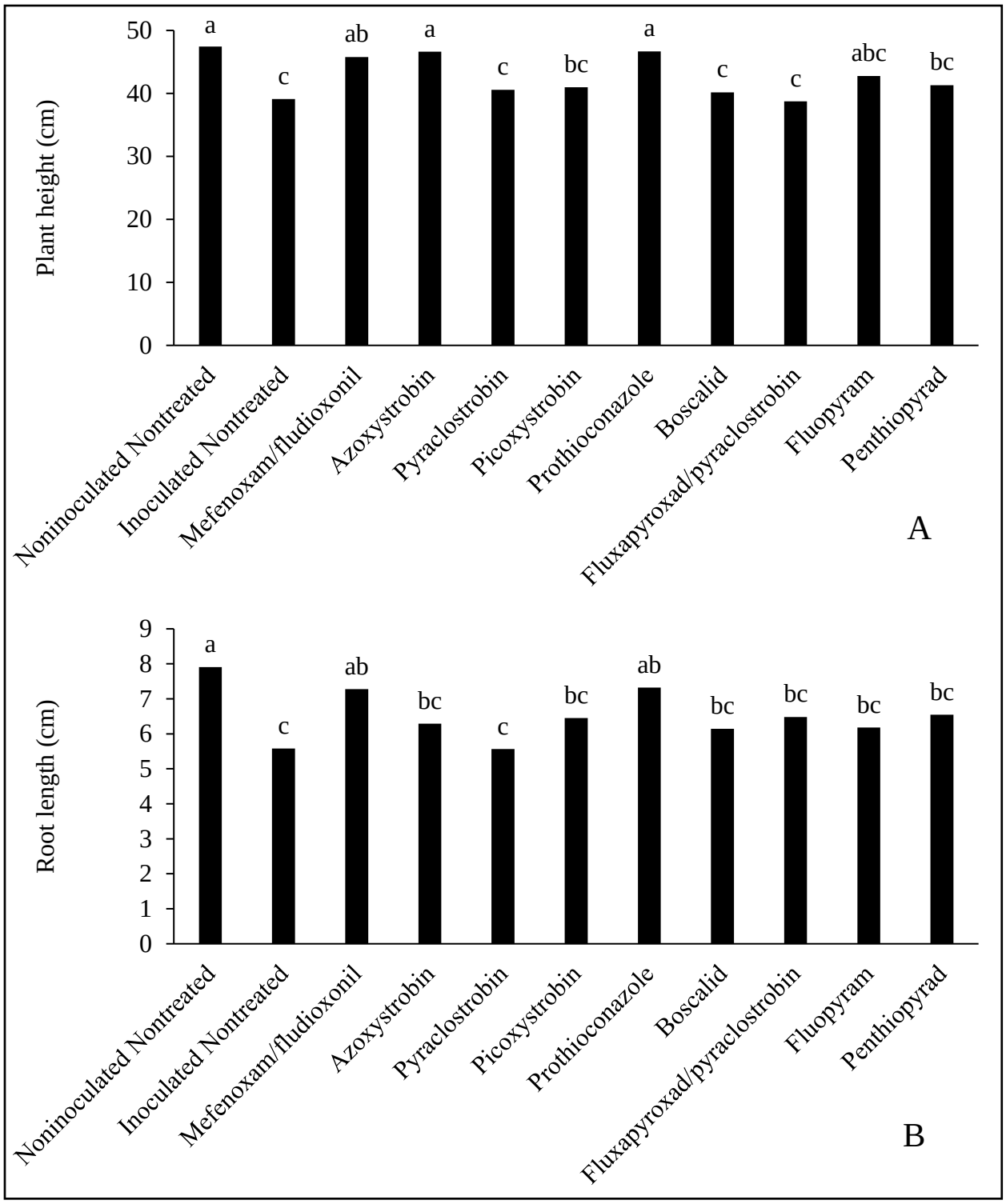

Figure 2.9. Plant height at the second sampling date (A) and root length at the first sampling date (B) of the *F. avenaceum* trial in Leonard, ND in 2015 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

At the first sampling date of the *F. solani* root rot trial in Leonard in 2015, prothioconazole and fluopyram displayed significantly reduced root rot severity compared to the inoculated control, though no in-furrow treatment performed significantly better than the mefenoxam/fludioxonil seed treatment. At the second sampling date, only prothioconazole showed significantly reduced root rot severity compared to the inoculated control, though not significantly more than the mefenoxam/fludioxonil seed treatment (Figure 2.10).

Only the mefenoxam/fludioxonil seed treatment showed significantly improved plant population compared to the inoculated control at both observation dates (Figure 2.11A). All treatments at the first observation date, and all treatments except picoxystrobin and fluopyram at the second observation date showed significantly increased vigor compared to the inoculated control, though none of the treatments performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 2.11B). At the first sampling date, only fluopyram showed significantly increased plant height compared to the inoculated control, though not compared to the mefenoxam/fludioxonil seed treatment (Appendix B; Table B.5). Though root length, shoot weight, and root weight at the first sampling, shoot weight at the second sampling, and yield showed significant differences among treatments, none of the treatments significantly improved performance compared to the inoculated control or the mefenoxam/fludioxonil seed treatment (Appendix B; Table B.6).

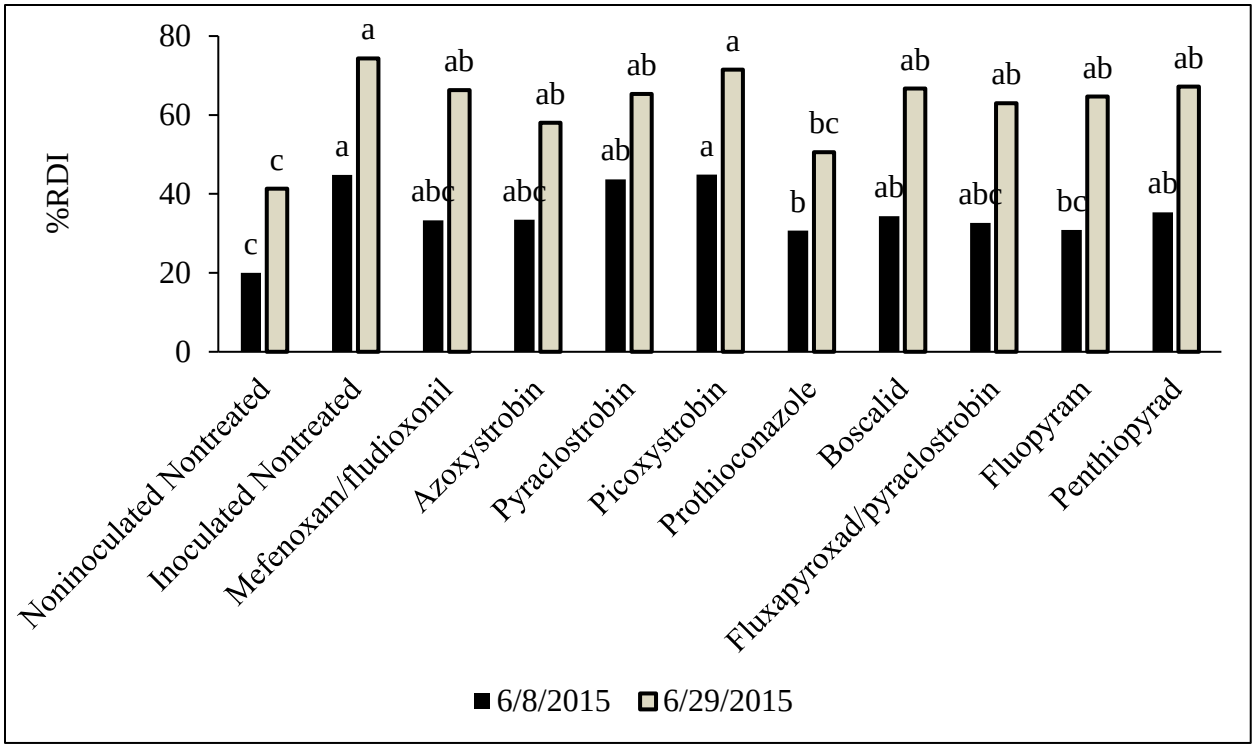

Figure 2.10. *F. solani* root rot severity (percent root disease index; %RDI) in Leonard in 2015 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

At the first sampling date of the *F. solani* trial in Carrington, all treatments significantly increased vigor compared to the inoculated control, though no treatment performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 2.12). Plant population, and vigor at both observation dates, shoot weight and root rot severity at both sampling dates, and plant height and root weight at the second sampling date showed no significant differences among treatments (Appendix B; Table B.7, B.8).

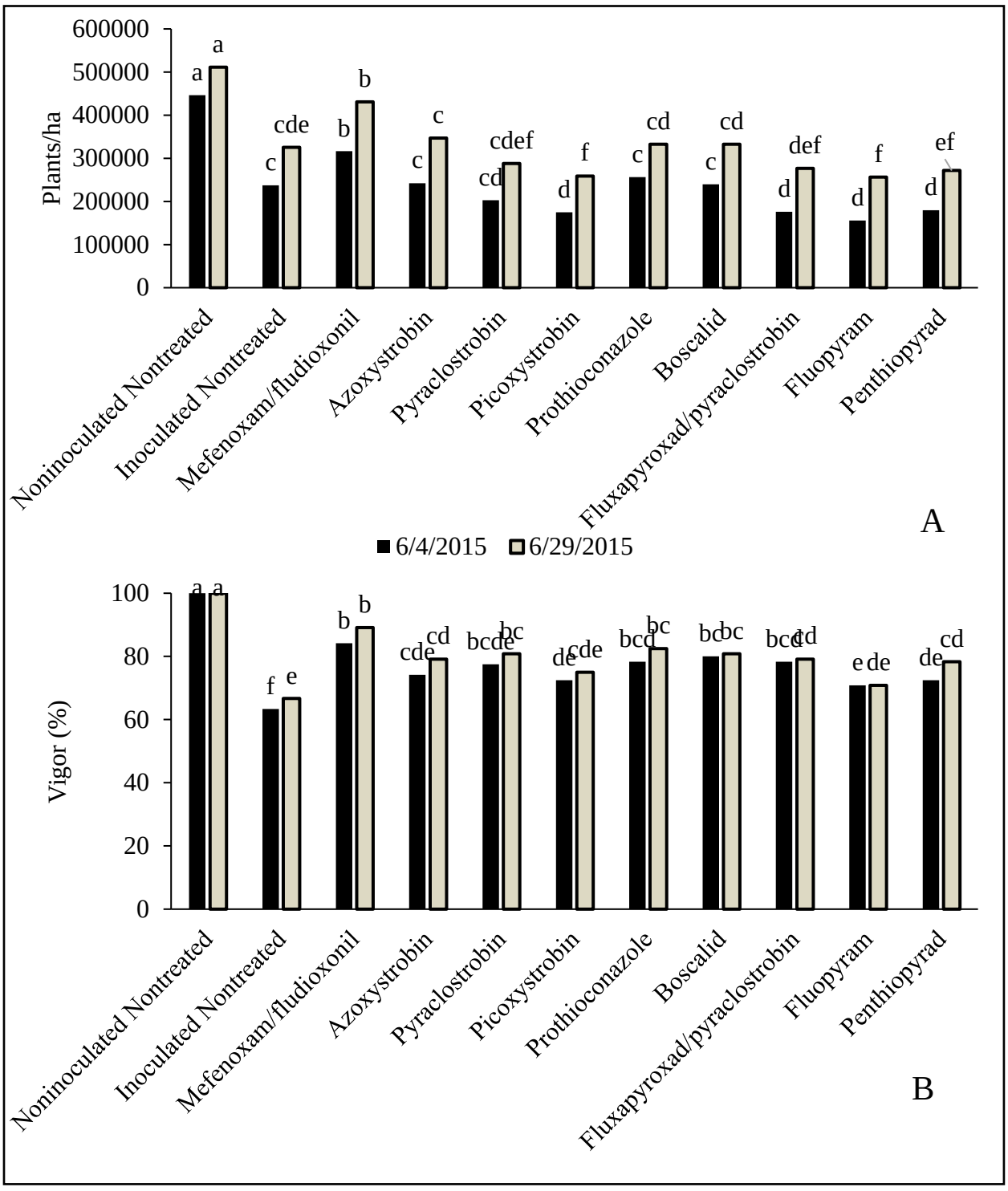

Figure 2.11. Plant population (A) and vigor (B) of the *F. solani* trial in Leonard, ND in 2015 under field conditions. Bars within the same sampling date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

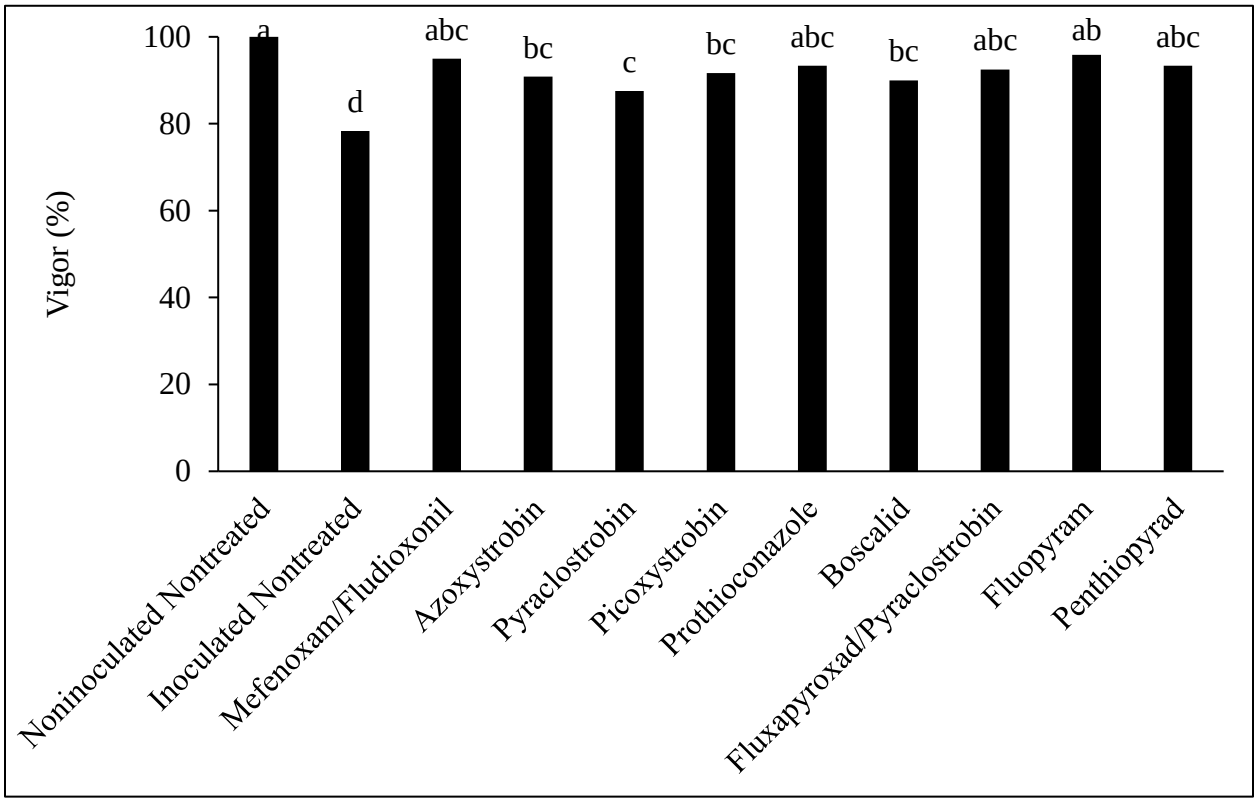

Figure 2.12. Vigor at the second sampling of the *F. solani* root rot trial in Carrington in 2015 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

2016 Field Trials

In the 2016 *F. avenaceum* and *F. solani* root rot trials in Carrington and Oakes, low to moderate levels of disease were observed, and significant increases were observed with all inoculations. In the Carrington *F. avenaceum* trial, the inoculated control %RDI was 35%, significantly higher than the non-inoculated control with a %RDI of 16%. In the Oakes *F. avenaceum* trial, the inoculated control %RDI was 61% which was significantly higher than the non-inoculated control with a %RDI of 41%.

In the Carrington *F. solani* trial, the inoculated control %RDI was 49% which was significantly higher than the non-inoculated control with a %RDI of 20%. In the Oakes *F. solani*

trial, the inoculated control %RDI was 83% which was significantly higher than the non-inoculated control with a %RDI of 49%. *F. avenaceum* and *F. solani* were isolated from all of their respective trials in Oakes and Carrington (Table 2.8).

Table 2.8. *Fusarium* species identified in 2016 field trials from the inoculated and non-inoculated control plots

Oakes *F. avenaceum*	Oakes *F. solani*	Carrington *F. avenaceum*	Carrington *F. solani*
F. avenaceum	*F. solani*	*F. avenaceum*	*F. solani*
F. oxysporum	*F. equeseti*	*F. acuminatum*	*F. equeseti*
	F. acuminatum	*F. equeseti*	
	F. avenaceum	*F. solani*	
		F. graminearum	
		F. redolens	

The mefenoxam/fludioxonil seed treatment, fluopyram, and penthiopyrad at both observation dates, and prothioconazole at the second observation date showed significantly improved vigor compared to the inoculated control at the 2016 *F. avenaceum* root rot trial in Oakes. None of the in-furrow fungicides performed significantly better than the mefenoxam/fludioxonil seed treatment (Figure 2.13). Only prothioconazole showed significantly reduced root rot severity and improved yield compared to the inoculated control and the mefenoxam/fludioxonil seed treatment (Figure 2.14A, 2.15). Plant population was not significantly different among the treatments at either observation date (Appendix B; Table B.9).

In the 2016 *F. avenaceum* root rot trial in Carrington, prothioconazole and fluopyram showed significantly reduced root rot severity compared to the inoculated control, and prothioconazole, fluopyram, and penthiopyrad displayed significantly reduced root rot severity compared to the mefenoxam/fludioxonil seed treatment (Figure 2.14B). Plant population, vigor,

and yield were not significantly different among the treatments at either observation date (Appendix B; Table B.10, B.11).

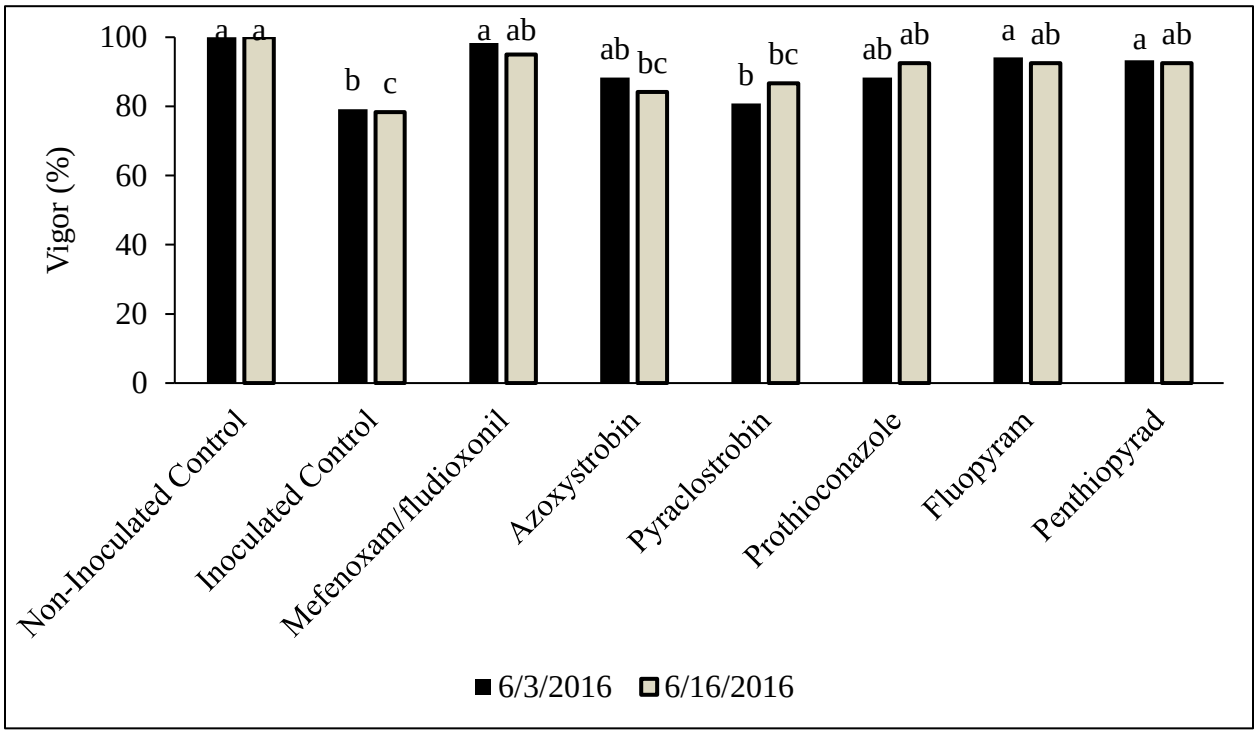

Figure 2.13. Vigor of the *F. avenaceum* trial in Oakes, ND in 2016 under field conditions. Bars within the same sampling date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

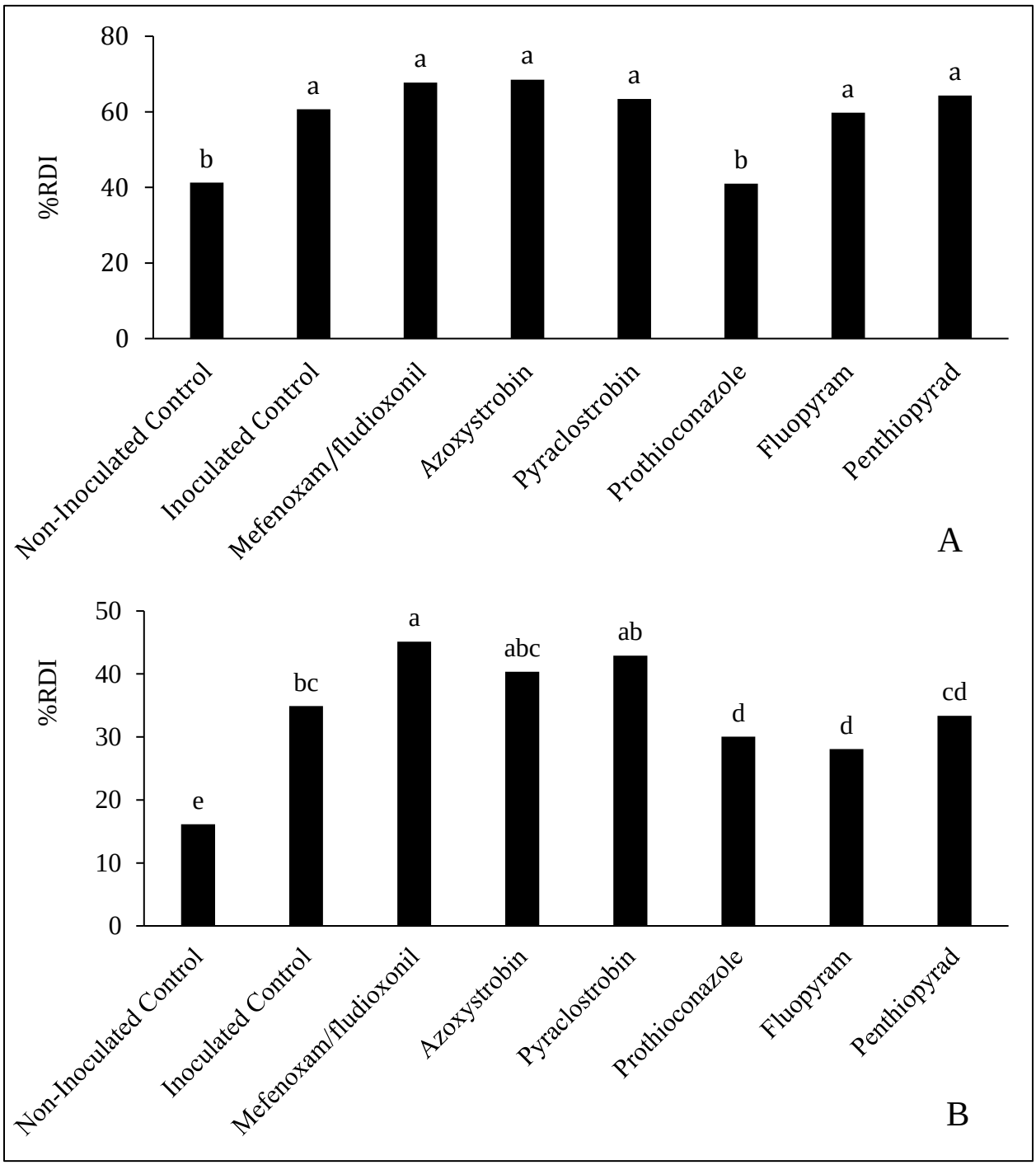

Figure 2.14. *F. avenaceum* root rot severity (percent root disease index; %RDI) in Oakes (A) and Carrington (B) in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

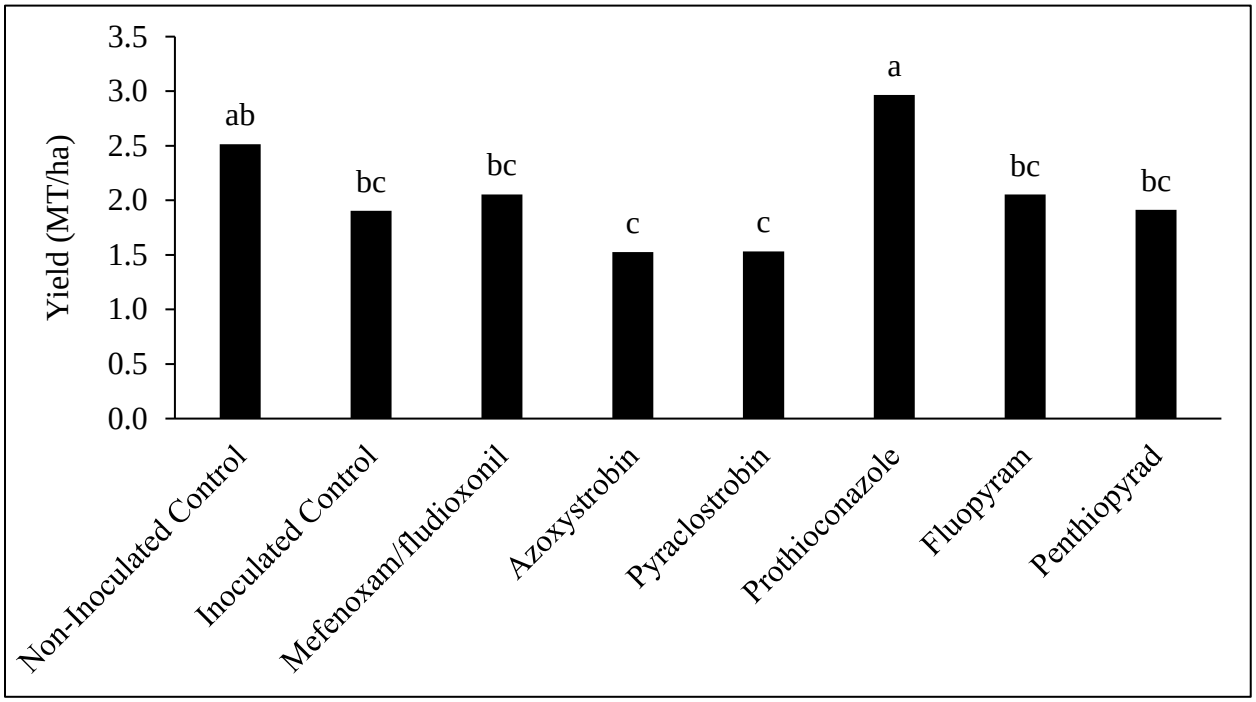

Figure 2.15. Yield of the *F. avenaceum* trial in Oakes in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

In the *F. solani* root rot trial in Oakes in 2016, prothioconazole and fluopyram showed significantly reduced root rot severity compared to the inoculated control and the mefenoxam/fludioxonil seed treatment (Figure 2.16). Only fluopyram displayed significantly improved vigor and the mefenoxam/fludioxonil seed treatment at both observation dates (Figure 2.17A). Though there was a significant difference in plant population and yield between the non-inoculated control and the inoculated control, none of the fungicide treatments significantly increased plant population or yield compared the mefenoxam/fludioxonil seed treatment (Appendix B; Table B.12).

In the *F. solani* root rot trial in Carrington in 2016, prothioconazole and penthiopyrad showed significantly increased vigor and yield compared to the inoculated control (Figure 2.17B, 1.18). None of the fungicide treatments significantly reduced root rot severity compared to the inoculated control (Appendix B; Table B.13).

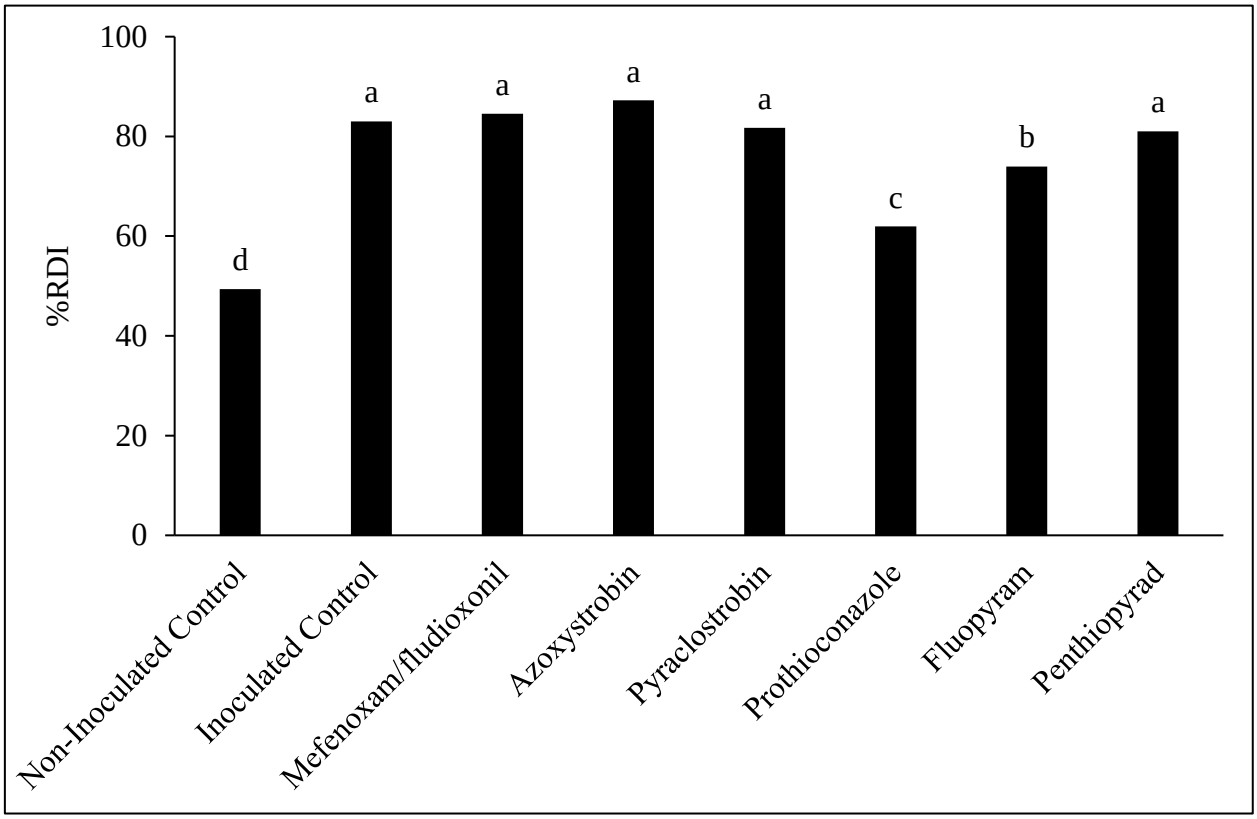

Figure 2.16. *F. solani* root rot severity (percent root disease index; %RDI) in Oakes in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

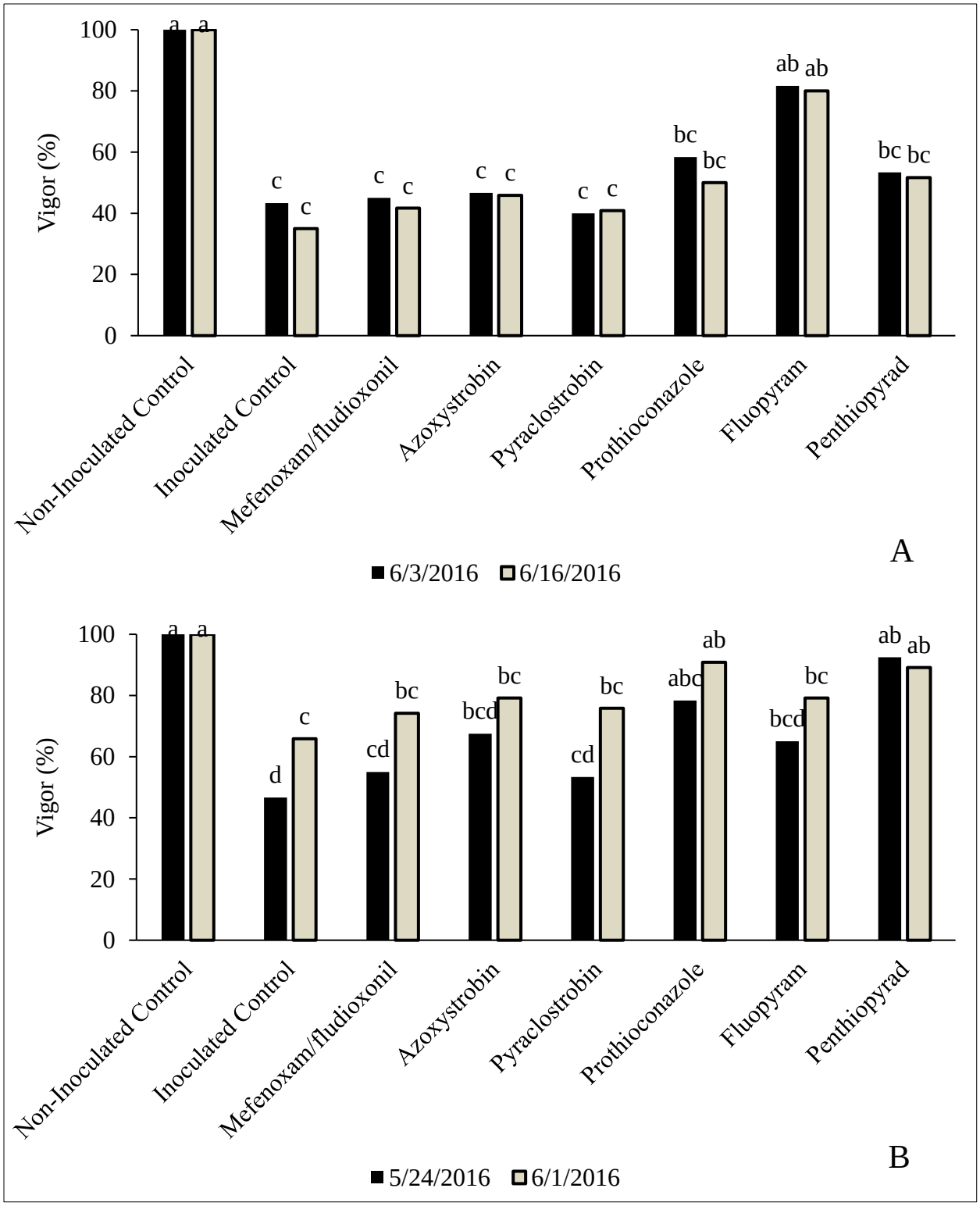

Figure 2.17. Vigor of the *F. solani* trials in Oakes (A) and Carrington (B) in 2016 under field conditions. Bars within the same sampling date with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

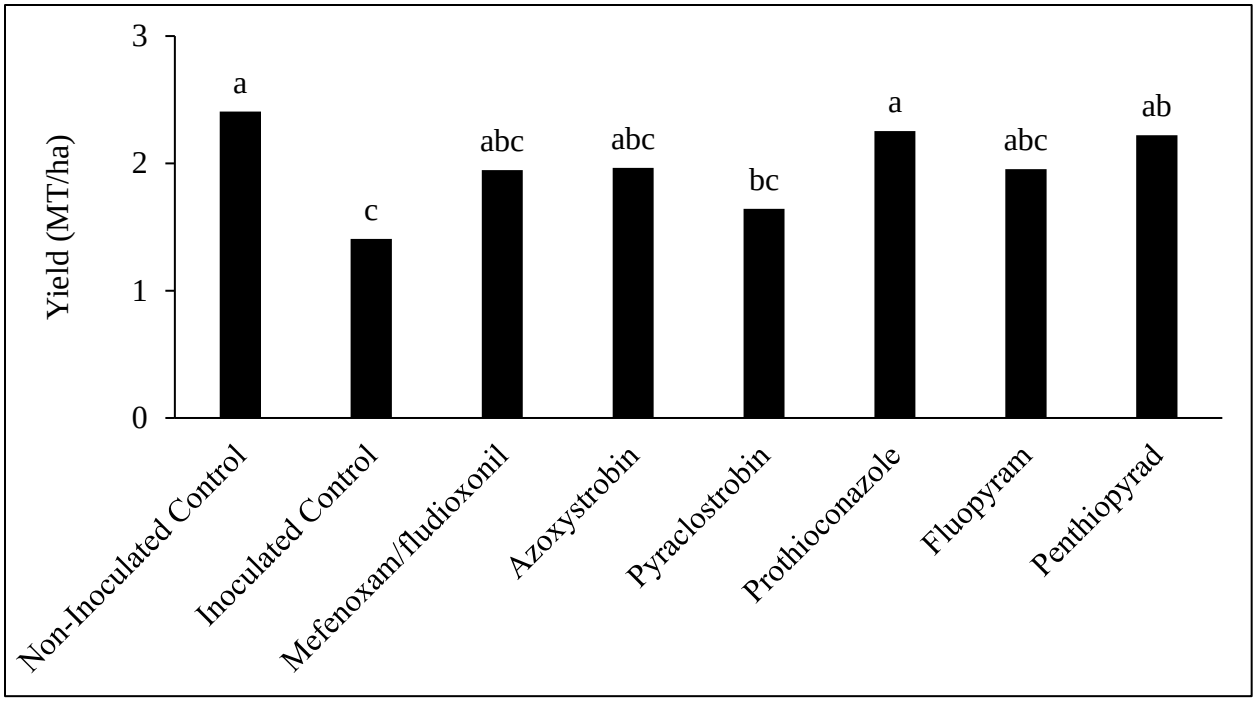

Figure 2.18. Yield of the *F. solani* trial in Carrington, ND in 2016 under field conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Discussion

Field pea Fusarium root rot is an important disease in North Dakota that does not have an adequate management strategy under severe disease pressure (Gossen et al., 2016). The application of in-furrow fungicides has provided benefit in several other crop pathosystems including *R. solani* on wheat, corn, and cotton, and Aspergillus crown rot and Southern stem rot in peanut. However, it was unclear if this management method would be beneficial for the many growers who are currently struggling with field pea root rot (Cotterill, 1991; Keyes, 2015; Rideout, 2002). To our knowledge, these are the first in-furrow fungicide efficacy trials conducted on field peas in field or greenhouse settings. Given the successes observed with other crops, and the massive damage incurred in field peas from Fusarium root rot, investigations to determine the efficacy of in-furrow fungicides were justified.

Results from greenhouse trials inoculated with *F. avenaceum* and *F. solani* were very different, suggesting these two pathogens are not controlled by the same chemistries. Root rot caused by *F. avenaceum* was well controlled by more than one product, while only prothioconazole reduced root rot caused by *F. solani*. Variability in the field may have been increased by inoculating with a mixture of three isolates of each pathogen. Even though the same isolates and quantities were used each year, each isolate may have responded differently to the environment.

Prothioconazole showed significantly reduced both *F. avenaceum* and *F. solani* root rot severity in all five field trials where significant differences were observed, and in all greenhouse trials. Fluopyram and penthiopyrad also displayed significantly reduced root rot severity in many trials. Prothioconazole also showed significantly improved yield in the *F. avenaceum* and *F. solani* trials in Oakes, 2016 which had the highest level of root rot severity of any trial, possibly due to supplemental irrigation.

The lack of significant differences in root rot severity in the Carrington 2015 *F. solani* trial may have been due to relatively high disease pressure from natural, underlying pathogens in the soil. Inoculations appear to have been lees effective, as no *F. solani* was isolated from roots from the inoculated control.

The Leonard 2015 trials are the only time that the mefenoxam/fludioxonil seed treatment performed best among treatments. This may be due to natural *Pythium* spp. in the soil that the mefenoxam in the seed treatment controlled, leading to lower root rot severity ratings. While roots were not cultured on selective media for *Pythium* spp., the roots had caramel-brown discolorations characteristic of Pythium root rot. In addition, in the 2016 *F. avenaceum* trials, more products were effective under lower disease pressure in Carrington than the higher disease

pressure in Oakes where only prothioconazole decreased root rot and increased yield. Therefore, yield differences develop more readily when disease levels are high, and root rot severity is more easily managed when disease levels are low.

This research indicates that in-furrow fungicides may be a viable option for management of root rot in dry beans caused by *F. avenaceum* and *F. solani*. Since the in-furrow fungicides showed no significant phytotoxic effects in either the field or greenhouse, they all would be good candidates for commercial use with prothioconazole, fluopyram, and penthiopyrad appearing to be the most promising.

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APPENDIX A: SECONDARY DRY BEAN RESULTS

Table A.1. Emergence and plant height for the QoIs for the phytotoxicity trial on dry beans under greenhouse conditions.

In-Furrow Treatment†	Spray Timing‡	Emergence (%)	Plant Height (cm)
Nontreated	Before	75.0 a§	15.30 a
Nontreated	After	83.3 a	16.26 a
Azoxystrobin 6 fl oz/a	Before	83.3 a	13.65 a
Azoxystrobin 6 fl oz/a	After	66.7 a	10.48 a
Azoxystrobin 9 fl oz/a	Before	91.7 a	16.71 a
Azoxystrobin 9 fl oz/a	After	91.7 a	15.07 a
Azoxystrobin 12 fl oz/a	Before	91.7 a	16.46 a
Azoxystrobin 12 fl zo/a	After	91.7 a	18.08 a
Pyraclostrobin 6 fl oz/a	Before	83.3 a	13.21 a
Pyraclostrobin 6 fl oz/a	After	91.7 a	14.77 a
Pyraclostrobin 9 fl oz/a	Before	58.3 a	9.08 a
Pyraclostrobin 9 fl oz/a	After	91.7 a	15.26 a
Pyraclostrobin 12 fl oz/a	Before	91.7 a	14.19 a
Pyraclostrobin 12 fl oz/a	After	91.7 a	14.75 a
Picoxystrobin 6 fl oz/a	Before	91.7 a	13.65 a
Picoxystrobin 6 fl oz/a	After	83.3 a	13.28 a
Picoxystrobin 9 fl oz/a	Before	100.0 a	15.18 a
Picoxystrobin 9 fl oz/a	After	75.0 a	11.41 a
Picoxystrobin 12 fl oz/a	Before	100.0 a	15.88 a
Picoxystrobin 12 fl oz/a	After	83.3 a	10.80 a
P value (0.05)		0.0755	0.0762
CV		29.3	45.3

† Soil for all treatments was non-infested

‡ Spray timing: Before = fungicide was sprayed before seeding, After = fungicide was sprayed after seeding

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.2. Effect of inoculum placement on root rot severity across rating dates caused by three *Rhizoctonia solani* isolates on dry beans under greenhouse conditions.

Inoculum Placement†	Root Rot Severity (%)
Non-infested	11.1 b‡
Under the seed	64.9 a
Next to the seed	73.4 a
P value (0.05)	0.0174
CV	25.2

† Soil for treatments 2 and 3 was infested with *Rhizoctonia solani*.
‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).

Table A.3. Effect of rating dates on root rot severity across inoculum placement caused by three *Rhizoctonia solani* isolates on dry beans under greenhouse conditions.

Inoculum Placement	Root Rot Severity (%)
14 days after planting	63.0 a†
30 days after planting	58.7 a
P value (0.05)	0.3699
CV	25.2

† Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference (α = 0.05).

Table A.4. Emergence, root length, and shoot weight for the *Rhizoctonia solani* in-furrow trial on dry beans under greenhouse conditions.

Treatment†	Emergence (%)	Root Length (cm)	Shoot Weight (g)
Nontreated/non-infested	83.3 a‡	17.5 c	1.87 a
Nontreated/infested	63.3 a	12.1 d	1.47 a
Azoxystrobin 6.1 fl oz/a	90.0 a	16.9 c	2.20 a
Azoxystrobin 9.2 fl oz/a	88.3 a	17.4 c	2.09 a
Azoxystrobin 12.3 fl oz/a	88.3 a	17.5 c	2.12 a
Pyraclostrobin 6 fl oz/a	85.0 a	18.3 bc	1.98 a
Pyraclostrobin 9 fl oz/a	83.3 a	16.9 c	2.10 a
Pyraclostrobin 12 fl oz/a	90.0 a	18.1 bc	2.07 a
Picoxystrobin 6.3 fl oz/a	81.7 a	18.5 abc	2.02 a
Picoxystrobin 9.4 fl oz/a	80.0 a	21.7 a	2.03 a
Picoxystrobin 12.6 fl oz/a	88.3 a	20.9 ab	2.14 a
Prothioconazole 4.3 fl oz/a	83.3 a	18.3 bc	1.97 a
Prothioconazole 5.7 fl oz/a	86.7 a	18.7 abc	1.96 a
Fluopyram 5.47 fl oz/a	76.7 a	18.4 bc	2.08 a
Fluopyram 6.84 fl oz/a	81.7 a	18.4 bc	1.88 a
Penthiopyrad 11 fl oz/a	85.0 a	17.9 bc	1.86 a
Penthiopyrad 16 fl oz/a	88.3 a	19.9 abc	2.16 a
Penthiopyrad 20 fl oz/a	86.7 a	19.9 abc	2.06 a
P value (0.05)	0.0677	0.0004	0.0797
CV	20.5	44.3	43.6

† Soil for treatments 2-18 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.5. Plant emergence, vigor, and yield for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/29/2014 in Fargo, ND.

		6/10/2014	6/18/2014		
In-Furrow Treatment†	Seed Treatment (+,-)‡	Emergence (plants/ha)	Emergence (plants/ha)	Vigor (%)	Yield (MT/ha)
No in-furrow	-	292473 a§	314218.7 a	97.5 a	1.84 a
No in-furrow	+	298997 a	305520.6 a	93.8 a	1.79 a
Azoxystrobin	-	227238 a	259855.6 a	88.8 a	1.95 a
Azoxystrobin	+	293561 a	303346.1 a	90.0 a	1.85 a
Pyraclostrobin	-	244634 a	275077.3 a	92.5 a	1.70 a
Pyraclostrobin	+	242459 a	276164.5 a	87.5 a	1.87 a
Picoxystrobin	-	254419 a	255506.6 a	87.5 a	1.60 a
Picoxystrobin	+	250070 a	283775.4 a	82.5 a	1.74 a
Prothioconazole	-	172875 a	210928.8 a	75.0 a	1.53 a
Prothioconazole	+	272903 a	276164.5 a	92.5 a	1.78 a
Metconazole	-	172875 a	196794.4 a	77.5 a	1.76 a
Metconazole	+	255507 a	282688.1 a	92.5 a	1.83 a
Boscalid	-	188096 a	207667 a	81.3 a	1.80 a
Boscalid	+	247896 a	254419.3 a	92.5 a	1.68 a
Fluxapyroxad/ pyraclostrobin	-	210929 a	266379.2 a	81.3 a	1.69 a
Fluxapyroxad/ pyraclostrobin	+	252245 a	280513.6 a	85.0 a	1.92 a
Fluopyram	-	272903 a	288124.4 a	86.3 a	1.68 a
Fluopyram	+	200056 a	221801.4 a	82.5 a	1.70 a
Penthiopyrad	-	247896 a	195707.2 a	72.5 a	1.71 a
Penthiopyrad	+	221801 a	264204.7 a	87.5 a	1.72 a
P value (0.05)		0.5699	0.3369	0.3607	0.8856
CV		32.5	25.8	14.5	15.1

† Soil for all treatments was infested with *Rhizoctonia solani*.

‡ + indicates presence of the mefenoxam/fludioxonil seed treatment, - indicates absence of the seed treatment

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.6. Root rot severity and plant height across three sample dates for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment (mefenoxam/fludioxonil) and/or fungicides were applied in-furrow at planting on 5/29/2014 in Fargo, ND. † Soil for all treatments was infested with *Rhizoctonia solani*.

		6/23/2017		7/7/2014		7/21/2014	
In-Furrow Treatment†	Seed Treatment (+,-)‡	Root Rot Severity (%)	Plant Height (cm)	Root Rot Severity (%)	Plant Height (cm)	Root Rot Severity (%)	Plant Height (cm)
No in-furrow	-	32.8 a§	16.8 abc	38.9 a	26.2 abcd	30.6 bcdef	37.4 a
No in-furrow	+	32.8 a	16.8 abc	32.8 a	28.7 a	26.7 def	33.6 bcdef
Azoxystrobin	-	23.3 a	15.1 cdef	28.9 a	27.8 ab	30.0 bcdef	33.3 bcdefg
Azoxystrobin	+	16.7 a	17.4 ab	26.7 a	26.4 abcd	25.0 ef	35.8 ab
Pyraclostrobin	-	24.4 a	17.9 a	29.4 a	27.6 ab	22.8 f	30.8 g
Pyraclostrobin	+	27.5 a	16.2 abcd	27.2 a	26.4 abcd	40.7 a	35.2 abcd
Picoxystrobin	-	26.7 a	15.3 cdef	31.7 a	24.0 d	40.0 a	31.4 fg
Picoxystrobin	+	23.9 a	16.8 abc	23.8 a	24.4 cd	32.8 abcde	33.7 bcdef
Prothioconazole	-	30.6 a	15.1 cdef	32.2 a	24.0 d	31.4 bcde	35.5 abc
Prothioconazole	+	19.4 a	16.4 abc	40.6 a	27.3 abc	36.7 ab	32.2 efg
Metconazole	-	26.7 a	15.6 bcde	40.6 a	27.8 ab	25.6 ef	34.2 bcdef
Metconazole	+	27.2 a	16.9 abc	36.1 a	27.6 ab	33.9 abcd	34.5 bcde
Boscalid	-	31.1 a	15.2 cdef	29.4 a	25.3 bcd	32.8 abcde	32.1 efg
Boscalid	+	26.7 a	15.1 cdef	28.9 a	25.1 bcd	31.1 bcde	32.2 efg
Fluxapyroxad/ pyraclostrobin	-	31.1 a	15.9 bcde	40.6 a	25.6 bcd	29.4 bcdef	32.8 cdefg
Fluxapyroxad/ Pyraclostrobin	+	30.0 a	14.4 ef	25.6 a	25.2 bcd	35.6 abc	32.8 cdefg
Fluopyram	-	22.8 a	15.7 bcde	33.9 a	25.6 bcd	28.5 cdef	33.0 cdefg
Fluopyram	+	25.0 a	15.3 cdef	35.6 a	25.3 bcd	28.3 cdef	32.2 efg
Penthiopyrad	-	28.2 a	14.5 def	27.8 a	23.7 d	29.4 bcdef	32.6 defg
Penthiopyrad	+	22.2 a	13.8 f	28.9 a	25.4 bcd	28.3 cdef	32.0 efg
P value (0.05)		0.6196	0.0003	0.1257	0.0178	0.0019	0.0002
CV		35.1	18.5	26.8	18.0	18.4	13.1

‡ + indicates presence of the mefenoxam/fludioxonil seed treatment, - indicates absence of the seed treatment

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.7. Shoot and root weight across three sample dates for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment (mefenoxam/fludioxonil) and/or fungicides were applied in-furrow at planting on 5/29/2014 in Fargo, ND. † Soil for all treatments was infested with *Rhizoctonia solani*.

		6/23/2014	7/7/2014		7/21/2014	
In-Furrow Treatment†	Seed Treatment (+,-)‡	Shoot Weight (g)	Shoot Weight (g)	Root Weight (g)	Shoot Weight (g)	Root Weight (g)
No in-furrow	-	0.5 cdef§	3.0 b	0.09 a	19.5 a	0.5 a
No in-furrow	+	0.4 ef	3.9 a	0.13 a	17.1 ab	0.5 a
Azoxystrobin	-	0.5 cdef	2.1 cde	0.10 a	11.1 cde	0.4 a
Azoxystrobin	+	0.6 abcd	2.0 cde	0.10 a	10.7 cde	0.6 a
Pyraclostrobin	-	0.7 ab	2.1 cd	0.11 a	10.1 cde	0.4 a
Pyraclostrobin	+	0.8 a	1.9 cdef	0.11 a	12.0 cd	0.5 a
Picoxystrobin	-	0.4 def	1.3 f	0.11 a	9.9 cde	0.4 a
Picoxystrobin	+	0.7 abc	1.4 ef	0.06 a	11.0 cde	0.3 a
Prothioconazole	-	0.5 bcdef	1.6 def	0.08 a	12.8 bcd	0.3 a
Prothioconazole	+	0.6 abcde	1.8 cdef	0.10 a	12.1 cd	0.4 a
Metconazole	-	0.6 abcdef	1.8 cdef	0.08 a	13.0 bcd	0.4 a
Metconazole	+	0.6 abcd	2.5 bc	0.11 a	11.3 cde	0.4 a
Boscalid	-	0.6 abcde	1.6 def	0.10 a	11.7 cde	0.4 a
Boscalid	+	0.5 def	1.4 ef	0.09 a	11.6 cde	0.5 a
Fluxapyroxad/ pyraclostrobin	-	0.7 ab	1.6 def	0.08 a	8.3 de	0.3 a
Fluxapyroxad/ Pyraclostrobin	+	0.5 bcdef	1.7 def	0.09 a	7.1 e	0.3 a
Fluopyram	-	0.5 cdef	1.8 def	0.10 a	13.9 bc	0.4 a
Fluopyram	+	0.6 abcde	1.6 def	0.10 a	10.5 cde	0.4 a
Penthiopyrad	-	0.5 cdef	1.7 def	0.11 a	13.6 bc	0.5 a
Penthiopyrad	+	0.4 f	1.5 def	0.11 a	12.3 bcd	0.4 a
P value (0.05)		0.0057	<.0001	0.1996	<.0001	0.1996
CV		53.9	59.1	59.5	59.1	59.5

‡ + indicates presence of the mefenoxam/fludioxonil seed treatment, - indicates absence of the seed treatment

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.8. Plant emergence, vigor, and yield for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/29/2014 in Fargo, ND.

		6/10/2014	6/18/2014		
In-Furrow Treatment†	Seed Treatment (+,-)‡	Emergence (plants/ha)	Emergence (plants/ha)	Vigor (%)	Yield (MT/ha)
No in-furrow	-	279426 a§	304433 a	92.5 a	2.13 a
No in-furrow	+	267466 a	301172 a	91.3 a	1.95 a
Azoxystrobin	-	210202 a	278339 a	93.3 a	2.17 a
Azoxystrobin	+	284863 a	289212 a	90.0 a	1.94 a
Pyraclostrobin	-	277252 a	295735 a	92.5 a	1.94 a
Pyraclostrobin	+	285950 a	295735 a	91.3 a	2.07 a
Picoxystrobin	-	275077 a	291386 a	90.0 a	1.95 a
Picoxystrobin	+	248983 a	267466 a	88.8 a	2.08 a
Prothioconazole	-	273990 a	322917 a	93.8 a	1.92 a
Prothioconazole	+	245721 a	297910 a	88.8 a	1.94 a
Metconazole	-	248983 a	298997 a	91.3 a	2.05 a
Metconazole	+	225063 a	267466 a	93.8 a	2.19 a
Boscalid	-	272903 a	288124 a	96.3 a	2.08 a
Boscalid	+	260943 a	294648 a	93.8 a	1.90 a
Fluxapyroxad/ pyraclostrobin	-	256594 a	273990 a	86.7 a	1.94 a
Fluxapyroxad/ pyraclostrobin	+	260943 a	302259 a	96.3 a	2.18 a
Fluopyram	-	237023 a	269641 a	91.3 a	2.00 a
Fluopyram	+	259856 a	284863 a	88.8 a	1.79 a
Penthiopyrad	-	272903 a	346837 a	97.5 a	2.04 a
Penthiopyrad	+	275077 a	309870 a	92.5 a	1.89 a
P value (0.05)		0.7316	0.4997	0.8436	0.5902
CV		17.0	12.8	7.2	11.4

† Soil for all treatments was infested with *Fusarium solani*.

‡ + indicates presence of the mefenoxam/fludioxonil seed treatment, - indicates absence of the seed treatment

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.9. Root rot severity and plant height across three sample dates for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment (mefenoxam/fludioxonil) and/or fungicides were applied in-furrow at planting on 5/29/2014 in Fargo, ND. † Soil for all treatments was infested with *Fusarium solani*.

		6/23/2014		7/9/2014		7/24/2014	
In-Furrow Treatment†	Seed Treatment (+,-)‡	Root Rot Severity (%)	Plant Height (cm)	Root Rot Severity (%)	Plant Height (cm)	Root Rot Severity (%)	Plant Height (cm)
No in-furrow	-	17.4 a§	17.4 a	22.8 a	32.1 ab	15.0 de	43.4 a
No in-furrow	+	13.9 a	16.7 a	20.1 a	31.7 abc	20.0 b	38.4 bcd
Azoxystrobin	-	12.2 a	17.5 a	18.9 a	31.1 abcde	18.3 bcde	39.5 b
Azoxystrobin	+	15.0 a	16.9 a	24.4 a	30.7 bcdef	14.4 e	37.7 bcd
Pyraclostrobin	-	14.7 a	17.3 a	21.7 a	30.1 bcdef	17.2 bcde	39.5 b
Pyraclostrobin	+	13.9 a	18.8 a	20.6 a	31.3 abcde	17.8 bcde	38.8 bc
Picoxystrobin	-	13.9 a	17.6 a	21.1 a	30.5 bcdef	18.9 bcd	33.3 e
Picoxystrobin	+	12.9 a	18.0 a	23.9 a	29.9 bcdef	17.2 bcde	39.6 b
Prothioconazole	-	13.9 a	17.6 a	18.2 a	29.5 cdef	16.7 bcde	36.8 bcd
Prothioconazole	+	14.4 a	17.2 a	22.2 a	28.7 f	17.2 bcde	37.5 bcd
Metconazole	-	15.6 a	19.8 a	25.6 a	31.4 abcd	19.4 bc	39.4 b
Metconazole	+	17.2 a	16.8 a	24.4 a	30.6 bcdef	18.3 bcde	36.9 bcd
Boscalid	-	13.9 a	16.8 a	21.1 a	33.1 a	17.8 bcde	38.0 bcd
Boscalid	+	19.4 a	15.4 a	18.9 a	29.5 cdef	24.4 a	35.3 de
Fluxapyroxad/ pyraclostrobin	-	15.6 a	16.2 a	21.5 a	28.7 f	17.0 bcde	36.5 bcde
Fluxapyroxad/ Pyraclostrobin	+	13.9 a	18.5 a	22.8 a	31.7 abc	15.6 cde	39.7 b
Fluopyram	-	15.6 a	17.6 a	22.8 a	31.1 abcde	16.7 bcde	37.7 bcd
Fluopyram	+	15.6 a	16.9 a	18.3 a	29.0 ef	20.0 b	35.6 cde
Penthiopyrad	-	16.7 a	18.0 a	27.8 a	29.0 def	20.0 b	38.6 bcd
Penthiopyrad	+	14.0 a	18.4 a	17.8 a	30.4 bcdef	17.2 bcde	38.3 bcd
P value (0.05)		0.3993	0.2315	0.1126	0.0094	0.0126	<.0001
CV		21.8	21.8	19.8	12.3	16.5	13.8

‡ + indicates presence of the mefenoxam/fludioxonil seed treatment, - indicates absence of the seed treatment

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.10. Shoot and root weight across three sample dates for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment (mefenoxam/fludioxonil) and/or fungicides were applied in-furrow at planting on 5/29/2014 in Fargo, ND. † Soil for all treatments was infested with *Fusarium solani*.

		6/23/2014		7/9/2014		7/24/2014	
In-Furrow Treatment†	Seed Treatment (+,-)‡	Shoot Weight (g)	Root Weight (g)	Shoot Weight (g)	Root Weight (g)	Shoot Weight (g)	Root Weight (g)
Nontreated	-	0.6 bcdef§	0.027 ef	5.8 a	0.155 a	31.2 a	1.10 a
Nontreated	+	0.7 abcdef	0.026 f	5.6 ab	0.184 a	20.5 bcd	0.62 bc
Azoxystrobin	-	0.5 ef	0.034 def	3.8 de	0.132 a	18.3 bcde	0.52 bc
Azoxystrobin	+	0.6 abcdef	0.044 bcd	3.7 de	0.140 a	22.1 bc	0.78 b
Pyraclostrobin	-	0.5 def	0.046 abcd	4.7 abcd	0.133 a	19.6 bcde	0.72 b
Pyraclostrobin	+	0.8 a	0.046 abcd	3.7 de	0.150 a	20.4 bcd	0.68 b
Picoxystrobin	-	0.6 cdef	0.035 def	3.5 de	0.117 a	13.6 ef	0.50 bc
Picoxystrobin	+	0.7 abcd	0.045 bcd	4.2 bcd	0.147 a	23.0 b	0.75 b
Prothioconazole	-	0.7 abcde	0.042 cd	4.2 bcd	0.148 a	16.2 cdef	0.67 b
Prothioconazole	+	0.7 abcdef	0.047 abcd	2.6 e	0.109 a	20.4 bcd	0.63 bc
Metconazole	-	0.7 abcde	0.043 cd	4.0 cde	0.159 a	21.2 bcd	0.55 bc
Metconazole	+	0.5 f	0.044 cd	3.5 de	0.119 a	18.4 bcde	0.66 b
Boscalid	-	0.7 abcdef	0.038 def	5.3 abc	0.169 a	17.7 bcde	0.52 bc
Boscalid	+	0.5 def	0.044 cd	2.6 e	0.128 a	10.1 f	0.37 c
Fluxapyroxad/ pyraclostrobin	-	0.5 def	0.037 def	2.7 e	0.085 a	18.0 bcde	0.57 bc
Fluxapyroxad/ Pyraclostrobin	+	0.8 ab	0.059 ab	4.5 abcd	0.171 a	21.7 bcd	0.74 b
Fluopyram	-	0.7 abcde	0.039 def	3.5 de	0.121 a	15.2 def	0.54 bc
Fluopyram	+	0.6 bcdef	0.055 abc	3.8 de	0.163 a	17.6 bcde	0.73 b
Penthiopyrad	-	0.8 ab	0.042 cde	3.5 de	0.147 a	16.9 bcde	0.58 bc
Penthiopyrad	+	0.8 abc	0.059 a	3.5 de	0.140 a	19.3 bcde	0.69 b
P value (0.05)		0.0076	<.0001	0.0002	0.0544	<.0001	0.0042
CV		50.6	53.3	58.8	54.6	56.1	70.4

‡ + indicates presence of the mefenoxam/fludioxonil seed treatment, - indicates absence of the seed treatment

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.11. Phytotoxicity, plant emergence, and vigor for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/19/2015 in Fargo, ND.

	6/30/2015		7/20/2015		
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)	Vigor (%)
Nontreated/ non-infested	0 a‡	400538 a	0 a	297173 a	100.0 a
Nontreated/ infested	0 a	386098 a	0 a	292614 a	91.7 a
Mefenoxam/ Fludioxonil	0 a	400538 a	0 a	284254 a	95.8 a
Azoxystrobin	0 a	373937 a	0 a	280453 a	96.7 a
Pyraclostrobin	0 a	405858 a	0 a	303254 a	98.3 a
Picoxystrobin	0 a	374698 a	0 a	276653 a	97.5 a
Prothioconazole	0 a	379258 a	0 a	291853 a	96.7 a
Boscalid	0 a	383818 a	0 a	281212 a	95.0 a
Fluxapyroxad/ Pyraclostrobin	0 a	374697 a	0 a	293374 a	98.3 a
Fluopyram	0 a	373937 a	0 a	288814 a	95.8 a
Penthiopyrad	0 a	382298 a	0 a	285773 a	95.0 a
P value (0.05)		0.8768		0.9297	0.2130
CV		10.6		10.3	4.7

† Soil for treatments 2-11 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.12. Plant height, shoot weight, root weight, and yield for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/19/2015 in Fargo, ND.

	7/6/2015			7/29/2015			9/22/2015
Treatment†	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Yield (MT/ha)
Nontreated/ non-infested	13.0 a‡	1.8 a	0.1 b	41.2 a	36.8 a	1.0 a	1.46 a
Nontreated/ infested	13.4 a	2.1 a	0.1 ab	39.9 ab	37.2 a	1.2 a	1.86 a
Mefenoxam/ Fludioxonil	13.6 a	2.0 a	0.2 a	37.5 c	31.4 a	1.1 a	1.67 a
Azoxystrobin	13.6 a	2.0 a	0.1 b	39.3 abc	35.8 a	1.1 a	1.71 a
Pyraclostrobin	14.8 a	2.1 a	0.2 a	38.2 bc	31.6 a	1.0 a	1.86 a
Picoxystrobin	13.7 a	2.2 a	0.1 ab	39.3 abc	31.6 a	1.1 a	1.90 a
Prothioconazole	12.8 a	1.7 a	0.1 ab	39.6 ab	32.1 a	1.0 a	1.70 a
Boscalid	13.2 a	2.0 a	0.1 b	38.6 bc	31.3 a	1.0 a	1.83 a
Fluxapyroxad/ Pyraclostrobin	12.9 a	2.0 a	0.1 b	38.8 bc	33.2 a	1.1 a	1.71 a
Fluopyram	13.6 a	2.0 a	0.1 ab	39.3 abc	34.0 a	1.2 a	1.75 a
Penthiopyrad	13.1 a	2.0 a	0.1 b	38.7 bc	31.7 a	1.4 a	1.78 a
P value (0.05)	0.1709	0.6686	0.0180	0.0413	0.7952	0.8511	0.5380
CV	19.4	45.6	46.9	9.7	47.3	81.1	18.1

† Soil for treatments 2-11 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.13. Phytotoxicity, plant emergence, and vigor for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/1/2015 in Carrington, ND.

	6/15/2015		7/9/2015		
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)	Vigor (%)
Nontreated/ non-infested	0 a‡	156575 a	0 a	151478 a	100.0 a
Nontreated/ infested	0 a	147836 a	0 a	138369 a	87.5 a
Mefenoxam/ Fludioxonil	0 a	152205 a	0 a	152206 a	95.8 a
Azoxystrobin	0 a	168956 a	0 a	155119 a	96.7 a
Pyraclostrobin	0 a	142010 a	0 a	139097 a	93.3 a
Picoxystrobin	0 a	183521 a	0 a	168228 a	96.7 a
Prothioconazole	0 a	177694 a	0 a	158760 a	95.8 a
Boscalid	0 a	162402 a	0 a	155847 a	90.8 a
Fluxapyroxad/ Pyraclostrobin	0 a	162401 a	0 a	152206 a	94.2 a
Fluopyram	0 a	174781 a	0 a	181336 a	96.7 a
Penthiopyrad	0 a	154391 a	0 a	155847 a	92.5 a
P value (0.05)		0.7731		0.7192	0.0573
CV		24.6		22.6	6.2

† Soil for treatments 2-11 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.14. Plant height, shoot weight, root weight, and yield for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/1/2015 in Carrington, ND.

	6/23/2015			7/14/2015			9/16/2015
Treatment†	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Yield (MT/ha)
Nontreated/ non-infested	14.6 de‡	2.9 bcd	0.33 a	38.2 a	37.3 a	1.19 a	1.03 a
Nontreated/ infested	14.5 de	2.8 bcd	0.23 a	40.6 a	34.8 a	1.16 a	0.95 a
Mefenoxam/ Fludioxonil	14.1 e	2.6 d	0.33 a	40.3 a	44.8 a	1.47 a	1.11 a
Azoxystrobin	16.4 ab	3.4 ab	0.29 a	39.9 a	41.7 a	1.33 a	1.05 a
Pyraclostrobin	16.1 abc	3.7 a	0.32 a	42.5 a	45.2 a	1.31 a	1.02 a
Picoxystrobin	16.3 ab	3.2 abcd	0.32 a	42.6 a	39.4 a	1.01 a	1.07 a
Prothioconazole	15.4 bcd	2.7 cd	0.33 a	40.0 a	41.4 a	1.21 a	1.07 a
Boscalid	17.0 a	3.3 abc	0.25 a	38.3 a	35.5 a	1.30 a	0.90 a
Fluxapyroxad/ Pyraclostrobin	15.2 bcde	2.9 bcd	0.31 a	41.0 a	39.5 a	1.30 a	1.17 a
Fluopyram	14.9 cde	2.8 bcd	0.27 a	40.7 a	39.3 a	1.30 a	1.16 a
Penthiopyrad	14.6 de	2.7 d	0.29 a	40.6 a	34.0 a	1.28 a	1.10 a
P value (0.05)	<.0001	0.0153	0.0704	0.1114	0.5478	0.6287	0.5863
CV	16.1	42.4	47.7	15.1	55.9	56.8	20.8

† Soil for treatments 2-11 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.15. Phytotoxicity and plant emergence for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/19/2015 in Fargo, ND.

Treatment†	6/30/2015		7/20/2015	
	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)
Nontreated/ non-infested	0 a‡	395218 a	0 a	365577 a
Nontreated/ infested	0 a	402059 a	0 a	349616 a
Mefenoxam/ Fludioxonil	0 a	393698 a	0 a	362537 a
Azoxystrobin	0 a	378498 a	0 a	329095 a
Pyraclostrobin	0 a	400538 a	0 a	370897 a
Picoxystrobin	0 a	392938 a	0 a	354176 a
Prothioconazole	0 a	367098 a	0 a	345816 a
Boscalid	0 a	366337 a	0 a	325295 a
Fluxapyroxad/ Pyraclostrobin	0 a	377737 a	0 a	353417 a
Fluopyram	0 a	362537 a	0 a	351896 a
Penthiopyrad	0 a	358736 a	0 a	333656 a
P value (0.05)		0.4726		0.5445
CV		10.4		10.9

† Soil for treatments 2-11 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.16. Plant height, shoot weight, root weight, and yield for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/19/2015 in Fargo, ND.

	7/6/2015			7/29/2015			9/22/2015
Treatment†	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Yield (MT/ha)
Nontreated/ non-infested	15.3 a‡	2.4 a	0.10 a	37.1 a	29.3 a	0.88 a	1.66 a
Nontreated/ infested	16.0 a	2.7 a	0.10 a	37.2 a	24.8 a	0.68 a	1.66 a
Mefenoxam/ Fludioxonil	16.0 a	2.6 a	0.08 a	38.8 a	26.3 a	0.82 a	1.62 a
Azoxystrobin	15.8 a	2.5 a	0.08 a	37.9 a	28.5 a	0.81 a	1.58 a
Pyraclostrobin	15.6 a	2.5 a	0.09 a	38.0 a	30.7 a	0.83 a	1.69 a
Picoxystrobin	14.8 a	2.3 a	0.09 a	38.4 a	26.3 a	0.56 a	1.61 a
Prothioconazole	16.3 a	2.5 a	0.10 a	36.9 a	26.6 a	0.73 a	1.68 a
Boscalid	16.2 a	2.8 a	0.11 a	39.5 a	35.7 a	0.97 a	1.68 a
Fluxapyroxad/ Pyraclostrobin	15.7 a	2.4 a	0.09 a	38.7 a	29.0 a	0.80 a	1.84 a
Fluopyram	15.9 a	2.4 a	0.10 a	36.9 a	29.5 a	0.84 a	1.68 a
Penthiopyrad	15.2 a	2.2 a	0.12 a	37.5 a	27.2 a	0.84 a	1.79 a
P value (0.05)	0.4665	0.3231	0.3870	0.1520	0.3328	0.1810	0.7757
CV	16.5	36.5	62.2	10.5	53.1	63.3	13.9

† Soil for treatments 2-11 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.17. Phytotoxicity and plant emergence for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/1/2015 in Carrington, ND.

	6/15/2015		7/9/2015	
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)
Nontreated/ non-infested	0 a‡	195901 a	0 a	205368 a
Nontreated/ infested	0 a	197357 a	0 a	190803 a
Mefenoxam/ Fludioxonil	0 a	190075 a	0 a	187162 a
Azoxystrobin	0 a	186433 a	0 a	181336 a
Pyraclostrobin	0 a	225760 a	0 a	221390 a
Picoxystrobin	0 a	205369 a	0 a	187890 a
Prothioconazole	0 a	190803 a	0 a	191531 a
Boscalid	0 a	193716 a	0 a	212360 a
Fluxapyroxad/ Pyraclostrobin	0 a	201727 a	0 a	195901 a
Fluopyram	0 a	206097 a	0 a	193716 a
Penthiopyrad	0 a	210466 a	0 a	201727 a
P value (0.05)		0.7586		0.5759
CV		17.0		16.1

† Soil for treatments 2-11 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.18. Plant height, shoot weight, root weight, and yield for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/1/2015 in Carrington, ND.

	6/23/2015			7/14/2015			9/17/2015
Treatment†	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Yield (MT/ha)
Nontreated/ non-infested	16.3 a‡	3.3 a	0.33 bc	35.1 d	30.6 a	0.93 bc	0.91 a
Nontreated/ infested	15.7 a	3.0 a	0.37 ab	40.2 ab	35.7 a	1.02 bc	0.94 a
Mefenoxam/ Fludioxonil	16.1 a	3.2 a	0.31 bc	38.1 abc	32.9 a	1.03 bc	0.87 a
Azoxystrobin	14.9 a	2.5 a	0.28 c	36.0 cd	33.4 a	1.00 bc	0.92 a
Pyraclostrobin	16.1 a	3.0 a	0.32 bc	40.1 ab	30.5 a	0.89 c	0.98 a
Picoxystrobin	15.0 a	3.4 a	0.43 a	39.5 ab	41.8 a	1.37 a	0.94 a
Prothioconazole	15.4 a	2.8 a	0.30 bc	37.9 abcd	28.0 a	0.84 c	0.99 a
Boscalid	16.0 a	3.0 a	0.36 ab	40.9 a	32.1 a	0.97 bc	0.92 a
Fluxapyroxad/ Pyraclostrobin	15.9 a	3.2 a	0.33 bc	38.9 abc	30.3 a	0.79 c	0.82 a
Fluopyram	16.2 a	3.0 a	0.32 bc	40.1 ab	36.9 a	1.19 ab	1.00 a
Penthiopyrad	16.0 a	3.2 a	0.33 bc	37.5 bcd	33.4 a	0.97 bc	0.94 a
P value (0.05)	0.0909	0.1585	0.0155	0.0015	0.3931	0.0083	0.7423
CV	12.7	36.0	43.1	15.1	61.1	57.4	17.1

† Soil for treatments 2-11 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.19. Phytotoxicity, plant emergence, and vigor for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/13/2016 in Fargo, ND.

	6/28/2016			7/13/2016		
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Vigor (%)	Phytotoxicity (%)	Emergence (plants/ha)	Vigor (%)
Nontreated/ non-infested	0 a‡	314978 a	100.0 a	0 a	291646 a	100 a
Nontreated/ infested	0 a	293104 a	90.0 a	0 a	273418 a	81 a
Mefenoxam/ Fludioxonil	0 a	293833 a	85.8 a	0 a	265398 a	82 a
Azoxystrobin	0 a	321540 a	84.2 a	0 a	289458 a	83 a
Pyraclostrobin	0 a	313520 a	87.5 a	0 a	298208 a	85 a
Prothioconazole	0 a	273418 a	82.5 a	0 a	261753 a	79 a
Fluopyram	0 a	265106 a	82.0 a	0 a	247608 a	84 a
Penthiopyrad	0 a	255919 a	82.5 a	0 a	242067 a	80 a
P value (0.05)		0.4798	0.2856		0.8250	0.1761
CV		20.9	14.9		26.0	15.0

† Soil for treatments 2-8 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.20. Yield for dry beans where soil was inoculated with *Rhizoctonia solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/13/2016 in Fargo, ND.

Treatment†	9/22/2016 Yield (MT/ha)
Nontreated/non-infested	1.36 a‡
Nontreated/infested	1.24 a
Mefenoxam/Fludioxonil	1.09 a
Azoxystrobin	1.09 a
Pyraclostrobin	1.11 a
Prothioconazole	1.10 a
Fluopyram	1.07 a
Penthiopyrad	1.14 a
P value (0.05)	0.7905
CV	31.9

† Soil for treatments 2-8 was infested with *Rhizoctonia solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.21. Phytotoxicity, plant emergence, and vigor for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/13/2016 in Fargo, ND.

	6/28/2016			7/13/2016	
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Vigor (%)	Phytotoxicity (%)	Emergence (plants/ha)
Nontreated/ non-infested	0 a‡	288729 a	100.0 a	0 a	254462 a
Nontreated/ infested	0 a	297479 a	84.2 b	0 a	250816 a
Mefenoxam/ Fludioxonil	0 a	293833 a	85.0 b	0 a	250816 a
Azoxystrobin	0 a	285813 a	92.5 ab	0 a	251545 a
Pyraclostrobin	0 a	282897 a	84.2 b	0 a	242795 a
Prothioconazole	0 a	288000 a	89.2 b	0 a	255191 a
Fluopyram	0 a	291646 a	86.7 b	0 a	250816 a
Penthiopyrad	0 a	306228 a	90.8 ab	0 a	259565 a
P value (0.05)		0.8246	0.0476		0.9645
CV		8.7	9.7		9.1

† Soil for treatments 2-8 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.22. Root rot severity and yield for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 6/13/2016 in Fargo, ND.

Treatment†	7/13/2016	9/22/2016
	Root Rot Severity (%)	Yield (MT/ha)
Nontreated/ non-infested	30.5 a‡	1.00 a
Nontreated/ infested	32.4 a	1.00 a
Mefenoxam/ Fludioxonil	31.6 a	1.18 a
Azoxystrobin	31.1 a	1.19 a
Pyraclostrobin	33.1 a	1.12 a
Prothioconazole	30.5 a	1.08 a
Fluopyram	30.8 a	0.91 a
Penthiopyrad	31.7 a	1.25 a
P value (0.05)	0.6746	0.8326
CV	8.8	28.6

† Soil for treatments 2-8 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table A.23. Phytotoxicity and plant emergence for dry beans where soil was inoculated with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/31/2016 in Carrington, ND.

	6/15/2016		6/27/2016	
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)
Nontreated/ non-infested	0 a‡	212501 a	0 a	227106 a
Nontreated/ infested	0 a	72295 bc	0 a	90550 bc
Mefenoxam/ Fludioxonil	0 a	73754 bc	0 a	79596 bc
Azoxystrobin	0 a	73754 bc	0 a	84708 bc
Pyraclostrobin	0 a	81057 bc	0 a	93472 bc
Prothioconazole	0 a	58419 c	0 a	76676 c
Fluopyram	0 a	56959 c	0 a	84125 bc
Penthiopyrad	0 a	89090 b	0 a	109537 b
P value (0.05)		<.0001		<.0001
CV		27.5		24.4

† Soil for treatments 2-8 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

APPENDIX B: SECONDARY FIELD PEA RESULTS

Table B.1. Emergence and plant height for the QoIs for the phytotoxicity trial on field peas under greenhouse conditions.

In-Furrow Treatment†	Spray Timing‡	Emergence (%)	Plant Height (cm)
Non-treated / non-infested	Before	75.0 a§	12.47 a
Non-treated / infested	After	83.3 a	6.33 a
Azoxystrobin 6 fl oz/a	Before	83.3 a	7.68 a
Azoxystrobin 6 fl oz/a	After	66.7 a	9.27 a
Azoxystrobin 9 fl oz/a	Before	91.7 a	9.80 a
Azoxystrobin 9 fl oz/a	After	91.7 a	9.20 a
Azoxystrobin 12 fl oz/a	Before	91.7 a	6.74 a
Azoxystrobin 12 fl zo/a	After	91.7 a	7.97 a
Pyraclostrobin 6 fl oz/a	Before	83.3 a	10.38 a
Pyraclostrobin 6 fl oz/a	After	91.7 a	7.77 a
Pyraclostrobin 9 fl oz/a	Before	58.3 a	12.87 a
Pyraclostrobin 9 fl oz/a	After	91.7 a	9.47 a
Pyraclostrobin 12 fl oz/a	Before	91.7 a	7.97 a
Pyraclostrobin 12 fl oz/a	After	91.7 a	7.31 a
Picoxystrobin 6 fl oz/a	Before	91.7 a	9.68 a
Picoxystrobin 6 fl oz/a	After	83.3 a	7.24 a
Picoxystrobin 9 fl oz/a	Before	100.0 a	5.15 a
Picoxystrobin 9 fl oz/a	After	75.0 a	7.93 a
Picoxystrobin 12 fl oz/a	Before	100.0 a	8.53 a
Picoxystrobin 12 fl oz/a	After	83.3 a	10.71 a
P value (0.05)		0.0755	0.1347
CV		29.4	83.2

† Soil for all treatments was non-infested

‡ Spray timing: Before = fungicide was sprayed before seeding, After = fungicide was sprayed after seeding

§ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.2. Emergence, plant height, root length, shoot weight, and root weight for the *Fusarium solani* in-furrow trial on field peas under greenhouse conditions.

In-Furrow Treatment†	Emergence (%)	Plant Height (cm)	Root Length (cm)	Shoot Weight (g)	Root Weight (g)
Non-treated / non-infested	78.3 a‡	15.1 a	19.5 a	0.68 a	0.28 bcd
Non-treated / infested	68.3 a	11.6 b	14.6 bcd	0.49 bcd	0.25 cdef
Azoxystrobin 6.1 fl oz/a	76.7 a	11.8 b	15.0 bc	0.48 bcde	0.25 cdef
Azoxystrobin 9.2 fl oz/a	85.0 a	10.9 bc	13.4 bcd	0.48 bcde	0.28 bcde
Azoxystrobin 12.3 fl oz/a	75.0 a	11.5 bc	14.6 bcd	0.49 bcd	0.29 bcd
Pyraclostrobin 6 fl oz/a	70.0 a	10.1 bcd	13.0 bcd	0.46 bcdef	0.30 bc
Pyraclostrobin 9 fl oz/a	70.0 a	10.2 bcd	12.3 cd	0.47 bcde	0.33 ab
Pyraclostrobin 12 fl oz/a	73.3 a	11.7 b	15.3 b	0.54 bc	0.37 a
Picoxystrobin 6.3 fl oz/a	70.0 a	11.6 b	15.1 bc	0.55 b	0.27 bcde
Picoxystrobin 9.4 fl oz/a	73.3 a	10.0 bcd	13.7 bcd	0.42 def	0.25 cdef
Picoxystrobin 12.6 fl oz/a	73.3 a	10.5 bcd	13.4 bcd	0.47 bcde	0.25 cdef
Prothioconazole 4.3 fl oz/a	73.3 a	8.5 de	12.8 bcd	0.38 ef	0.22 ef
Prothioconazole 5.7 fl oz/a	71.7 a	7.8 e	11.9 d	0.35 f	0.24 def
Fluopyram 5.47 fl oz/a	76.7 a	8.6 de	11.7 d	0.36 f	0.21 f
Fluopyram 6.84 fl oz/a	73.3 a	9.4 cde	12.7 bcd	0.40 def	0.21 f
Penthiopyrad 11 fl oz/a	73.3 a	9.8 bcde	13.6 bcd	0.44 bcdef	0.23 def
Penthiopyrad 16 fl oz/a	75.0 a	9.9 bcde	15.3 b	0.43 cdef	0.24 def
Penthiopyrad 20 fl oz/a	68.3 a	9.8 bcde	14.6 bcd	0.41 def	0.24 cdef
P value (0.05)	0.9781	<.0001	<.0001	<.0001	0.0001
CV	28.9	49.6	49.7	55.5	52.8

† Soil for treatments 2-18 was infested with *Fusarium solani*.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.3. Phytotoxicity, plant height, root length, shoot weight, and root weight for field peas where soil was infested with *Fusarium avenaceum* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/21/2015 in Leonard, ND.

	6/8/2015				6/29/2015			
Treatment†	Phytotoxicity (%)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Phytotoxicity (%)	Root Length (cm)	Shoot Weight (g)	Root Weight (g)
Non-treated/ non-infested	0 a‡	16.6 a	1.4 ab	0.3 a	0 a	8.3 a	18.5 ab	0.34 bcd
Non-treated/ infested	0 a	15.4 a	1.2 cd	0.3 a	0 a	5.6 a	18.1 ab	0.26 cd
Mefenoxam/ fludioxonil	0 a	16.5 a	1.4 a	0.3 a	0 a	7.6 a	19.2 ab	0.39 bc
Azoxystrobin	0 a	16.1 a	1.3 abc	0.3 a	0 a	8.7 a	19.8 a	0.60 a
Pyraclostrobin	0 a	16.3 a	1.1 d	0.2 a	0 a	7.3 a	14.7 bc	0.34 bcd
Picoxystrobin	0 a	15.5 a	1.2 bcd	0.2 a	0 a	5.6 a	15.9 abc	0.28 cd
Prothioconazole	0 a	15.4 a	1.2 abcd	0.3 a	0 a	8.4 a	19.0 ab	0.44 b
Boscalid	0 a	14.8 a	1.2 cd	0.2 a	0 a	7.1 a	15.1 abc	0.38 bc
Fluxapyroxad/ Pyraclostrobin	0 a	14.1 a	1.1 d	0.3 a	0 a	5.8 a	16.0 abc	0.23 d
Fluopyram	0 a	14.8 a	1.1 d	0.2 a	0 a	6.5 a	16.6 abc	0.26 cd
Penthiopyrad	0 a	14.7 a	1.2 bcd	0.3 a	0 a	6.6 a	13.2 c	0.31 bcd
P value (0.05)		0.1288	0.0019	0.7414		0.0770	0.1222	0.0001
CV		27.3	31.9	54.8		62.6	55.6	79.1

† Soil for treatments 2-11 was infested with *Fusarium avenaceum*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.4. Root rot severity at the first sampling date and yield for field peas where soil was infested with *Fusarium avenaceum* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/21/2015 in Leonard, ND.

	6/8/2015	8/27/2015
Treatment†	Root rot severity (%)	Yield (MT/ha)
Non-treated/ non-infested	16.7 a‡	4.36 a
Non-treated/ infested	48.6 a	3.82 abcde
Mefenoxam/ fludioxonil	30.0 a	4.20 ab
Azoxystrobin	33.7 a	3.81 bcde
Pyraclostrobin	36.9 a	4.04 abcd
Picoxystrobin	37.1 a	3.40 e
Prothioconazole	32.0 a	3.97 abcd
Boscalid	39.2 a	4.07 abc
Fluxapyroxad/ Pyraclostrobin	43.0 a	3.73 bcde
Fluopyram	41.3 a	3.50 de
Penthiopyrad	42.0 a	3.63 cde
P value (0.05)	0.2547	0.0470
CV	49.8	11.6

† Soil for treatments 2-11was infested with *Fusarium avenaceum*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.5. Plant height and root length for field peas where soil was infested with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/21/2015 in Leonard, ND.

	6/8/2015		6/29/2015	
Treatment†	Plant Height (cm)	Root Length (cm)	Plant Height (cm)	Root Length (cm)
Non-treated/ non-infested	17.4 a‡	7.5 ab	39.9 a	7.9 a
Non-treated/ infested	14.2 cd	6.8 abc	35.3 a	7.5 a
Mefenoxam/ fludioxonil	15.1 bcd	6.6 bc	34.8 a	8.9 a
Azoxystrobin	15.3 bcd	5.7 c	35.9 a	8.8 a
Pyraclostrobin	13.8 d	6.8 abc	31.8 a	7.8 a
Picoxystrobin	14.5 bcd	5.8 c	35.6 a	6.7 a
Prothioconazole	15.5 bc	6.2 bc	37.7 a	9.0 a
Boscalid	15.5 bcd	8.1 a	33.9 a	8.7 a
Fluxapyroxad/ Pyraclostrobin	15.5 bc	6.5 bc	37.1 a	9.8 a
Fluopyram	16.0 ab	6.9 abc	37.8 a	9.3 a
Penthiopyrad	15.4 bcd	6.3 bc	34.6 a	7.9 a
P value (0.05)	0.0036	0.0306	0.1210	0.2077
CV	21.1	39.5	27.0	48.4

† Soil for treatments 2-11was infested with *Fusarium solani*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.6. Shoot weight, root weight, and yield for field peas where soil was infested with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/21/2015 in Leonard, ND.

	6/8/2015		6/29/2015		8/27/2015
Treatment†	Shoot Weight (g)	Root Weight (g)	Shoot Weight (g)	Root Weight (g)	Yield (MT/ha)
Non-treated/ non-infested	1.5 a	0.27 abc	15.8 a	0.35 a	4.37 a
Non-treated/ infested	1.1 bc	0.26 abc	13.3 abc	0.38 a	2.94 b
Mefenoxam/ fludioxonil	1.3 b	0.30 a	11.5 bc	0.41 a	3.46 a
Azoxystrobin	1.3 bc	0.21 d	13.1 abc	0.34 a	3.06 ab
Pyraclostrobin	1.1 bc	0.29 ab	9.2 c	0.33 a	2.84 b
Picoxystrobin	1.2 bc	0.20 d	12.3 abc	0.25 a	2.78 b
Prothioconazole	1.2 bc	0.22 cd	15.1 ab	0.46 a	3.46 ab
Boscalid	1.2 bc	0.28 ab	10.4 c	0.39 a	3.06 ab
Fluxapyroxad/ Pyraclostrobin	1.1 c	0.27 abc	12.5 abc	0.39 a	2.99 ab
Fluopyram	1.1 bc	0.25 bcd	15.0 ab	0.38 a	2.46 b
Penthiopyrad	1.2 bc	0.26 abc	11.2 bc	0.41 a	2.58 b
P value (0.05)	0.0019	0.0002	0.0407	0.0697	0.0167
CV	30.0	37.4	64.0	57.8	11.2

† Soil for treatments 2-11 was infested with *Fusarium solani*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.7. Phytotoxicity and plant population for field peas where soil was infested with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/12/2015 in Carrington, ND.

	6/2/2015		6/23/2015		8/5/2015
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)	Yield (MT/ha)
Non-treated/ non-infested	0 a‡	443047 a	0 a	474966 a	1.73 a
Non-treated/ infested	0 a	397082 a	0 a	458368 a	1.51 a
Mefenoxam/ fludioxonil	0 a	464752 a	0 a	519654 a	1.67 a
Azoxystrobin	0 a	408573 a	0 a	483904 a	1.63 a
Pyraclostrobin	0 a	395805 a	0 a	518377 a	1.64 a
Picoxystrobin		429002 a		460922	1.66 a
Prothioconazole	0 a	427725 a	0 a	476243 a	1.62 a
Boscalid		421341 a		478796	1.69 a
Fluxapyroxad/ Pyraclostrobin		412403 a		467305	1.71 a
Fluopyram	0 a	437939 a	0 a	463475 a	1.50 a
Penthiopyrad	0 a	418788 a	0 a	496671 a	1.57 a
P value (0.05)		0.4239		0.4643	0.9436
CV		13.6		13.2	18.0

† Soil for treatments 2-11 was infested with *Fusarium solani*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.8. Root rot severity, plant height, shoot weight, and root weight for field peas where soil was infested with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/12/2015 in Carrington, ND.

	6/2/2015				6/23/2015			
Treatment†	Root Rot Severity (%)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)	Root Rot Severity (%)	Plant Height (cm)	Shoot Weight (g)	Root Weight (g)
Non-treated/ non-infested	30.0 a‡	11.0 a	0.98 a	0.42 a	46.0 a	29.6 a	6.1 a	0.45 a
Non-treated/ infested	23.0 a	10.1 a	0.92 a	0.33 a	54.0 a	30.9 a	6.5 a	0.46 a
Mefenoxam/ fludioxonil	28.8 a	9.6 a	0.93 a	0.42 a	61.3 a	28.4 a	5.5 a	0.44 a
Azoxystrobin	26.0 a	10.1 a	0.95 a	0.44 a	58.0 a	31.8 a	6.7 a	0.48 a
Pyraclostrobin	31.0 a	8.9 a	0.84 a	0.35 a	56.0 a	32.9 a	8.4 a	0.39 a
Picoxystrobin	26.7 a	9.8 a	0.93 a	0.35 a	54.7 a	32.6 a	7.3 a	0.45 a
Prothioconazole	29.8 a	10.2 a	0.93 a	0.43 a	46.7 a	30.8 a	5.9 a	0.38 a
Boscalid	25.8 a	10.3 a	0.92 a	0.39 a	49.8 a	33.5 a	8.2 a	0.46 a
Fluxapyroxad/ Pyraclostrobin	35.3 a	9.7 a	0.85 a	0.37 a	59.3 a	31.2 a	6.7 a	0.43 a
Fluopyram	22.8 a	9.6 a	0.92 a	0.37 a	54.0 a	28.6 a	6.3 a	0.46 a
Penthiopyrad	33.8 a	10.1 a	0.88 a	0.40 a	61.3 a	30.5 a	7.3 a	0.43 a
P value (0.05)	0.2833	0.1067	0.6182	0.1095	0.1939	0.2781	0.0747	0.8777
CV	31.2	22.7	27.9	42.1	20.1	26.9	54.8	54.6

† Soil for treatments 2-11 was infested with *Fusarium solani*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.9. Phytotoxicity and plant population for field peas where soil was infested with *Fusarium avenaceum* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/16/2016 in Oakes, ND.

	6/3/2016		6/16/2016	
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)
Non-treated/ non-infested	0 a‡	421042 a	0 a	574147 a
Non-treated/ infested	0 a	444007 a	0 a	492491 a
Mefenoxam/ fludioxonil	0 a	537147 a	0 a	567767 a
Azoxystrobin	0 a	463146 a	0 a	475904 a
Pyraclostrobin	0 a	432525 a	0 a	452939 a
Prothioconazole	0 a	429973 a	0 a	515457 a
Fluopyram	0 a	515457 a	0 a	528215 a
Penthiopyrad	0 a	426145 a	0 a	472077 a
P value (0.05)		0.2332		0.2889
CV		19.8		19.0

† Soil for treatments 2-8 was infested with *Fusarium avenaceum*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.10. Phytotoxicity and plant population for field peas where soil was infested with *Fusarium avenaceum* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/5/2016 in Carrington, ND.

	5/24/2016		6/1/2016	
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)
Non-treated/ non-infested	0 a‡	376386 a	0 a	465698 a
Non-treated/ infested	0 a	384042 a	0 a	511629 a
Mefenoxam/ fludioxonil	0 a	361076 a	0 a	486112 a
Azoxystrobin	0 a	385317 a	0 a	529491 a
Pyraclostrobin	0 a	370007 a	0 a	486111 a
Prothioconazole	0 a	431248 a	0 a	528215 a
Fluopyram	0 a	367455 a	0 a	498870 a
Penthiopyrad	0 a	384041 a	0 a	496319 a
P value (0.05)		0.7616		0.6484
CV		18.1		12.6

† Soil for treatments 2-8 was infested with *Fusarium avenaceum*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.11. Vigor and yield for field peas where soil was infested with *Fusarium avenaceum* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/5/2016 in Carrington, ND.

	5/24/2016	6/1/2016	8/16/2016
Treatment†	Vigor (%)	Vigor (%)	Yield (MT/ha)
Nontreated / non-infested	100.0 a‡	100.0 a	2.71 a
Nontreated / infested	72.5 a	81.7 a	2.46 a
Mefenoxam / fludioxonil	82.5 a	89.2 a	2.34 a
Azoxystrobin	83.3 a	89.2 a	2.54 a
Pyraclostrobin	83.3 a	88.3 a	2.37 a
Prothioconazole	86.7 a	94.2 a	2.44 a
Fluopyram	83.3 a	86.7 a	2.43 a
Penthiopyrad	84.2 a	84.2 a	2.53 a
P value (0.05)	0.1115	0.0931	0.1965
CV	16.1	11.3	9.4

† Soil for treatments 2-8 was infested with *Fusarium avenaceum*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.12. Phytotoxicity, plant population, and yield for field peas where soil was infested with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/16/2016 in Oakes, ND.

	6/3/2016		6/16/2016		8/15/2016
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)	Yield (MT/ha)
Non-treated/ non-infested	0 a‡	428697 a	0 a	483560 a	2.96 a
Non-treated/ infested	0 a	155658 bc	0 a	185003 bc	0.64 b
Mefenoxam/ fludioxonil	0 a	114830 c	0 a	144175 c	0.43 b
Azoxystrobin	0 a	107174 c	0 a	126313 c	0.73 b
Pyraclostrobin	0 a	93140 c	0 a	121209 c	0.36 b
Prothioconazole	0 a	233486 abc	0 a	246245 bc	1.33 b
Fluopyram	0 a	330454 ab	0 a	344489 ab	1.51 b
Penthiopyrad	0 a	145451 bc	0 a	164589 bc	1.00 b
P value (0.05)		0.0121		0.0029	0.0053
CV		83.9		69.4	98.2

† Soil for treatments 2-8 was infested with *Fusarium solani*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Table B.13. Phytotoxicity, plant population, and root rot severity for field peas where soil was infested with *Fusarium solani* under field conditions. Seeds were treated with a standard seed treatment and/or fungicides were applied in-furrow at planting on 5/5/2016 in Carrington, ND.

	5/24/2016		6/1/2016		6/2/2016
Treatment†	Phytotoxicity (%)	Emergence (plants/ha)	Phytotoxicity (%)	Emergence (plants/ha)	Root rot severity (%)
Non-treated/ non-infested	0 a‡	371283 a	0 a	500146 a	19.8 b
Non-treated/ infested	0 a	229659 a	0 a	348316 a	48.8 a
Mefenoxam/ fludioxonil	0 a	278143 a	0 a	427422 a	50.3 a
Azoxystrobin	0 a	231190 a	0 a	435077 a	47.0 a
Pyraclostrobin	0 a	256453 a	0 a	441456 a	46.4 a
Prothioconazole	0 a	348317 a	0 a	478457 a	41.3 a
Fluopyram	0 a	278143 a	0 a	405732 a	46.7 a
Penthiopyrad	0 a	408283 a	0 a	557561 a	41.6 a
P value (0.05)		0.0735		0.0584	<.0001
CV		37.1		23.3	18.1

† Soil for treatments 2-8 was infested with *Fusarium solani*. Mefenoxam/fludioxonil was applied as a seed treatment.

‡ Within columns, values followed by the same letter are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

APPENDIX C: SUMMARY OF STATISTICAL ANALYSES FOR DRY BEAN

Table C.1. Analysis of variance for 3x2x2 factorial randomized complete block design (RCBD) of root rot severity for the dry bean *Rhizoctonia solani* pathogenicity and aggressiveness trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	2	404.25800	1.72	0.1993
Isolate	2	12825.39234	54.48	<.0001
Inoculum placement	1	656.04284	2.79	0.1070
Isolate x Inoculum placement	2	1118.66069	4.75	0.0174
Timing	1	196.04161	0.83	0.3699
Isolate x Timing	2	308.53765	1.31	0.2921
Inoculum placement x Timing	1	267.64960	1.14	0.2961
Isolate x Inoculum placement x Timing	2	88.63097	0.38	0.6899

Table C.2. Analysis of variance of randomized complete block design (RCBD) of root rot severity for the dry bean *Fusarium solani* pathogenicity and aggressiveness trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	3	92.327661	0.98	0.4288
Treatment	5	1086.767887	11.52	0.0001

Table C.3. Analysis of variance of randomized complete block design (RCBD) of root rot severity for the dry bean *Rhizoctonia solani* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	38.293123	0.31	0.9064
Treatment	17	584.053697	4.73	<.0001

Table C.4. Analysis of variance of randomized complete block design (RCBD) of plant height for the dry bean *Rhizoctonia solani* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	27.8809614	1.10	0.3578
Treatment	17	50.1653784	1.98	0.0102

Table C.5. Analysis of variance of randomized complete block design (RCBD) of root weight for the dry bean *Rhizoctonia solani* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	0.18330186	1.84	0.1022
Treatment	17	0.24264759	2.44	0.0010

Table C.6. Analysis of variance of 2x9 factorial randomized complete block design (RCBD) for root weights at the first sampling date of the Fargo 2014 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	3	0.00034076	0.69	0.5564
Seed treatment	1	0.00046233	0.94	0.3326
In-furrow	9	0.00375645	7.65	<.0001
Seed treatment x In-furrow	9	0.00151189	3.08	0.0014

Table C.7. Analysis of variance of randomized complete block design (RCBD) for the first sampling of root rot severity of the Fargo 2015 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	64.845554	1.55	0.1903
Treatment	10	122.855891	2.94	0.0055

Table C.8. Analysis of variance of randomized complete block design (RCBD) for the second sampling of root rot severity of the Fargo 2015 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	91.5079479	5.01	0.0009
Treatment	10	34.9696148	1.91	0.0652

Table C.9. Analysis of variance of randomized complete block design (RCBD) for the first observation of vigor at the Fargo 2015 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	76.0606061	3.89	0.0047
Treatment	10	60.3787879	3.09	0.0039

Table C.10. Analysis of variance of randomized complete block design (RCBD) for the first sampling of root rot severity at the Carrington 2015 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	213.282534	1.10	0.3744
Treatment	10	234.996941	1.21	0.3092

Table C.11. Analysis of variance of randomized complete block design (RCBD) for the second sampling of root rot severity at the Carrington 2015 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	42.1474961	1.34	0.2643
Treatment	10	85.4043961	2.71	0.0098

Table C.12. Analysis of variance of randomized complete block design (RCBD) for vigor at the second observation date of the Carrington 2015 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	184.242424	1.97	0.1001
Treatment	10	345.378788	3.68	0.0010

Table C.13. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the first sampling date of the Fargo 2015 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	24.0136109	1.76	0.1393
Treatment	10	88.5960842	6.48	<.0001

Table C.14. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the second sampling date of the Fargo 2015 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	29.1605057	1.40	0.2391
Treatment	10	74.1003729	3.57	0.0013

Table C.15. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the first sampling date of the Carrington 2015 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	152.932057	2.06	0.0861
Treatment	10	168.623379	2.27	0.0279

Table C.16. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the second sampling date of the Carrington 2015 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	81.864155	3.14	0.0153
Treatment	10	129.567514	4.97	<.0001

Table C.17. Analysis of variance of randomized complete block design (RCBD) for vigor at the first observation date of the Carrington 2015 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	99.696970	4.43	0.0021
Treatment	10	173.712121	7.71	<.0001

Table C.18. Analysis of variance of randomized complete block design (RCBD) for vigor at the second observation date of the Carrington 2015 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	22.1969697	1.14	0.3535
Treatment	10	42.3484848	2.17	0.0357

Table C.19. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the Fargo 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	11.2052491	1.10	0.3783
Treatment	7	26.2961350	2.58	0.0301

Table C.20. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the Carrington 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	177.837258	3.07	0.0215
Treatment	7	1346.446554	23.27	<.0001

Table C.21. Analysis of variance of randomized complete block design (RCBD) for plant population at the first observation date of the Carrington 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	404058710	3.00	0.0240
Treatment	7	4936347109	36.59	<.0001

Table C.22. Analysis of variance of randomized complete block design (RCBD) for plant population at the second observation date of the Carrington 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	319380876	2.30	0.0668
Treatment	7	5180709544	37.26	<.0001

Table C.23. Analysis of variance of randomized complete block design (RCBD) for vigor at the first observation date of the Carrington 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	653.65524	3.39	0.0136
Treatment	7	6180.72993	32.09	<.0001

Table C.24. Analysis of variance of randomized complete block design (RCBD) for vigor at the second observation date of the Carrington 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	367.62095	3.08	0.0212
Treatment	7	6735.06259	56.49	<.0001

Table C.25. Analysis of variance of randomized complete block design (RCBD) for yield of the Carrington 2016 dry bean *Rhizoctonia solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	160816.37	1.26	0.3056
Treatment	7	6198791.52	48.39	<.0001

Table C.26. Analysis of variance of randomized complete block design (RCBD) for vigor at the second observation date of the Fargo 2016 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	123.333333	1.88	0.1223
Treatment	7	169.940476	2.60	0.0288

Table C.27. Analysis of variance of randomized complete block design (RCBD) for vigor at the first observation date of the Carrington 2016 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	306.13095	2.64	0.0404
Treatment	7	2655.27211	22.89	<.0001

Table C.28. Analysis of variance of randomized complete block design (RCBD) for vigor at the second observation date of the Carrington 2016 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	93.27381	0.48	0.7900
Treatment	7	1771.97279	9.08	<.0001

Table C.29. Analysis of variance of randomized complete block design (RCBD) for root rot severity at the Carrington 2016 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	36.995733	2.62	0.0414
Treatment	7	177.847435	12.61	<.0001

Table C.30. Analysis of variance of randomized complete block design (RCBD) for yield at the Carrington 2016 dry bean *Fusarium solani* trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	132568.450	1.08	0.3902
Treatment	7	1303570.132	10.59	<.0001

APPENDIX D: SUMMARY OF STATISTICAL ANALYSES FOR FIELD PEA

Table D.1. Analysis of variance for 3x2 factorial randomized complete block design (RCBD) for the field pea *Fusarium avenaceum* pathogenicity and aggressiveness trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	3	263.85714	1.47	0.2555
Isolate	3	4320.57143	24.11	<.0001
Inoculum placement	1	1014.00000	5.66	0.0286
Isolate x Inoculum placement	2	666.00000	3.72	0.0445

Table D.2. Analysis of variance for 5x2 factorial randomized complete block design (RCBD) for the field pea *Fusarium solani* pathogenicity and aggressiveness trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	2	183.0476190	0.91	0.4279
Isolate	3	286.0555556	1.43	0.2784
Inoculum placement	1	128.0000000	0.64	0.4401
Isolate x Inoculum placement	2	110.1666667	0.55	0.5914

Table D.3. Analysis of variance of randomized complete block design (RCBD) of emergence for the field pea *Fusarium avenaceum* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	510.00000	1.03	0.3990
Treatment	17	2836.27451	5.75	<.0001

Table D.4. Analysis of variance of randomized complete block design (RCBD) of root rot severity for the field pea *Fusarium avenaceum* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	780.03497	2.13	0.0634
Treatment	17	3465.16654	9.47	<.0001

Table D.5. Analysis of variance of randomized complete block design (RCBD) of plant height for the field pea *Fusarium avenaceum* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	39.004863	1.77	0.1167
Treatment	17	187.308080	8.50	<.0001

Table D.6. Analysis of variance of randomized complete block design (RCBD) of root length for the field pea *Fusarium avenaceum* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	122.869836	2.48	0.0308
Treatment	17	158.001420	3.19	<.0001

Table D.7. Analysis of variance of randomized complete block design (RCBD) of shoot weight for the field pea *Fusarium avenaceum* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	0.11645480	1.73	0.1262
Treatment	17	0.48535636	7.20	<.0001

Table D.8. Analysis of variance of randomized complete block design (RCBD) of root weight for the field pea *Fusarium avenaceum* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	0.10214400	4.00	0.0014
Treatment	17	0.07241452	2.84	0.0001

Table D.9. Analysis of variance of randomized complete block design (RCBD) of root rot severity for the field pea *Fusarium solani* in-furrow trial under greenhouse conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	58.60897	0.29	0.9155
Treatment	17	1620.94135	8.15	<.0001

Table D.10. Analysis of variance of randomized complete block design (RCBD) of root rot severity at the second sampling date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	108.52925	0.31	0.9050
Treatment	10	1123.27427	3.20	0.0030

Table D.11. Analysis of variance of randomized complete block design (RCBD) of plant population at the first observation date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	4727951468	7.99	<.0001
Treatment	10	3558046541	6.02	<.0001

Table D.12. Analysis of variance of randomized complete block design (RCBD) of plant population at the second observation date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	7626229240	5.88	0.0002
Treatment	10	3939313343	3.04	0.0044

Table D.13. Analysis of variance of randomized complete block design (RCBD) of vigor at the first observation date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	224.545455	4.19	0.0029
Treatment	10	800.000000	14.94	<.0001

Table D.14. Analysis of variance of randomized complete block design (RCBD) of vigor at the second observation date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	37.878788	1.02	0.4172
Treatment	10	444.393939	11.94	<.0001

Table D.15. Analysis of variance of randomized complete block design (RCBD) of plant height at the second sampling date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	903.542840	10.06	<.0001
Treatment	10	322.643632	3.59	0.0002

Table D.16. Analysis of variance of randomized complete block design (RCBD) of root length at the first sampling date of the 2015 Leonard field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	17.4129351	2.74	0.0195
Treatment	10	14.7518442	2.32	0.0122

Table D.17. Analysis of variance of randomized complete block design (RCBD) of root rot severity at the first sampling date of the 2015 Leonard field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	201.360297	1.43	0.2304
Treatment	10	325.022055	2.31	0.0257

Table D.18. Analysis of variance of randomized complete block design (RCBD) of root rot severity at the second sampling date of the 2015 Leonard field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	175.102384	0.66	0.6558
Treatment	10	538.928327	2.03	0.0496

Table D.19. Analysis of variance of randomized complete block design (RCBD) of plant population at the first observation date of the 2015 Leonard field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	2148273864	5.67	0.0003
Treatment	10	6796122682	17.93	<.0001

Table D.20. Analysis of variance of randomized complete block design (RCBD) of plant population at the second observation date of the 2015 Leonard field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	6566065237	14.48	<.0001
Treatment	10	6084031936	13.42	<.0001

Table D.21. Analysis of variance of randomized complete block design (RCBD) of vigor at the first observation date of the 2015 Leonard field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	356.060606	8.71	<.0001
Treatment	10	518.712121	12.68	<.0001

Table D.22. Analysis of variance of randomized complete block design (RCBD) of vigor at the second observation date of the 2015 Leonard field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	251.590909	3.97	0.0042
Treatment	10	469.242424	7.40	<.0001

Table D.23. Analysis of variance of randomized complete block design (RCBD) of vigor at the first observation date of the 2016 Oakes field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	198.437500	1.80	0.1380
Treatment	7	346.354167	3.15	0.0110

Table D.24. Analysis of variance of randomized complete block design (RCBD) of vigor at the second observation date of the 2016 Oakes field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	88.333333	0.83	0.5347
Treatment	7	278.273810	2.63	0.0273

Table D.25. Analysis of variance of randomized complete block design (RCBD) of root rot severity at the 2016 Oakes field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	56.816362	0.65	0.6620
Treatment	7	731.429538	8.39	<.0001

Table D.26. Analysis of variance of randomized complete block design (RCBD) of yield at the 2016 Oakes field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	88.927848	1.28	0.2962
Treatment	7	309.747004	4.44	0.0013

Table D.27. Analysis of variance of randomized complete block design (RCBD) of root rot severity at the 2016 Carrington field pea *Fusarium avenaceum* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	167.947662	2.59	0.0427
Treatment	7	526.752871	8.13	<.0001

Table D.28. Analysis of variance of randomized complete block design (RCBD) of root rot severity at the 2016 Oakes field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	95.301077	2.66	0.0385
Treatment	7	1038.748716	29.02	<.0001

Table D.29. Analysis of variance of randomized complete block design (RCBD) of vigor at the first observation date of the 2016 Oakes field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	352.08333	0.51	0.7666
Treatment	7	2725.89286	3.95	0.0028

Table D.30. Analysis of variance of randomized complete block design (RCBD) of vigor at the second observation date of the 2016 Oakes field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	425.00000	0.50	0.7733
Treatment	7	3038.98810	3.58	0.0052

Table D.31. Analysis of variance of randomized complete block design (RCBD) of vigor at the first observation date of the 2016 Carrington field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	1328.33333	2.10	0.0892
Treatment	7	2188.98810	3.45	0.0065

Table D.32. Analysis of variance of randomized complete block design (RCBD) of vigor at the second observation date of the 2016 Carrington field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	465.520833	2.02	0.1000
Treatment	7	711.235119	3.09	0.0122

Table D.33. Analysis of variance of randomized complete block design (RCBD) of yield at the 2016 Carrington field pea *Fusarium solani* in-furrow trial under field conditions.

Source of variation	Degrees of freedom	Mean squares	F value	P value
Rep	5	112.967870	2.03	0.0987
Treatment	7	144.159193	2.59	0.0292

APPENDIX E: EFFICACY OF IN-FURROW FUNGICIDES FOR MANAGEMENT OF DRY BEAN ROOT ROT CAUSED BY *RHIZOCTONIA SOLANI* IN LOW AND HIGH ORGANIC MATTER SOIL UNDER GREENHOUSE CONDITIONS

Materials and Methods

Greenhouse Trials

Field soil was collected from the top, middle, and bottom of a catena at the Ekre Grassland Preserve near Kindred, North Dakota. Soil with 0.6 % and 5.1% organic matter was collected from the top and bottom of the catena, respectively. The soil was analyzed by the North Dakota State University soil testing laboratory (Table E.1).

Table E.1. Average nutrient content (nitrate, phosphorus, potassium), pH, electrical conductivity (EC), percent organic matter (OM), and texture of soil collected from the Ekre Grassland Preserve for in-furrow trial in the greenhouse.

Collection Site	NO_3-N† (kg/ha)	P‡ (kg/ha)	K§ (kg/ha)	pH¶	EC# mmhos/cm	OM†† %	Texture‡‡
Lowland High OM	20.3	15.7	179.3	7.00	0.28	5.10	Sand
Highland Low OM	4.5	17.9	201.8	7.40	0.36	0.60	Sand

† Nitrate kg/ha was determined by the water extraction method
‡ Phosphorus kg/ha was determined by the Olson procedure
§ Potassium kg/ha was determined by the 1N ammonium acetate method
¶ pH was tested in water
# Electrical conductivity was determined with a 1:1 soil to water ratio
†† Percent organic matter was determined by loss on ignition
‡‡ Texture was determined by the hydrometer method

Pots were filled with equal masses of dried, homogenized, sieved field soil. The soil was watered to 80% field capacity, determined by saturating three test pots and recording 80% of that pot's weight once all gravitational water had leached away. A 4 cm deep furrow was made down

the center of the pot, and the soil was inoculated by placing a single wheat kernel infested with *R. solani* 1.5 cm below the furrow. Five 'Montcalm' bean seeds were placed into the furrow made in each pot.

The furrow was left uncovered and each fungicide was applied directly onto the seeds and furrow. The pots were sprayed as described above with either two or three rates of six fungicides (Table E.2). The furrows were covered with soil and each pot was weighed and watered daily to maintain 80% field capacity moisture. After 14 days, plant emergence was recorded, plants were removed, roots were washed, and plants were evaluated for plant height, shoot weight, and root weight. Root rot severity was measured using a 1 to 9 linear scale (Figure E.1). The experiment was conducted twice in an RCBD with 18 treatments and six replicates, totaling 108 experimental units.

The K_{oc} value was found for each chemical through the Environmental Protection Agency (EPA). The tendency of an organic compound, such as a fungicide, to remain within a soil is termed the soil distribution coefficient (K_d). This coefficient is the ratio of the amount of chemical adsorbed by the soil to the amount of chemical remaining in solution (Brady and Weil, 2008). The K_d for chemicals tends to vary widely depending upon the organic matter level of the soil in which it is distributed. Therefore, soil scientists use a similar distribution ratio that focuses on adsorption by organic matter; it is termed the organic carbon distribution coefficient (K_{oc}) and is the ratio of the amount of chemical adsorbed in organic carbon to the amount of chemical remaining in solution. Chemicals with higher K_{oc} values are more tightly adsorbed by the soil and are therefore less available for movement or uptake by plants and microorganisms (Brady and Weil, 2008). Therefore, fungicide efficacy, either in the form of seed treatment or in-furrow application, depend upon the interaction with differing soil types.

Table E.2. In-furrow fungicide active ingredients, trade names, companies, fungicide resistance action committee (FRAC) groups, and formulated product rates for the greenhouse trials.

Fungicide active ingredient	K_{oc}	Trade name	Company	FRAC	Rate 1 (L/ha)	Rate 2 (L/ha)	Rate 3 (L/ha)
Azoxystrobin	1590	Quadris	Syngenta	11	.45	.66	.88
Pyraclostrobin	9300	Headline	BASF	11	.45	.66	.88
Picoxystrobin	1089	Aproach	DuPont	11	.45	.66	.88
Prothioconazole	1760	Proline	Bayer	3	.31	.42	
Fluopyram	690	Velum Prime	Bayer	7	.40	.50	
Penthiopyrad	720	Vertisan	DuPont	7	.80	1.02	1.46

(EPA)

Figure E.1. Dry bean root rot scale. 1 = no visible symptoms, 3 = lesion(s) covering approximately 10% of hypocotyl and root tissue, 5 = lesion(s) covering approximately 25% of the hypocotyl and root tissue, 7 = lesion(s) covering approximately 50% of the hypocotyl and root tissue, 9 = 75% or more of the hypocotyl and root tissue are covered in lesions, or the taproot is severed (Van Schoonhoven and Pastor-Corrales, 1987).

Statistical Analysis

Categorical root rot severity data was converted to a percent root disease index (%RDI) using the formula:

$$\%\text{DI} = \left[\frac{(a * 1) + (b * 2) + (c * 3) + (d * 4) + (e * 5) + (f * 6) + (g * 7) + (h * 8) + (i * 9)}{(a + b + c + d + e + f + g + h + i) * j}\right] * 100$$

where *a, b, c, d, e, f, g, h,* and *i* represent the number of plants with the disease severity ratings of 1, 2, 3, 4, 5, 6, 7, 8, and 9, respectively, and *j* represents the highest root rot severity rating (Li et al., 2014).

One-way analysis of variance (ANOVA) was conducted for both field and greenhouse studies using the PROC GLM procedure in SAS 9.4 (SAS Institute, Cary, NC). Fisher's protected LSD was used to determine differences among treatment means ($\alpha = 0.05$).

Results

Greenhouse Trials

In the low organic matter trial, the inoculated control had a root rot severity of 50.6% at the first performance and 34.9% at the second performance. These were significantly higher than the non-inoculated controls with severities of 16.4% and 20.8%. In the high organic matter trial, the inoculated control had a root rot severity of 60.4% at the first performance and 48.4% at the second performance. These were significantly higher than the non-inoculated controls with severities of 16.7% and 16.7%.

In the first performance of the low organic matter trial, all treatments at all rates significantly reduced root rot severity compared to the inoculated control (Figure E.2). In the second performance, all treatments except prothioconazole at 5.7 fl oz/a and both rates of fluopyram significantly reduced root rot severity compared to the inoculated control.

In the high organic matter trial, all treatments except pyraclostrobin at 6 fl oz/a, prothioconazole at 5.7 fl oz/a, and fluopyram at 5.47 fl oz/a at the first performance, and all treatments at all rates at the second performance significantly reduced root rot severity compared to the inoculated control (Figure E.3).

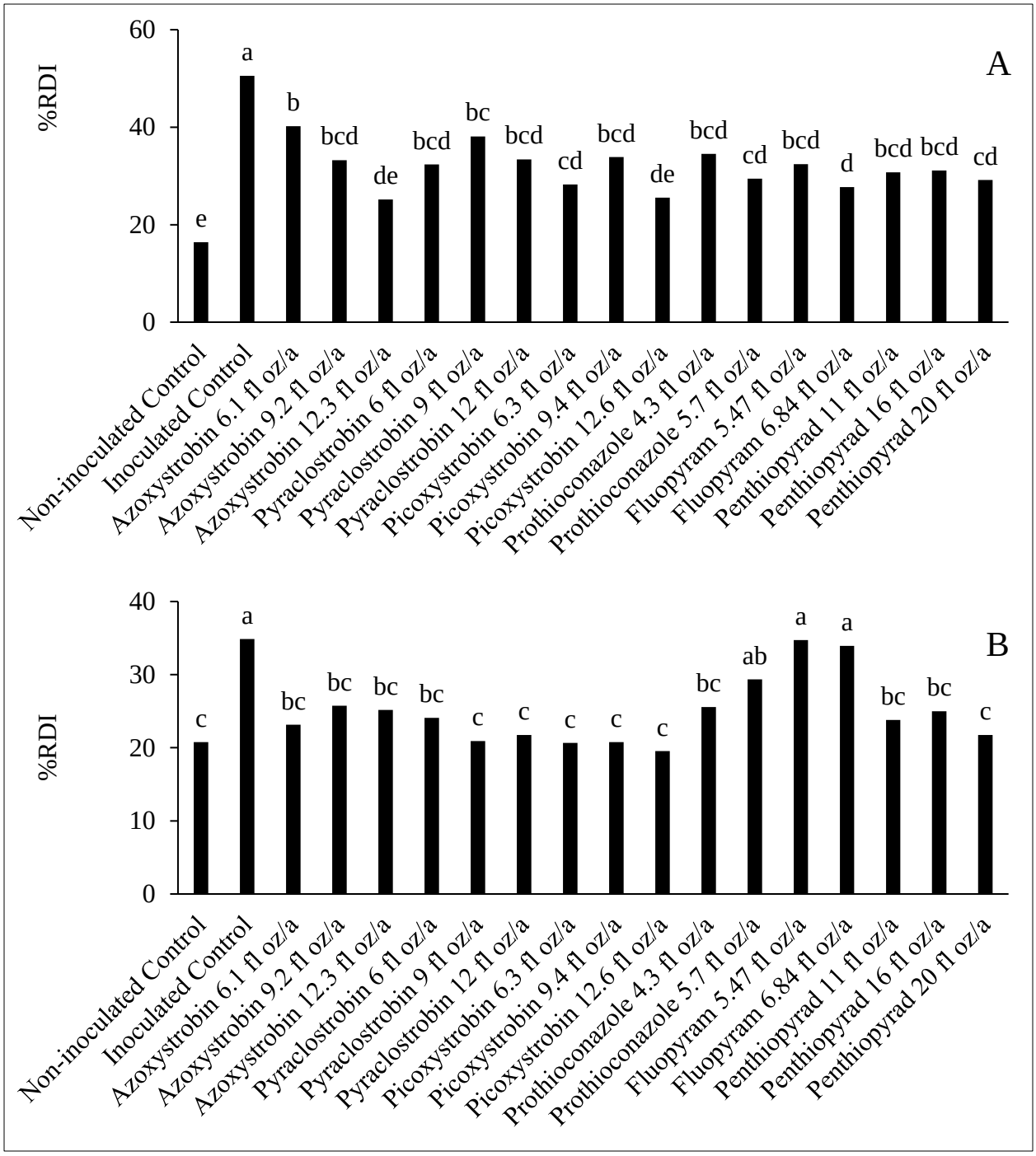

Figure E.2. Rhizoctonia root rot severity (percent root disease index; %RDI) of the first (A) and second (B) performances of the in-furrow trial in low organic matter soil under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

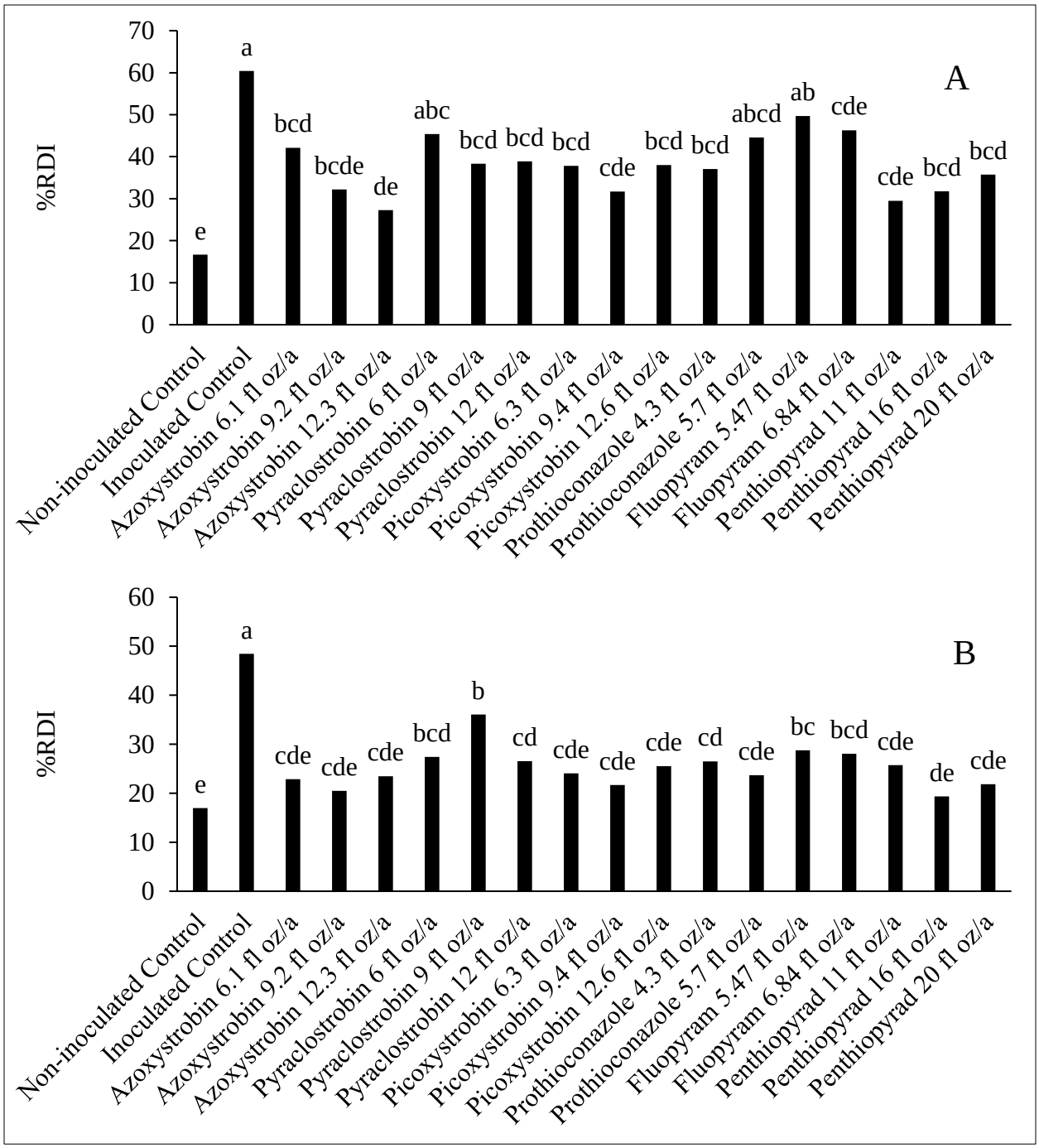

Figure E.3. Rhizoctonia root rot severity (percent root disease index; %RDI) of the first (A) and second (B) performances of the in-furrow trial in high organic matter soil under greenhouse conditions. Bars with the same letter above are not significantly different based on Fisher's protected least significant difference ($\alpha = 0.05$).

Literature Cited

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