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Abstract

Phytophthora root rot caused by *Phytophthora cinnamomi* Rands is one of the major diseases of flowering dogwoods (*Cornus florida* L.). The severity of root rot disease increases when the plants are exposed to flooding conditions. A study was conducted to determine the efficacy and timing of application of different fungicides, biofungicides, host plant defense inducers, and fertilizer to manage Phytophthora root rot in month-old seedlings in simulated flooding events for 1-, 3-, and 7- days. Preventative treatments were drench applied 3 weeks and 1 week before flooding whereas curative treatments were applied 24 hrs. after flooding. Dogwood seedlings were inoculated with *P. cinnamomi* 3 days before the flooding. Plant height and width were recorded at the beginning and end of the study. At the end of the study, plant total weight and root weight were recorded and disease severity in the root was assessed using a scale of 0-100%. Root samples were plated using PARPH-V8 medium to determine the percentage recovery of the pathogen. Empress Intrinsic, Pageant Intrinsic, Segovis, and Subdue MAXX, as preventative and curative applications, were able to suppress the disease severity compared to the inoculated control in all flooding durations. All treatments, with the exception of Stargus as preventative application 3 weeks before flooding and Orkestra Intrinsic as curative application, were able to suppress the disease severity compared to the inoculated control for 1-day flooding event. Aliette and ON-Gard were effective in the first trial when applied preventatively in both 1 week and 3 weeks before flooding but not in the second trial. Signature Xtra was effective as preventative application but not as a curative application. Interface was effective as curative application but not as preventative application. The findings of this study will help nursery growers to understand the performance of fungicides, biofungicides, host-plant defense inducers, and fertilizer in different time intervals and repeated applications to manage Phytophthora root rot in flooding conditions.

Keywords: biological control, chemical control, *Phytophthora cinnamomi*, soilborne pathogen, woody ornamental

Introduction

Phytophthora root rot caused by *Phytophthora cinnamomi* Rands (family Peronosporaceae) is one of the most important diseases of the ornamental crops (Brown et al. 2019a,b; Duan et al. 2008; Ferguson and Jeffers 1999; Hu et al. 2010; Neupane et al. 2021). *Phytophthora* causes root rot diseases in more than 5,000 species of woody plants worldwide (Balci et al. 2007; Erwin and Ribeiro 1996; Hardham and Blackman 2018; Shakya et al. 2021). The infestation of *P. cinnamomi* has caused the extinction of a few native species of forest plants in Australia and has posed a threat in the United States (Hardham 2005; Hu et al. 2010). Among the woody ornamental crops, the major host for the notorious *P. cinnamomi* oomycete includes *Acer* spp., *Cornus* spp., *Juglans* spp., *Prunus* spp., *Rhododendron* spp. and *Quercus* spp. (Dai et al. 2020; Erwin and Ribeiro 1996; Ribeiro and Linderman 1991; Zentmyer 1980). The economic and scientific importance of this pathogen can be estimated as it has been ranked in the top 10 oomycete plant pathogens of the world (Kamoun et al. 2015) and addressed as a "key threatening process to Australia's biodiversity" in the Environmental Protection and Biodiversity Conservation Act 1999 (Shakya et al. 2021). *P. cinnamomi* causes rotting of the fine and fibrous roots limiting the supply of food and water to the shoot region. As a result, the plant suffers wilting, dieback, and stem cankers (Hardham 2005; Hardham and Blackman 2018). It also causes gradual tree decline, large basal cankers with bleeding spots, root rot, and death of the forest trees (Robin et al. 2012).

Flooding has a direct impact on the severity of Phytophthora root rot. The susceptibility of the plant to the pathogen increases when exposed to flooding (de Silva et al. 1999; Jacobs and Johnson 1996). Trees infected with the root rot pathogen decline faster when they are exposed to flooding conditions (Brown et al. 2019b; Ploetz and Schaffer 1989; Ploetz and Schaffer 1987; Reeksting et al. 2016). In some cases, flooding becomes the only reason for destruction of trees which otherwise would have survived with just a *P. cinnamomi* infection (Weste and Marks 1987). The destructive potentiality of the *Phytophthora* pathogens increases with flooding because flooding creates favorable conditions for infection such as limited oxygen and increased zoospores movement (Kawase 1981; Kozlowski 1997; Wilcox and Mircetich 1985). In a study conducted by Brown et al. (2019b), there were 1.7%, 15.7%, and 34.8% increases in the mortality of flowering dogwood seedlings for 1 day, 3 days, and 7 days of simulated flooding conditions, respectively.

Management of Phytophthora root rot is challenging not only because of the wide host range of the pathogen but for various other reasons: a) higher production of chlamydospores (Zentmyer 1980), b) unexpressed pathogens in contaminated plants and growth media (Benson and Grand 2000; Hardham and Blackman 2018; Kong et al. 2003), and c) high dispersal of pathogen either by zoospores or running water (Duniway 1976; Erwin and Ribeiro 1996).

Different cultural, biological, and chemical practices have been applied for the management of Phytophthora root rot (Baysal-Gurel et al. 2016; Brown et al. 2019b; Gould 2012; Neupane et al. 2021; Parajuli et al. 2021; Williams-Woodward and DeMott 2013). However, most of these practices have been inconsistent. The application of mulches, composts, and animal manure was found to restrict the growth of *P. cinnamomi* (Aryantha and Guest 2006; Evidente et al. 2009; Richter et al. 2011). Hu et al. (2010) claimed that chemical control is the most effective strategy to manage *P. cinnamomi* among other practices being used. Application of fungicides like mefenoxam and fosetyl-Al have been effective in preventing the development and spread of the pathogen Neupane et al. 2021; Ribeiro and Linderman 1991; Weiland et al. 2021). In the studies conducted by Benson and Blazich (1989) and Hu et al. (2010), systemic mefenoxam alone successfully managed Phytophthora root rot in *Azalea*, *Rhododendron*, *Ilex*, *Myrica*, *Berberis*, *Kalmia*, *Heliamphora*, *Rhododendron,* and *Viburnum*, respectively. Fosetyl-Al alone, acibenzolar-S-methyl, and pyaclostrobin with boscalid were also able to manage *P. cinnamomi* in avocado, redbuds, and tulip poplar trees (Addesso et al. 2018; Benson 1985; Bezuidenhout et al. 1987).

Biofungicides and fertilizers were also found effective in the management of Phytophthora root rot. *Trichoderma*, *Pseudomonas*, *Bacillus*, *Streptomyces,* and *Enterobacter* resulted in increased plant resistance to disease and enhanced growth and productivity (Belimov et al. 2001; Harman 2006; Harman et al. 2004; Pieterse et al. 2000; Pieterse et al. 2001; Wang et al. 2000). Rootshield Plus (*Trichoderma harzianum* strain T-22, *T. virens* strain G-41) and Stargus (*Bacillus amyloliquefaciens* F727) reduced the disease severity of *P. cinnamomi* in flowering dogwoods for 1-day flooding when used preventatively (Brown et al. 2019b). Biogen (*Azotobacter vinaudit* + *A. chroococum*), Nitrobein (*A. chroococum* + *Azospirillum lipoferum*), and Bioarc (*B. megaterium*) were found to be effective against Phytophthora root rot of apple and citrus (Sharkawy et al. 2014). Host plant defense inducers, strobilurin, paclobutrazol, and triazole fungicides also helped in effective management of *P. cinnamomi* by increasing the immune system of the plants against flooding, drought, extreme temperatures, and pollutants (Han et al. 2012; Lin et al. 2006; Neupane et al. 2021).

Different fungicides, biofungicides, and host-plant defense inducers have been used for the management of Phytophthora root rot but most of them have been inconsistent when used in flooding conditions. Many research studies have already demonstrated that flooding exacerbates the root rot infection caused by *Phytophthora*. In this study, selected products were used as two different preventative applications (1 week and 3 weeks before flooding) and at least two or more curative applications on flowering dogwood seedlings in simulated flooding conditions of 1-, 3- and 7- days to assess their effectiveness in successful management of Phytophthora root rot. The major objective of this study is to evaluate products to provide potential management strategies to protect woody ornamental crops against *P. cinnamomi* exposed to the flooding conditions. This study assesses the performance of different fungicides, biofungicides, host-plant defense inducers, and fertilizer with different application intervals or repeated applications to combat Phytophthora root rot in flooding conditions.

Materials and Methods

Study location and growing conditions: This greenhouse study was conducted at Otis L. Floyd Nursery Research Center, Tennessee State University, McMinnville, Tennessee. One-year old seeds of flowering dogwoods ‘Cherokee Princess’ were stratified with the potting substrate (Morton’s Grow Mix #2: Canadian sphagnum peat [60%], vermiculite [20%], and perlite [20%], average substrate bulk density 144 kg/m^3) (Morton’s Horticultural Products, McMinnville, TN, USA) in a clear zip lock bag starting from August of 2019 (trial 1) and September of 2020 (trial 2) for four and three months, respectively (Reed 2005). As the seeds broke their dormancy and radicles emerged out, they were transferred to the No. 72 tray (Morton’s Horticultural Products) on 6 January 2020 (trial 1) and 10 January 2021 (trial 2) using the same potting substrate used for stratification. Overhead irrigation was provided daily for 1 min twice a day. The seedlings were transplanted to 10.2 cm pots containing potting substrate (Morton’s Nursery Mix: processed pine bark [55%-65%], Canadian sphagnum peat and sand) (Morton’s Horticultural

Products) on 11 February 2020 (trial 1) and 21 February 2021 (trial 2). Seedlings were irrigated daily for 2 min throughout the experimental period.

Treatments: A total of thirteen treatments (7 fungicides, 3 host plant defense inducers, 2 biofungicides, and 1 fertilizer) were used with two controls (inoculated and non-inoculated) as a preventative application to assess their effectiveness against *P. cinnamomi* on flowering dogwood seedlings in simulated flooding conditions. For the curative application, only nine treatments (7 fungicides and 2 host plant defense inducers) were used with two controls similar to the preventative application. The list of the treatments used in the study is provided in Table 1. All treatments were drench applied in both preventative and curative applications. The preventative application of the treatments was categorized into two different timings: 3 weeks before the flooding and 1 week before the flooding. Preventative application of treatments 3 weeks before flooding was carried out on 2 April 2020 (trial 1) and 12 April 2021 (trial 2). Preventative application 1 week before flooding was carried out on 16 April 2020 (trial 1) and 26 April 2021 (trial 2). Curative treatments were applied 24 hrs. after flooding for all 1-, 3-, and 7-days. The first application of curative treatments for 1-day flooding was 25 April 2020 (trial 1) and 5 May 2021 (trial 2), 3-days flooding was 27 April 2020 (trial 1) and 7 May 2021 (trial 2), and 7 days flooding was 1 May 2020 (trial 1) and 11 May 2021 (trial 2). All curative applications were made at least twice or more following standard protocol from the manufacturing company, and their application interval is given in Table 1. TRIACT® 70 (clarified hydrophobic extract of neem oil (70%), OHP, Inc., Mainland, PA, USA) was sprayed over the seedlings in trial 2 on 26 March and 2, 9, and 16 April 2021 to suppress the infection of powdery mildew. Powdery mildew symptoms were not observed in the seedlings during trial 1.

Pathogen inoculation and flooding: Inoculum of the pathogen was prepared exactly two weeks before the inoculation date using the isolate FBG201510 of *P. cinnamomi* (GenBank accession no. MK099813) following standard protocol (Brown et al. 2019b; Neupane et al. 2021). For the first trial, flowering dogwood seedlings were inoculated on 20 April 2020, and for the second trial on 30 April 2021. After 3 days of pathogen inoculation, flooding was carried out. Flooding was simulated by placing the pots containing seedlings in a zip-lock bag filled with water. Flooding was done on the same day, 23 April 2020 (trial 1) and 3 May 2021 (trial 2) for all seedlings from preventative and curative treatments. All the flowering dogwood seedlings were inoculated with *P. cinnamomi* except for the non-inoculated treatments.

Data recording: Data were recorded on plant growth, severity of Phytophthora root rot, and percentage recovery of the pathogen from the root samples. Plant growth data including plant height and plant width was recorded at the beginning and end of the study. Total fresh plant weight and total fresh root weight were recorded at the end of the study. Disease severity was assessed after the completion of study by removing the soil and washing the roots. Disease severity was ranked by visual observation using a scale of 0-100% based on the percentage of root with symptoms where 0% = healthy and 100% = completely damaged.

For the percentage recovery of the pathogen, ten randomly selected root cuttings of approx. 15 mm were plated on PARPH-V8 medium. After 7 days post plating, the plated roots were assessed to determine the recovery of the pathogen exhibiting growth patterns similar to *P. cinnamomi*. PARPH-V8 media was prepared following the standard protocol (Ferguson and Jeffers 1999).

Trichoderma colonies were assessed for the treatment Rootshield Plus $^+$ and non-inoculated control using *Trichoderma* selective medium. *Trichoderma* selective medium was prepared by mixing 0 0.1 g of $MgSO_4^-.7H_2O$ (Sigma-Aldrich), 0.45 g of KH_2PO_4 (Sigma-Aldrich), 0.5 g of NH_4NO_3 (Alfa Aesar, Tewksbury, MA, USA), 0.075 g of KCl (Sigma-Aldrich), 1.5 g of dextrose (VWR, Radnor, PA, USA), 0.01 g of $FeSO_4^-.7H_2O$ (VWR), 0.01 g of $MnSO_4^-.H_2O$ (Fisher Scientific, Pittsburgh, PA, USA), 0.01 g of $ZnSO_4^-.7H_2O$ (Fisher Scientific), 0.015 g of rose bengal (Fisher Scientific), 10.0 g of agar (Sigma-Aldrich) with 500 ml of deionized water and autoclaved for 15 minutes (Chung and Hoitink 1990). Additionally, 0.05 g of PCNB (99% [GC]), 5 µl of Subdue MAXX (Syngenta International AG), 0.025 g chloramphenicol (Sigma-Aldrich), and 0.025 g streptomycin sulfate (Acros Organics) were mixed to the medium. One-gram root sample of each plant were ultrasonicated with 10 ml of sterilized deionized water (5.7 liters of Fisherbrand M-Series Mechanical Ultrasonic Cleaning Bath; Thermo Fisher Scientific Inc., Waltham, MA, USA) for 3 min and then agitated with a shaker (Fisherbrand Incubating Mini-Shaker; Thermo Fisher Scientific Inc.) at 250 rpm for 30 min at room temperature. The particles were then allowed to settle for 30 min. Serial dilutions of 10^{-2} and 10^{-4} were prepared and spread-plated using glass beads (3-mm solid glass beads; Walter

Stern Inc., Manorhaven, NY, USA), as well as 100 µl of the undiluted sample. *Trichoderma* colonies on plates were recorded after incubation for 10-days in a dark container at room temperature. The number of colony forming units (CFU) per gram of root sample was calculated using the plate counts, the dilution factor, and the plated volume [CFU= (number of colonies x dilution factor)/volume plated (ml)].

Data analysis: The study was designed in a completely randomized design with six replications of each treatment. Data analysis for the plant growth data were done using one-way analysis of variance (ANOVA) with SAS statistical software and means separated by Fisher's Least Significant Difference test ($\alpha = 0.05$) (Proc GLM). Welch *t*-test ANOVA was used for data with unequal variance (Welch 1947; Zheng et al. 2013). Percentage data on root rot disease severity and pathogen recovery from root samples were analyzed using Generalized Linear Mixed Model (GLMM) with beta distribution (PROC GLIMMIX). Data with the values 0% and 100% were changed to 0.01 and 0.99 to meet the assumption of GLMM. Data on the *Trichoderma* colonies were analyzed using PROC GENMOD with negative binomial distribution (Agresti 2003).

Results

Performance of the treatments varied in preventative and curative applications except for Empress Intrinsic, Pageant Intrinsic, Segovis, and Subdue MAXX. They were consistent in suppressing Phytophthora root rot disease severity compared to the inoculated control in both trials.

Signature Xtra performed better in the first trial with both preventative and curative applications for 1-day, 3-days and 7-days flooding in suppressing disease severity. Efficacy was also demonstrated in preventative treatments for all the flooding conditions in trial 2 including 1-day flooding preventative treatment. However, it was not effective in suppressing disease severity in 3-days and 7-days flooding for the curative application in trial 2. Actigard suppressed Phytophthora root rot disease severity significantly in all flooding days when applied preventatively 3 weeks before flooding. But it was ineffective in 7-days flooding in trial 2 when applied 1 week before flooding. Interface was effective as a curative application compared to the preventative application. Stargus and ON-Gard did not perform well when applied preventatively 3 weeks or 1 week before flooding. Rootshield Plus was effective against Phytophthora root rot in 1-day flooding and 3-days flooding. The highest pathogen recovery was obtained from the inoculated control and the least from the non-inoculated control. *Trichoderma* colonies were higher in 1-day and 3-days flooding periods than at 7-days flooding.

Preventative treatments - 3 weeks before flooding

1-day flooding: In trial 1, no significant differences were observed among the treatments for plant height increase and plant width increase compared to the inoculated control (Height: F = 1.69, P = 0.0746; Width: F = 0.97, P = 0.4931). Seedlings treated with ON-Gard, Aliette, Signature Xtra, Interface, and the non-inoculated control had significantly higher total fresh plant weight when compared to the inoculated control (F = 3.27, P = 0.0036). For the fresh root weight, all treatments had significantly higher total fresh root weight except for Actigard, Empress Intrinsic, Stargus, RootShield Plus, Segovis, Subdue MAXX, and Tartan as compared to the inoculated control (F = 3.39, P = 0.0028). All treatments significantly lowered the disease severity except Stargus when compared to the inoculated control (F = 7.29, P = 0.0004, Fig. 1). Percentage recovery of the pathogen from the plated roots was significantly lower for the treatments Orkestra Intrinsic, Segovis, Subdue MAXX, Signature Xtra, Tartan, and Interface among the preventative treatments compared to the inoculated control (F = 2.37, P = 0.0089, Table 2).

In trial 2, Empress Intrinsic, Subdue MAXX, and Signature Xtra had significantly higher plant height increase among the treated seedlings compared to the inoculated control (F = 6.94, $P \leq 0.0001$). No significant differences were observed among the treated seedlings for average plant width increase, total fresh plant weight, and total fresh root weight (Width: F = 0.84, P = 0.6223; Total plant weight: F = 0.47, P = 0.9397; Total root weight: F = 0.54, P = 0.9019). All treatments significantly suppressed Phytophthora root rot disease severity compared to the inoculated control (F = 5.16, $P \leq 0.0001$, Fig. 1). Pathogen recovery was significantly lower for all treatments except for Actigard, Aliette, RootShield Plus and Tartan (F = 2.59, P = 0.0042, Table 2).

3-days flooding: In trial 1, no significant differences were observed among the treatments for plant height increase compared to the inoculated control (F =1.52, P = 0.1230). Average plant width increase was higher for all treatments except for Actigard and RootShield Plus as compared to the inoculated control (F = 2.32, P = 0.0279). Flowering dogwood seedlings treated with Signature Xtra had significant higher total fresh plant weight and total fresh root weight compared to the inoculated control (Total plant weight: $F = 4.45$, $P = 0.0004$; Total root weight: $F = 2.83$, $P = 0.0092$). All treatments significantly suppressed Phytophthora root rot disease severity except for Stargus and Interface compared to the inoculated control ($F = 8.31$, $P \leq 0.0001$, Fig. 1). Percentage recovery of the pathogen was significantly lower for Subdue MAXX, Signature Xtra and Tartan compared to the inoculated control ($F = 1.84$, $P = 0.0477$, Table 2).

In trial 2, plant height increase was significantly higher for all treatments except for Actigard, Tartan, ON-Gard, and Stargus ($F = 3.28$, $P = 0.0035$). No significant differences were observed among the treated seedlings for average plant width increase ($F = 0.72$, $P = 0.7446$). Fresh plant weight was significantly higher for all treatments except for Stargus, ON-Gard, and Tartan among the treated seedlings compared to the inoculated control ($F = 1.87$, $P = 0.0434$). No significant differences were observed among the treatments for fresh root weight compared to the inoculated control ($F = 1.60$, $P = 0.0980$). Seedlings treated with all other treatments except for Stargus and ON-Gard had significantly suppressed disease severity compared to the inoculated control ($F = 5.80$, $P \leq 0.0001$, Fig. 1). All treatments had significantly lower percentage recovery of the pathogen compared to the inoculated control ($F = 5.11$, $P \leq 0.0001$, Table 2).

7-days flooding: In trial 1, there were significant differences among the treatments for plant height increase, average plant width increase, total fresh plant weight, total fresh root weight, Phytophthora root rot disease severity, and pathogen recovery. Aliette, Stargus, ON-Gard, Pageant Intrinsic, and Interface had significantly higher plant height increase as compared to the inoculated control ($F = 2.17$, $P = 0.0383$). Average plant width increase was higher for seedlings treated with Aliette, ON-Gard, and Signature Xtra compared to the inoculated control ($F = 6.44$, $P \leq 0.0001$). Seedlings treated with Aliette, ON-Gard, Pageant Intrinsic, Signature Xtra and Interface had significantly higher total fresh plant weight and those treated with only ON-Gard and Pageant Intrinsic had significantly higher total fresh root weight as compared to the inoculated control (Total plant weight: $F = 2.20$, $P = 0.0366$; Total root weight: $F = 1.96$, $P = 0.0324$). All treatments significantly suppressed Phytophthora root rot disease severity compared to the inoculated control except Stargus and Interface ($F = 9.23$, $P \leq 0.0001$, Fig. 1). Aliette, ON-

Gard and Subdue MAXX had significantly lower percentages of pathogen recovery compared to the inoculated control among the treated seedlings ($F = 2.19$, $P = 0.0157$, Table 2).

In trial 2, no significant differences were observed among the treatments for plant height increase, average plant width increase, total fresh plant weight, and total root weight compared to the inoculated control (Height: $F = 1.56$, $P = 0.1110$; Width: $F = 1.64$, $P = 0.0875$; Total plant weight: $F = 0.80$, $P = 0.6703$; Total root weight: $F = 0.62$, $P = 0.8364$). All treatments except Aliette, Stargus, ON-Gard, RootShield Plus, and Interface significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 3.97$, $P \leq 0.0001$, Fig. 1). Percentage recovery of the pathogen was significantly lower for all treatments except Stargus, RootShield Plus, Tartan and Interface compared to the inoculated control ($F = 5.41$, $P \leq 0.0001$, Table 2).

In trial 1, *Trichoderma* colonies of RootShield Plus were significantly higher for 1-day flooding and 3-days flooding compared to 7-days flooding ($\chi^2 = 11.57$, $P = 0.0031$) whereas in trial 2, *Trichoderma* colonies in 1-day flooding were significantly higher compared to 7-days flooding but those in 3-days flooding were not significantly different than 7-days flooding ($\chi^2 = 7.41$, $P = 0.0246$, Fig. 2).

Preventative application - 1 week before flooding

1-day flooding: In trial 1, flowering dogwood seedlings treated with Signature Xtra and Aliette had significantly higher plant height increase, and those treated with Signature Xtra and Interface had significantly higher total fresh plant weight compared to the inoculated control (Height: $F = 3.02$, $P = 0.0010$; Total plant weight: $F = 4.57$, $P = 0.0003$). No significant differences were observed among the treatments for average plant width increase compared to the inoculated control ($F = 1.19$, $P = 0.3029$). Total fresh root weight was significantly higher for the seedlings treated with Interface when compared to the inoculated control ($F = 3.99$, $P = 0.0009$). Disease severity was significantly suppressed by all treatments compared to the inoculated control ($F = 7.06$, $P \leq 0.0001$, Fig. 3). All treatments had significantly lower percentages of pathogen recovery compared to the inoculated control ($F = 4.89$, $P \leq 0.0001$, Table 3).

In trial 2, no significant differences were observed among the treatments for plant height increase, plant width increase, total plant weight and total root weight compared to the inoculated control (Height: $F = 1.45$, $P = 0.1521$; Width: $F = 1.04$, $P = 0.4278$;Total plant weight: $F = 0.42$, $P = 0.9654$; Total root weight: $F = 0.35$, $P = 0.9832$). All treatments significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 5.48$, $P \leq 0.0001$, Fig. 3). Percentage recovery of the pathogen was significantly lower for all treatments except for Actigard and Aliette compared to the inoculated control ($F = 2.64$, $P = 0.0036$, Table 3).

3-days flooding*:* In trial 1, no significant differences were observed among the treatments for plant height increase, total plant weight and total root weight (Height: $F = 1.72$, $P = 0.0684$; Total plant weight: $F = 1.52$, $P = 0.1260$; Total root weight: $F = 1.68$, $P = 0.0778$) whereas Actigard and RootShield Plus had significantly higher average plant width increase compared to the inoculated control ($F = 2.20$, $P = 0.0365$). Disease severity was significantly lowered by all treatments compared to the inoculated control ($F = 6.03$, $P \leq 0.0001$, Fig. 3). All treatments had significantly lower percentage of pathogen recovery compared to the inoculated control except Stargus ($F = 3.06$, $P = 0.0009$, Table 3).

In trial 2, Empress Intrinsic, Segovis, Subdue MAXX, and Signature Xtra had significantly higher plant height increase compared to the inoculated control ($F = 2.58$, $P = 0.0156$). Seedlings treated with Subdue MAXX and Signature Xtra had significantly higher average plant width increase among the treated seedlings compared to the inoculated control ($F = 3.22$, $P = 0.0040$). ON-Gard, Segovis, Subdue MAXX, Signature Xtra, and Stargus had significantly higher total fresh plant weight ($F = 3.36$, $P = 0.0030$) whereas only Segovis, Subdue MAXX, and Signature Xtra had significantly higher total fresh root weight ($F = 3.04$, $P = 0.0058$) among the treated dogwood seedlings compared to the inoculated control. All treatments significantly suppressed Phytophthora root rot disease severity except Stargus and Interface compared to the inoculated control ($F = 11.10$, $P \leq 0.0001$, Fig. 3). Percentage recovery of the pathogen was significantly lower in all treatments compared to inoculated control except Stargus and Interface ($F = 4.24$, $P \leq 0.0001$, Table 3).

7-days flooding: In trial 1, no treated seedlings had significantly higher plant height increase and average plant width increase compared to the inoculated control (Height: $F = 0.83$, $P = 0.6303$; Width: $F = 0.74$, $P = 0.7299$). Aliette, Stargus, Orkestra Intrinsic, RootShield Plus, Subdue MAXX, and Signature Xtra treatments had significantly higher total fresh plant weight compared to the inoculated control ($F = 15.31$, $P \leq 0.0001$). However, all these treatments resulted in significantly higher total fresh plant weight and higher total fresh root weight except for Subdue MAXX compared to the inoculated control ($F = 6.69$, $P \leq 0.0001$). For the disease severity, all treatments except for Interface significantly suppressed Phytophthora root rot compared to the inoculated control ($F = 8.06$, $P \leq 0.0001$, Fig. 3). Treatments Stargus, ON-Gard, Segovis, Tartan, and Interface had similar pathogen recovery as inoculated control ($F = 9.05$, $P \leq 0.0001$, Table 3).

In trial 2, no significant differences were observed among the treatments for plant height increase and average plant width increase (Height: $F = 0.92$, $P = 0.5454$; Width: $F = 0.88$, $P = 0.5840$). Total fresh plant weight and total fresh root weight were significantly higher in seedlings treated with Segovis and Subdue MAXX compared to the inoculated control (Total plant weight: $F = 3.69$, $P = 0.0015$; Total root weight: $F = 2.90$, $P = 0.0077$). All treatments except for Actigard, Aliette, Stargus, ON-Gard, Tartan, and Interface significantly suppressed disease severity compared to the inoculated control ($F = 7.10$, $P \leq 0.0001$, Fig. 3). All treatments had significantly lower pathogen recovery compared to the inoculated control except Actigard, Aliette, Stargus, ON-Gard, Tartan, and Interface ($F = 6.25$, $P \leq 0.0001$, Table 3).

Trichoderma colonies were significantly higher for 1-day flooding and 3-days flooding compared to 7-days flooding in both trials (Trial 1: $\chi^2 = 10.22$, $P = 0.0006$; Trial 2: $\chi^2 = 12.3$, $P = 0.0021$, Fig. 2).

Curative application

1-day flooding: In trial 1, flowering dogwood seedlings treated with Signature Xtra and Interface had significantly higher plant height increase, total fresh plant weight, and total fresh root weight compared to the inoculated control (Height: $F = 2.40$, $P = 0.0419$; Total plant weight: $F = 3.19$, $P = 0.0113$; Total root weight: $F = 3.47$, $P = 0.0073$). All fungicidal treatments except Subdue MAXX had higher average plant width increase compared to the inoculated control ($F = 4.35$, $P = 0.0020$). All treatments significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 1.94$, $P \leq 0.0001$, Fig. 4). All treatments except Interface had significantly lower pathogen recovery compared to the inoculated control ($F = 2.18$, $P = 0.0332$, Table 4).

In trial 2, no significant differences were observed among the treatments for plant height increase ($F = 1.88$, $P = 0.0686$) and total fresh root weight ($F = 1.90$, $P = 0.0645$) as compared to the inoculated control. Empress Intrinsic and Interface treated seedlings had significantly higher total fresh plant weight ($F = 3.15$, $P = 0.0030$), compared to the inoculated control among the fungicidal treatments. All treatments had significantly higher average plant width increase except Pageant Intrinsic and Tartan compared to the inoculated control ($F = 2.85$, $P = 0.0063$). All treatments except Orkestra Intrinsic significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 5.19$, $P \leq 0.0001$, Fig. 4). All treatments had significantly lower percentage of pathogen recovery compared to the inoculated control ($F = 2.30$, $P = 0.0246$, Table 4).

3-days flooding: In trial 1, seedlings treated with Signature Xtra and Interface had significantly higher plant height increase, average plant width increase, total fresh plant weight, and total fresh root weight as compared to the inoculated control (Height: $F = 11.95$, $P \leq 0.0001$; Width: $F = 28.50$, $P \leq 0.0001$; Total plant weight: $F = 7.74$, $P \leq 0.0001$; Total root weight: $F = 9.23$ $P \leq 0.0001$). All treatments significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 14.48$, $P \leq 0.0001$, Fig. 4). No differences were observed among the fungicidal treatments for the percentage of pathogen recovery compared to the inoculated control ($F = 1.25$, $P = 0.0028$, Table 4).

In trial 2, no significant differences were observed among the treatments for the plant height increase, average plant width increase, total fresh plant weight, and total fresh root weight (Height: $F = 0.90$, $P = 0.5401$; Width: $F = 0.59$, $P = 0.8145$; Total plant weight: $F = 0.31$, $P = 0.9757$; Total root weight: $F = 0.19$, $P = 0.9960$). All treatments except Orkestra Intrinsic and Signature Xtra significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 6.18$, $P \leq 0.0001$, Fig. 4). All treatments except Orkestra Intrinsic had significantly lower pathogen recovery compared to the inoculated control ($F = 2.83$, $P = 0.0065$, Table 4).

7-days flooding: In trial 1, no treated seedlings had significantly higher plant height increase, average plant width increase, total plant weight and total fresh root weight compared to the inoculated control (Height: $F = 1.87$, $P = 0.0699$; Width: $F = 2.04$, $P = 0.0460$; Total plant weight: $F = 1.54$, $P = 0.1512$; Total root weight: $F = 1.92$, $P = 0.0623$). Similar to 1-day and 3-

days flooding, all treatments significantly suppressed Phytophthora root rot disease severity compared to the inoculated control ($F = 7.35$, $P \leq 0.0001$, Fig. 4). All treatments except Aliette, Orkestra Intrinsic, and Interface significantly lower pathogen recovery compared to the inoculated control ($F = 4.14$, $P = 0.0003$, Table 4).

In trial 2, Subdue MAXX and Interface had significantly higher plant height increase compared to the inoculated control (Height: $F = 5.41$, $P = 0.0005$). No significant differences were observed among the treated dogwood seedlings for average plant width increase, total fresh weight and total fresh root weight compared to the inoculated control (Width: $F = 6.15$, $P = 0.0002$; Total plant weight: $F = 5.97$, $P = 0.0002$; Total root weight: $F = 6.66$, $P = 0.0001$). All treatments except for Orkestra Intrinsic and Signature Xtra significantly suppressed the disease severity compared to the inoculated control ($F = 9.60$, $P \leq 0.0001$, Fig. 4); however, only Empress Intrinsic, Segovis, Subdue MAXX, and Interface were the fungicidal treatments with significantly lower pathogen recovery compared to the inoculated control ($F = 3.90$, $P = 0.0005$, Table 4).

Discussion

Fungicides, biofungicides, host-plant defense inducers, and fertilizer had varied results in their ability to suppress Phytophthora root rot severity during flooding conditions. Some of the treatments were effective when used preventatively 3 weeks before the flooding whereas some of them were effective when used 1 week before flooding. Most of the treatments used as curative applications, except for Orkestra Intrinsic and Signature Xtra, successfully suppressed Phytophthora root rot disease severity. The effectiveness of some of the treatments also varied between the trials. Irrespective of the treatments being able to suppress root rot disease symptoms caused by *P. cinnamomi*, all inoculated seedlings exhibited the disease symptoms. The highest disease severity was observed in the inoculated control while the lowest disease severity was observed in the non-inoculated control. The physical appearances (shedding of leaves, plants vigor) of the non-inoculated control plants were better than those of the inoculated control plants (visual observation).

The results displayed that the severity of the disease increased with increased flooding duration, which is consistent with the results of Brown et al. (2019b, 2019a) using *Cornus florida*

L. seedlings. The severity of Phytophthora root rot in dogwood seedlings was higher in 7-days flooding than 3-days or 1-day flooding in both preventative and curative treatments. Wilcox and Mircetich (1985) and de Silva et al. (1999) observed increased root rot severity in increased flooding conditions in two species of *Prunus* and *Vaccinium corymbosum* L., respectively. In a study conducted by Ploetz and Schaffer (1987), a contrast between the disease severity in the fine loamy soil and potting mixture was observed in the avocado seedlings where the fine loamy soil had increased root rot severity but not in potting mixture. The author explained the differences were because of the water holding capacity of the two soil types. In our study, as the simulated flooding conditions were created for 1-, 3-, and 7-days using zip-lock bags, the disease severity increased with increased flooding duration. This shows that proper drainage is important to manage the *Phytophthora* infections. The moisture condition in pine bark substrate is less compared to the usual field soil where nursery crops are grown. In a study conducted by Ownley et al. (1990), the moisture retained in pine bark was comparatively less than that of pine bark mixed with peat or soil. But in another study conducted by Wisdom et al. (2017), the total porosity of the pine bark substrate alone was comparatively less than the combination of pine bark and vermiculite. The increased porosity in the potting substrate helps to increase oxygen amount in the root zone and delays root rot disease development. Increased soil moisture creates favorable conditions for the production, dispersal, and germination of zoospores. Also, the saturated soil conditions make root and collar regions more susceptible for *Phytophthora* infestation (Newhook and Podger 1972; Weste and Marks 1987). In the absence of soil moisture, chlamydospores are formed and once the environmental conditions become favorable, they germinate to form either mycelium or sporangium with zoospores to start re-infection (Weste and Vithanage 1978, 1979). Thus, appropriate cultural measures like soil reclamation, specifically proper drainage, are important for managing Phytophthora root rot.

Several systemic fungicides were effective against *P. cinnamomi* during flooding conditions. Mefenoxam (Subdue MAXX) fungicide has been used preventatively and curatively to manage the oomycetes in nurseries, turf, and landscape. In our study, mefenoxam was one of the few fungicides that was effective in suppressing Phytophthora root rot disease severity in both preventative and curative applications for all 1-, 3-, and 7-days flooding. In other studies, conducted by Baysal-Gurel et al. (2016) and Gray et al. (2020), mefenoxam was effective in managing Phytophthora root rot in dogwood, hydrangea, and citrus seedlings, respectively. Soil drench application of mefenoxam fungicide was able to control root rot caused by *P. cinnamomi* in ornamental crops (Hu et al. 2010). Mefenoxam acts against both mycelial growth and sporulation, and checks the synthesis of ribosomal RNA to suppress the pathogenic activity of *P. cinnamomi* (Cohen and Coffey 1986; Davidse et al. 1983). However, excessive use of fungicides can lead to the emergence of a fungicide insensitive pathogen population.

Along with Subdue MAXX, Intrinsic brand fungicides like Empress Intrinsic and Pageant Intrinsic suppressed Phytophthora root rot severity in both preventative and curative applications. Intrinsic brand fungicides are a strobilurin class of fungicides, which are found to act as host-plant defense inducers (Chandrasekhar et al. 2017). Host-plant defense inducers act to improve the plant's immune system and enhance the defensive/response mechanism of plants in biotic and abiotic stress conditions (Chandrasekhar et al. 2017; Brown et al. 2019b). Brown et al. (2019 a,b) and Baysal-Gurel et al. (2016) evaluated the efficacy of pyroclostrobin (strobilurin) to manage Phytophthora root rot in flowering dogwoods and hydrangeas, respectively, and found it to be effective. Similarly, a higher rate of pyroclostrobin in comparison to its lower rate was found to be effective as seed treatment of soybean and corn against Phytophthora root rot (Li et al. 2020; Radmer et al. 2017). Strobilurin inhibits mitochondrial respiration of the oomycetes along with enhancing physiological changes to embrace plant vigor, stress tolerance, and disease resistance (Han et al. 2012; Herms et al. 2002; Jaleel et al. 2008; Venancio et al. 2003).

In this study, Segovis (piperidinyl-thiazole isooxazoline) showed promising results in managing root rot disease caused by *P. cinnamomi* in all flooding durations as both preventative and curative applications. The drench application of the fungicide significantly reduced Phytophthora root rot in impatiens (*Impatiens walleriana* Hooker) even after 120 days of application (Harlan and Hausbeck 2019). In another study conducted by Gray et al. (2020), a lower dose of oxathiapiprolin (piperidinyl-thiazole isooxazoline) was effective in management of root rot disease in citrus seedlings. Piperidinyl-thiazole isooxazoline targets the oxysterol binding protein to provide resistance against the oomycete pathogens (Mboup et al. 2021; Miao et al. 2016; Pasteris et al. 2016). This fungicide highly inhibits mycelial growth, sporangial production, and cystospore germination, especially in *Phytophthora* spp. (Lin et al. 2020).

Some of the fungicides were inconsistent in their efficacy against *P. cinnamomi* during the flooding conditions. Treatments such as Actigard (acibenzolar-S-methyl) were effective in both trials of preventative application 3 weeks before flooding. But they were ineffective in the second trial of preventative application 1 week before flooding. The preventative application of acibenzolar-S-methyl and mefenoxam was previously found to be effective against Phytophthora root rot of pepper in the flooding conditions (Matheron and Porchas 2002). Similarly, a curative application of acibenzolar-S-methyl was able to significantly reduce *P. cinnamomi* infection in *Pinus radiata* D. Don, *Banksia integrifolia* L., and *Isopogon cuneatus* R. Br. (Ali et al. 2000). In recent years, increasing cases of acibenzolar-S-methyl consistency against fungal pathogens have been observed in many studies (Bokshi et al. 2006; Darras et al. 2006). One of the reasons might be different environmental conditions or seasonal timing between the trials. Brown et al. (2019b) and Darvas and Becker (1984) mentioned that extensive application of mefenoxam in nurseries could lead to fungicide resistance affecting the effectiveness of other fungicides.

Phosphoric acid compound of fosetyl-al (Aliette, Signature Xtra) is a recommended chemical control for *P. cinnamomi*. However, the inconsistency appeared with curative and preventative applications in this study. Aliette was effective in trial 1 but failed to suppress Phytophthora root rot severity compared to the inoculated control in trial 2 for both preventative and curative applications. Unlike Aliette, Signature Xtra was effective in preventative application but performed poorly in trial 2 as a curative application. Previously, Coffey (1987), Duvenhage (1994), and Darvas et al. (1983) found that fosetyl-al was effective against Phytophthora root rot of avocado caused by *P. cinnamomi*. Similarly, fosetyl-al was recommended for the long-term management of crown rot and root rot disease in apples (Utkhede and Smith 1993).

The effect of Stargus (*Bacillus amyloliquefaciens* strain F727) to suppress Phytophthora root rot severity was negligible as it was not effective in all 1-, 3- and 7-days flooding when applied 3 weeks before flooding. However, it was effective in 1-day flooding when applied 1 week before flooding. A similar result was observed by Brown et al. (2019b) where Stargus was effective in 1-day flooding but not for a longer duration. *Bacillus amyloliquefaciens* was found to be effective in controlling Phytophthora root rot disease severity in soybean in non-flooding conditions (Liu et al. 2019). Another biofungicide, Rootshield Plus (*Trichoderma harzianum* Rifai strain T-22 and *T. virens* strain G-41), was effective in all flooding durations when applied 1 week before flooding; but was effective only in 1-day flooding when applied 3 weeks before flooding. The number of *Trichoderma* colonies decreased with increased flooding duration. This suggests that the application of biofungicides should be done closer to the flooding duration to ensure maximum protection. The efficacy of the microorganisms against the pathogen may decrease with time and flooding duration as the number of colonies are reduced. Similar suggestions were recommended by Knudsen and Li (1990) as an increase in soil moisture could decrease hyphal proliferation.

Similarly, effectiveness of the Stressgard formulated fungicides (multiple modes of action), Tartan and Interface, varied. Tartan significantly suppressed Phytophthora root rot disease severity in all 1-, 3-, and 7-days flooding in curative and preventative applications but failed in the second trial of preventative application 1 week before flooding. Interface could not suppress the disease severity in all flooding durations when applied 3 weeks before flooding. However, it suppressed disease severity during 1-day flooding duration when applied 1 week before flooding. Intrinsic brand fungicide Orkestra was effective as a preventative application in both the trials but was ineffective in trial 2 of curative application.

In all these inconsistencies, we observed that most of the treatments failed in the second trial, irrespective of the application method. This might be because of the increased disease pressure in the second trial. The possible reasons for increased disease severity in trial 2 may be a) the difference in environmental conditions between trial 1 and trial 2, and b) the occurrence of powdery mildew in trial 2, c) TRIACT® 70 might have performed poorly against powdery mildew and the effect of root rot and powdery mildew might have caused the treatments to perform poorly. However, the foliar spray of TRIACT® 70 should have had uniform effects across all treatments.

In this study, comparatively less disease severity was observed in curative treatments than the preventative treatments, which might be because of the repeated application of the curative treatments. The differences in root rot severity of the inoculated controls in preventative application 3 weeks before flooding and 1 week before flooding were minimal. However, some of the fungicides performed differently in two application timings. Actigard was more effective when applied 3 weeks before flooding than 1 week before flooding. Contrastingly, RootShield Plus was more effective when applied 1 week before flooding than 3 weeks before flooding. ON-

Gard was effective in 1-day and 3-days flooding when applied 1 week before flooding but was effective only for 1-day flooding when applied 3 weeks before flooding.

The efficacy of the fungicides, biofungicides, host-plant defense inducers, and fertilizer have varied in different application timings, application methods, flooding durations, and between the trials. The growers should take these factors into consideration when looking for management practices for their crops. As severity of infection by *P. cinnamomi* increases with increasing soil moisture, cultural practices to improve drainage are highly recommended. Based on this study, both the preventative and curative applications of Empress Intrinsic, Pageant Intrinsic, Segovis, and Subdue MAXX can be used as chemical control in nurseries. As flooding conditions cannot be accurately predicted, curative application of these fungicides might be helpful in managing Phytophthora root rot disease. The strategic repeated application of curative fungicides may provide longer protection to the crop and prevent economic loss. Some of the fungicides work best when applied preventatively while some work best as curative application. In this study, Actigard and Tartan were effective when applied preventatively 3 weeks before the flooding whereas RootShield Plus performed well when applied 1 week before the flooding. Similarly, Signature Xtra and Orkestra Intrinsic were effective as preventative application measure but not as curative application measure. This shows that effectiveness of the chemicals depends on the application timing. Thus, selection of treatments based on its efficacy in different application methods and application timing will help in effective management of *P. cinnamomi* in flooding conditions.

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Tables

Table 1. Fungicides, biofungicides, host plant defense inducers and fertilizer used in this study.

Treatment[a]	Application type	Application rate ml/liter	Application rate g/liter	Application interval	Product group	Manufacturer[b]
Actigard 50 WG	Preventative		0.30	1 week	Host plant defense inducer	Syngenta
Aliette 80 WDG	Preventative, Curative		3.74	6 weeks	Host plant defense inducer	Bayer
Empress Intrinsic	Preventative, Curative	0.47		3 weeks	Strobilurin	BASF
Interface Stressgard	Preventative, Curative	6.25		3 weeks	Strobilurin + dicarboximide	Bayer
ON-Gard® 5-0-0	Preventative	25		3 weeks	Fertilizer	BioWorks
Orkestra Intrinsic	Preventative, Curative	0.78		3 weeks	Strobilurin + succinate dehydrogenase inhibitor	BASF
Pageant Intrinsic	Preventative, Curative		1.35	3 weeks	Strobilurin + succinate dehydrogenase inhibitor	BASF
RootShield Plus+ WP	Preventative		0.60	6 weeks	Biofungicide	BioWorks
Segovis	Preventative, Curative	0.25		3 weeks	Piperidinyl-thiazole isoxazoline	Syngenta
Signature Xtra Stressgard	Preventative, Curative		5.99	2 weeks	Host plant defense inducer	Bayer
Stargus	Preventative	10.00		1 week	Biofungicide	Marrone
Subdue MAXX	Preventative, Curative	0.16		10 weeks	Phenylamide	Syngenta
Tartan Stressgard	Preventative Curative	3.12		3 weeks	Strobilurin + triazole	Bayer

[a] Active ingredients (% A.I.): Actigard = acibenzolar-S-methyl (50%); Aliette = aluminum tris (0-ethyl phosphanate) (80%); Empress Intrinsic = pyraclostrobin (23.3%); Interface Stressgard = trifloxystrobin (1.44%) + iprodione (23.1%); Stargus = *Bacillus amyloliquefaciens* strain F727; ON-Gard® 5-0-0 = Total Nitrogen (5%); Orkestra Intrinsic = pyraclostrobin (21.26%) + fluxapyroxad (21.26%); Pageant Intrinsic = pyraclostrobin (12.8%) + boscalid (25.2%); RootShield Plus+ = *Trichoderma harzianum* Rifai strain T-

22 (1.15%) + *T. virens* strain G-41 (0.61%); Segovis = oxathiapiprolin (18.7%); Signature Xtra Stressgard = aluminum tris (0-ethyl phosphanate) (60%); Subdue MAXX = mefenoxam (22%); Tartan Stressgard = trifloxystrobin (4.17%) + triadimefon (20.86%).

[b] BASF=BASF Corporation, Florham Park, NJ; Bayer=Bayer AG, Monheim an Rhein, Germany; BioWorks=BioWorks Inc., Victor, NY; Marrone =Marrone Bio Innovations, Inc., Davis, CA; Syngenta=Syngenta International AG, Basel, Switzerland

Table 2. Percent recovery of *Phytophthora cinnamomi* from root samples (mean ± SE) treated with preventively applied fungicides, biofungicides, fertilizer or host plant defense inducers 3 weeks before flooding.

Treatment[a]	Average (Mean ± SE) percent recovery of *P. cinnamomi* from root samples of preventative application 3 weeks before flooding at different flood durations					
	Trial 1			Trial 2		
	1 day	3 days	7 days	1 day	3 days	7 days
Actigard	60.00 ± 8.94 ab	43.33 ± 8.03 abc	43.33 ± 9.55 ab	60.00 ± 13.66 ab	46.67 ± 9.89 bcd	53.33 ± 9.89 bcd
Aliette	46.67 ± 6.67 a-d	40.00 ± 7.30 abc	26.67 ± 4.22 b	50.00 ± 12.38 ab	23.33 ± 8.03 cde	36.67 ± 8.03 de
Empress	43.33 ± 12.02 a-e	46.67 ± 16.06 abc	36.67 ± 10.85 ab	23.33 ± 15.85 cd	23.33 ± 13.08 ef	56.67 ± 6.15 cd
Interface	26.67 ± 4.22 de	53.33 ± 11.16 a	43.33 ± 6.15 ab	36.67 ± 9.55 bc	46.67 ± 8.43 b	70.00 ± 11.25 abc
ON-Gard	40.00 ± 11.55 a-e	50.00 ± 12.38 ab	33.33 ± 6.67 b	43.33 ± 14.06 bc	41.67 ± 9.1 bcd	60.00 ± 10.33 bcd
Orkestra	36.67 ± 6.15 b-e	46.67 ± 11.16 abc	40.00 ± 11.55 ab	30.00 ± 6.83 bc	23.33 ± 6.15 cde	63.33 ± 8.03 bcd
Pageant	40.00 ± 5.16 a-e	50.00 ± 11.25 abc	43.33 ± 6.15 ab	30.00 ± 4.47 bc	43.33 ± 9.55 bc	53.33 ± 11.16 bcd
RootShield Plus[+]	46.67 ± 4.22 a-d	53.33 ± 16.87 a	46.67 ± 9.89 ab	66.67 ± 8.43 ab	33.33 ± 8.43 b-e	76.67 ± 10.85 ab
Segovis	36.67 ± 8.03 b-e	26.67 ± 6.67 a-d	46.67 ± 8.43 ab	36.67 ± 14.98 bc	36.67 ± 6.15 bcd	36.67 ± 6.15 de
Signature Xtra	33.33 ± 9.89 cde	30.00 ± 8.56 bcd	46.67 ± 12.29 ab	43.33 ± 13.08 bc	23.33 ± 9.55 def	53.33 ± 12.29 bcd
Stargus	56.67 ± 8.03 abc	40.00 ± 5.16 abc	36.67 ± 8.03 ab	40.00 ± 16.93 bc	46.67 ± 8.43 b	73.33 ± 9.89 abc
Subdue MAXX	23.33 ± 3.33 de	26.67 ± 6.67 cd	33.33 ± 8.43 b	23.33 ± 9.55 cd	16.67 ± 6.15 ef	26.67 ± 9.89 ef
Tartan	33.33 ± 4.22 cde	30.00 ± 6.83 bcd	46.67 ± 6.67 ab	43.33 ± 12.02 abc	40.00 ± 7.3 bcd	66.67 ± 11.16 abc
Non-inoculated control	20.00 ± 12.65 e	10.00 ± 4.47 d	3.33 ± 3.33 c	0.00 ± 0.00 d	0.00 ± 0.00 f	0.00 ± 0.00 f
Inoculated control	63.33 ± 10.85 a	60.00 ± 5.16 ab	56.67 ± 6.15 a	76.67 ± 8.03 a	80.00 ± 8.94 a	93.33 ± 4.22 a
F	2.37	1.84	2.19	2.59	5.11	5.41
df	14	14	14	14	14	14
P	0.0089	0.0477	0.0157	0.0042	<0.0001	<0.0001

[a] For each plant (six replications per treatment), ten randomly selected flowering dogwood root samples were plated on PARPH-V8 *Phytophthora*-selective medium to determine the percent recovery of *P. cinnamomi* from root samples.

Table 3. Percent recovery of *Phytophthora cinnamomi* from root samples (mean ± SE) treated with preventively applied fungicides, biofungicides, fertilizer or host plant defense inducers 1 week before flooding.

Treatment[a]	**Average (Mean ± SE) percent recovery of *P. cinnamomi* from root samples of preventative application 1 week before flooding at different flood durations**					
	Trial 1			**Trial 2**		
	1 day	**3 days**	**7 days**	**1 day**	**3 days**	**7 days**
Actigard	26.67 ± 8.43 bc	26.67 ± 4.22 bc	63.33 ± 12.02 b-f	66.67 ± 6.67 ab	56.67 ± 8.03 bc	86.67 ± 6.67 ab
Aliette	13.33 ± 4.22 bcd	23.33 ± 6.15 cd	40.00 ± 10.33 f	53.33 ± 11.16 abc	53.33 ± 6.67 bc	73.33 ± 9.89 a-d
Empress	10.00 ± 4.47 cd	36.67 ± 6.15 bc	56.67 ± 10.85 def	30.00 ± 15.28 cd	36.67 ± 10.85 cde	63.33 ± 14.98 c-f
Interface	23.33 ± 6.15 bc	30.00 ± 8.56 bcd	80.00 ± 12.65 abc	43.33 ± 12.02 bcd	53.33 ± 11.16 ab	86.67 ± 6.67 ab
ON-Gard	26.67 ± 8.43 bc	36.67 ± 14.98 bcd	73.33 ± 8.43 a-e	26.67 ± 12.29 de	53.33 ± 13.33 bc	66.67 ± 16.06 ab
Orkestra	10.00 ± 4.47 cd	26.67 ± 12.29 cde	50.00 ± 11.25 ef	33.33 ± 13.33 bcd	56.67 ± 12.02 bc	60.00 ± 7.3 c-f
Pageant	16.67 ± 8.03 bcd	26.67 ± 12.29 cde	66.67 ± 6.67 c-f	46.67 ± 11.16 bcd	50.00 ± 15.28 bcd	50.00 ± 11.25 def
RootShield Plus[+]	26.67 ± 6.67 bc	36.67 ± 12.02 bc	13.33 ± 4.22 g	40.00 ± 13.66 bcd	50.00 ± 16.12 bcd	46.67 ± 9.89 ef
Segovis	16.67 ± 6.15 bcd	20.00 ± 8.94 cde	83.33 ± 9.55 ab	40.00 ± 10.33 bcd	36.67 ± 8.03 b-e	26.67 ± 13.33 gh
Signature Xtra	16.67 ± 6.15 bcd	6.67 ± 4.22 de	16.67 ± 6.15 g	36.67 ± 8.03 bcd	26.67 ± 9.89 def	60.00 ± 11.55 b-f
Stargus	30.00 ± 6.83 b	46.67 ± 12.29 ab	73.33 ± 9.89 a-d	33.33 ± 14.3 bcd	60.00 ± 5.16 ab	76.67 ± 13.08 abc
Subdue MAXX	10.00 ± 4.47 cd	10.00 ± 4.47 cde	6.67 ± 4.22 g	30.00 ± 11.25 cd	20.00 ± 8.94 ef	40.00 ± 12.65 fg
Tartan	20.00 ± 10.33 bc	27.5 ± 10.47 cde	70.00 ± 10 a-d	46.67 ± 8.43 bcd	43.33 ± 12.02 b-e	73.33 ± 8.43 a-e
Non-inoculated control	0.00 ± 0.00 d	0.00 ± 0.00 e	0.00 ± 0.00 g	0.00 ± 0.00 e	0.00 ± 0.00 f	0.00 ± 0.00 h
Inoculated control	63.33 ± 6.15 a	70.00 ± 6.83 a	90.00 ± 6.83 a	83.33 ± 6.15 a	90.00 ± 4.47 a	93.33 ± 4.22 a
F	4.89	3.06	9.05	2.64	4.24	6.25
df	14	14	14	14	14	14
P	<0.0001	0.0009	<0.0001	0.0036	<0.0001	<0.0001

[a] For each plant (six replications per treatment), ten randomly selected flowering dogwood root samples were plated on PARPH-V8 *Phytophthora*-selective medium to determine the percent recovery of *P. cinnamomi* from root samples.

Table 4. Percent recovery of *Phytophthora cinnamomi* from root samples (mean ± SE) treated with curatively applied fungicides or host plant defense inducers.

Treatment[a]	**Average (Mean ± SE) percent recovery of *P. cinnamomi* from root samples of curative application at different flood durations**					
	Trial 1			**Trial 2**		
	1 day	**3 days**	**7 days**	**1 day**	**3 days**	**7 days**
Aliette	10.00 ± 6.83 bc	33.33 ± 8.43 ab	50.00 ± 13.42 a-d	30.00 ± 11.25 bc	23.33 ± 8.03 bcd	46.67 ± 12.29 abc
Empress	20.00 ± 10.33 bc	23.33 ± 12.02 ab	63.33 ± 12.02 c-f	23.33 ± 9.55 bc	23.33 ± 9.55 bcd	33.33 ± 8.43 bc
Interface	30.00 ± 19.15 ab	36.67 ± 14.06 a	53.33 ± 12.29 abc	16.67 ± 8.03 bc	20.00 ± 8.94 bcd	36.67 ± 10.85 bc
Orkestra	10.00 ± 6.83 bc	43.33 ± 17.45 a	60.00 ± 8.94 ab	26.67 ± 9.89 bc	53.33 ± 14.3 ab	50.00 ± 11.25 ab
Pageant	10.00 ± 4.47 bc	30.00 ± 15.28 ab	30.00 ± 11.25 def	20.00 ± 5.16 bc	36.67 ± 14.06 bc	43.33 ± 12.02 ab
Segovis	16.67 ± 6.15 bc	20.00 ± 10.33 ab	20.00 ± 7.3 efg	23.33 ± 8.03 bc	20.00 ± 7.3 bcd	36.67 ± 9.55 bc
Signature Xtra	6.67 ± 4.22 bc	36.67 ± 15.85 a	23.33 ± 8.03 efg	20.00 ± 10.33 bc	36.67 ± 12.02 bc	53.33 ± 8.43 ab
Subdue MAXX	23.33 ± 6.15 bc	13.33 ± 6.67 ab	26.67 ± 16.06 fg	15.00 ± 8.06 bc	13.33 ± 6.67 cd	20.00 ± 5.16 cd
Tartan	10.00 ± 4.47 bc	40.00 ± 10.33 a	36.67 ± 6.15 b-e	26.67 ± 8.43 b	36.67 ± 14.06 bc	40.00 ± 12.65 abc
Non-inoculated control	0.00 ± 0.00 c	0.00 ± 0.00 b	0.00 ± 0.00 g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d
Inoculated control	50.00 ± 16.12 a	40.00 ± 10.33 a	66.67 ± 9.89 a	53.33 ± 11.16 a	73.33 ± 9.89 a	66.67 ± 8.43 a
F	2.18	1.25	4.14	2.30	2.83	3.90
df	10	10	10	14	14	10
P	0.0332	0.0028	0.0003	0.0246	0.0065	0.0005

[a] For each plant (six replications per treatment), ten randomly selected flowering dogwood root samples were plated on PARPH-V8 *Phytophthora*-selective medium to determine the percent recovery of *P. cinnamomi* from root samples.

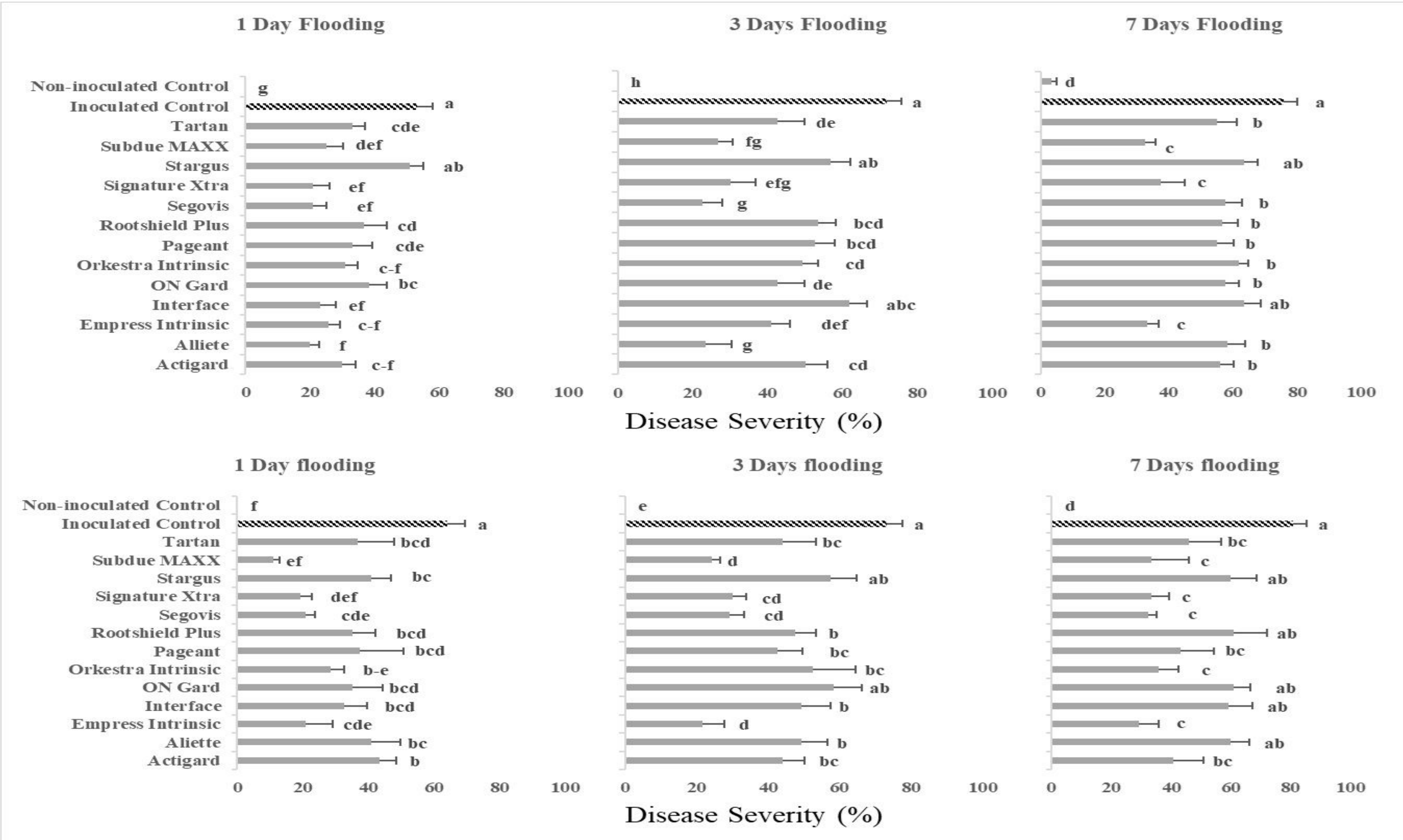
Figure Captions

Fig. 1. Disease severity (mean ± SE) of plants treated preventively 3 weeks before flooding with fungicides, biofungicides, fertilizer or host plant defense inducers at 1-, 3-, or 7-days of flooding in trials 1 (top) and 2 (bottom). For root rot disease severity, each plant was evaluated using a scale of 0−100% roots affected. Control treatments included the non-treated, inoculated and non-treated, non-inoculated plants. Letters above the error bars represent significant differences in disease severity (α=0.05, Fisher's LSD test).

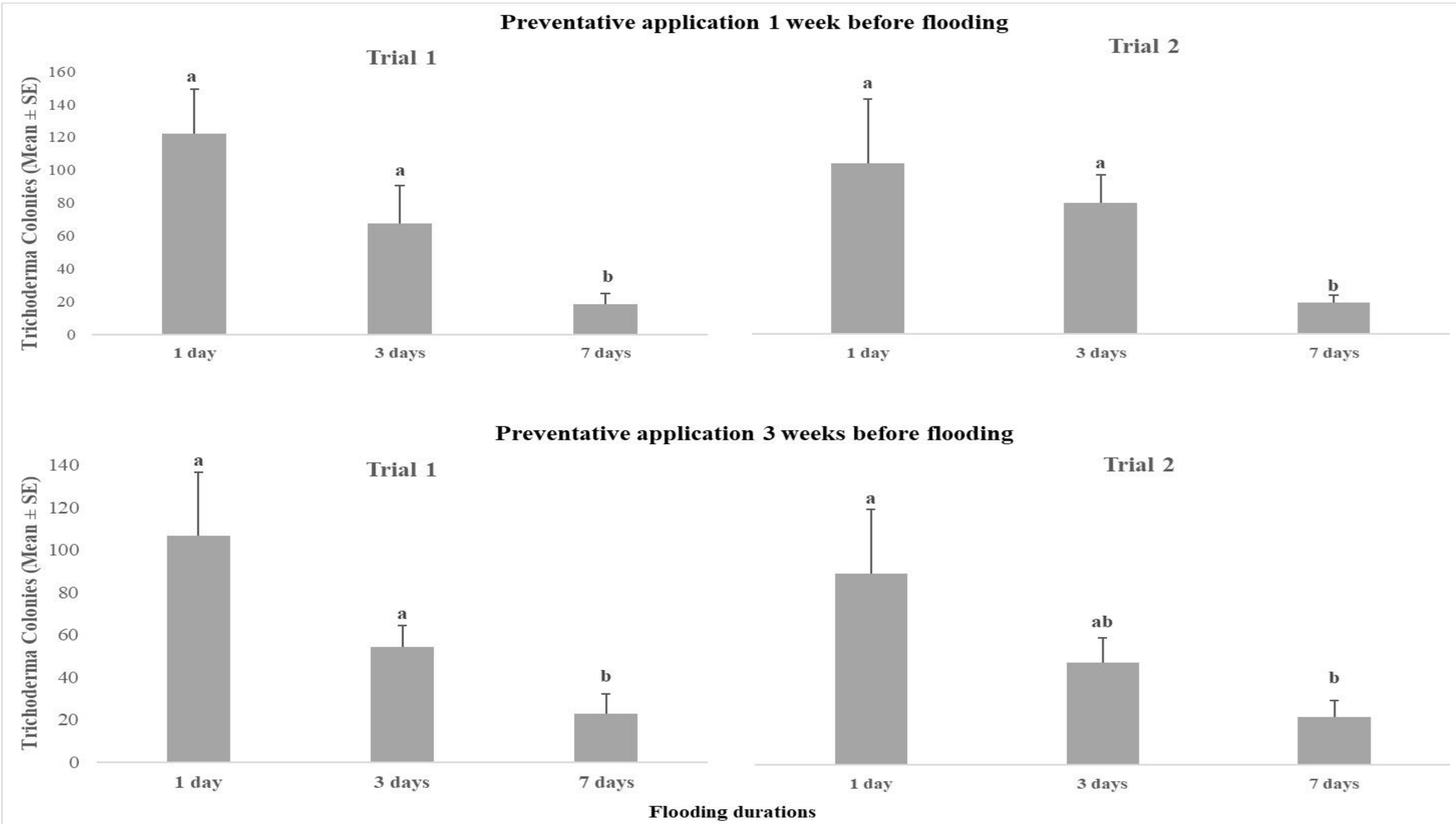
Fig. 2. *Trichoderma* (mean ± SE) colony counts on *Trichoderma*-selective medium at 1-, 3-, or 7-days of flooding in preventative application 1 week (top) and 3 weeks (bottom) before flooding. RootShield Plus$^+$-treated plants, undiluted root samples, as well as dilutions of 10^{-2} and 10^{-4}, were plated on *Trichoderma*-selective medium, and the colonies were counted after 10 days of incubation. Letters above bars represent significant differences in the number of *Trichoderma* colonies within flooding durations and trials (α=0.05, Least Squares Means).

Fig. 3. Disease severity (mean ± SE) of plants treated preventively 1 week before flooding with fungicides, biofungicides, fertilizer or host plant defense inducers at 1-, 3-, or 7-days of flooding in trials 1 (top) and 2 (bottom). For root rot disease severity, each plant was evaluated using a scale of 0−100% roots affected. Control treatments included the non-treated, inoculated, and non-treated, non-inoculated plants. Letters above the error bars represent significant differences in disease severity (α=0.05, Fisher's LSD test).

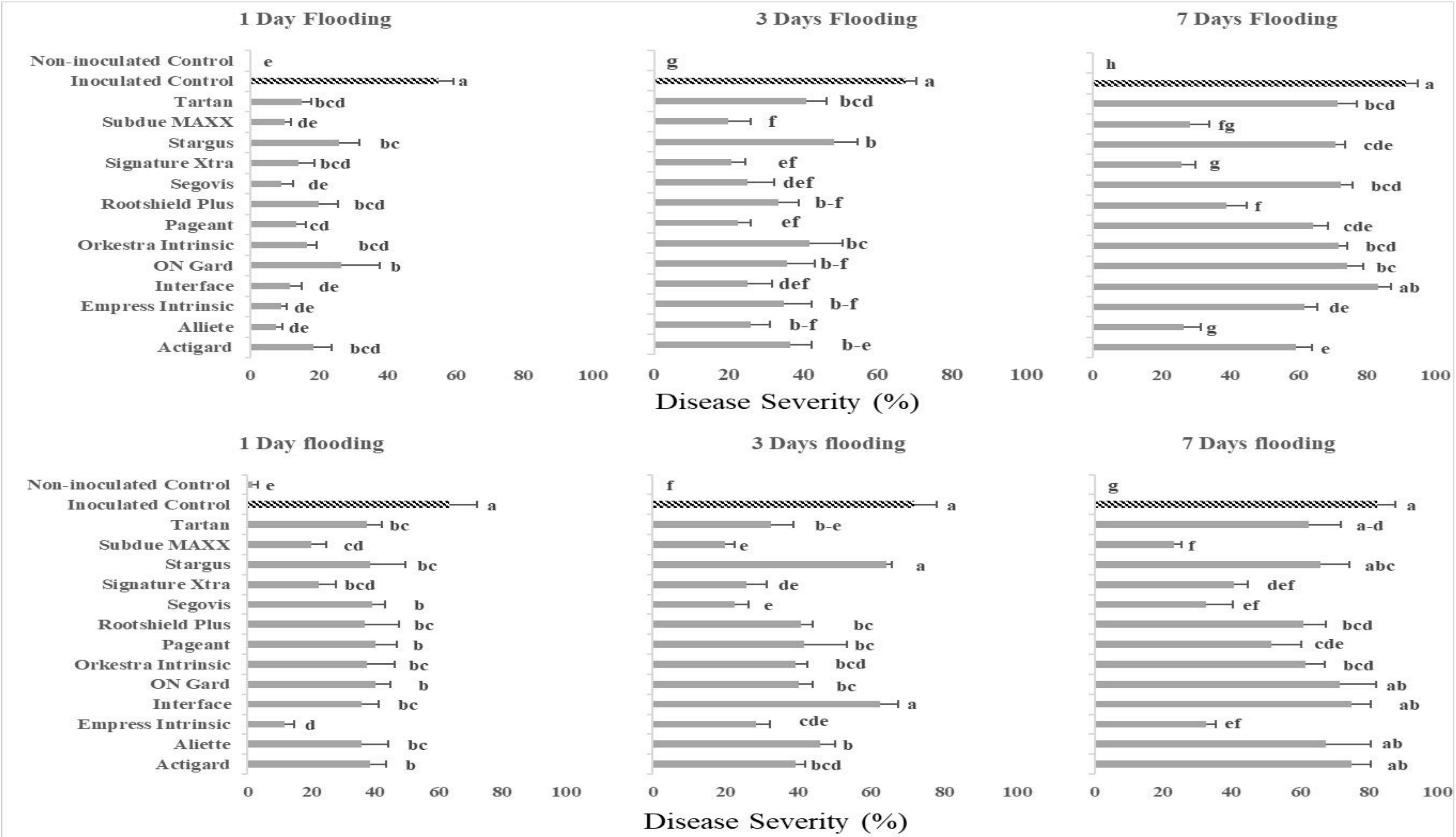
Fig. 4. Disease severity (mean ± SE) of plants treated curatively with fungicides and host plant defense inducers at 1-, 3-, or 7-days of flooding in trials 1 (top) and 2 (bottom). For root rot disease severity, each plant was evaluated using a scale of 0−100% roots affected. Control treatments included the non-treated, inoculated, and non-treated, non-inoculated plants. Letters above the error bars represent significant differences in disease severity (α=0.05, Fisher's LSD test).



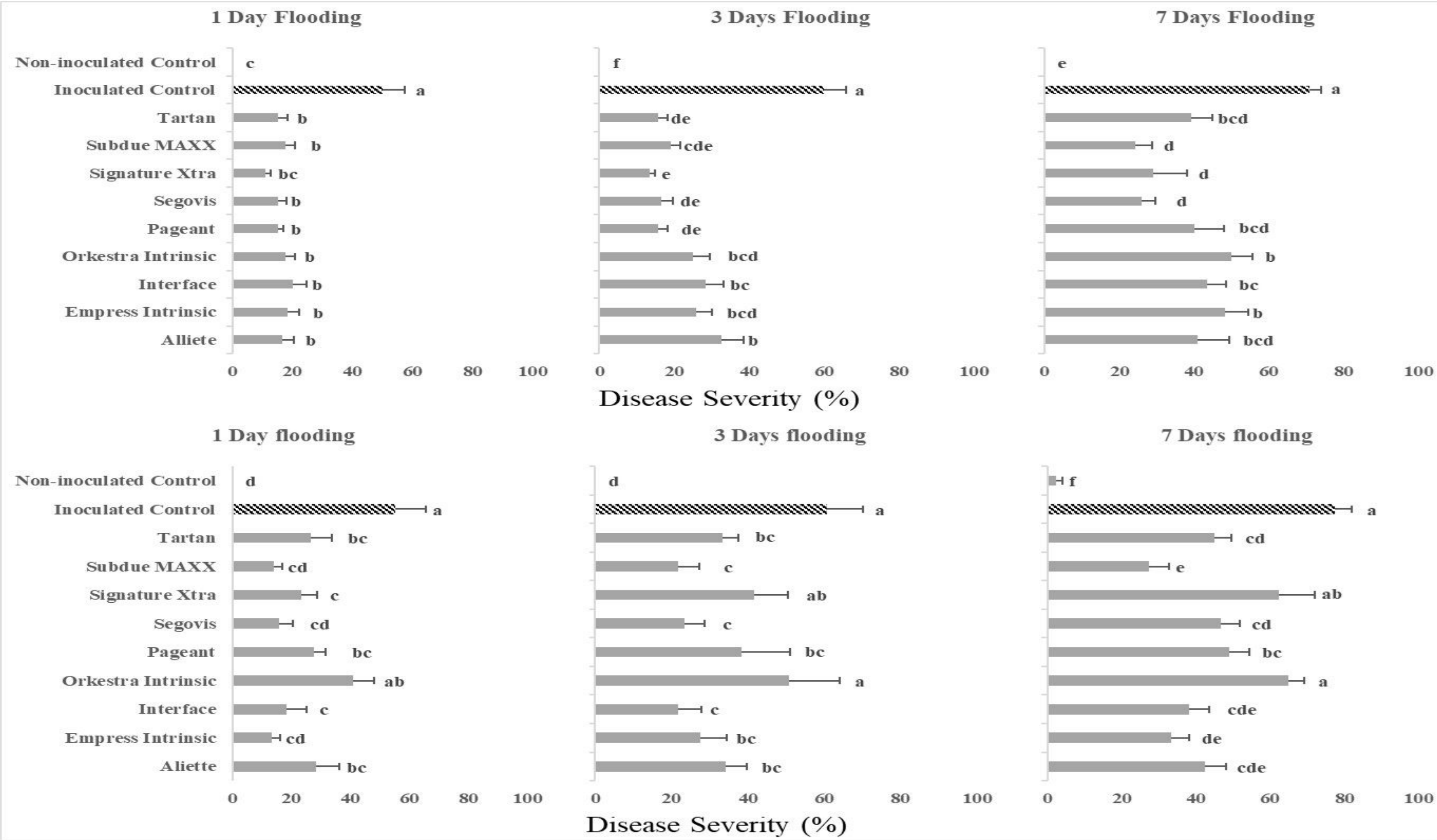
871 **Fig. 1.** Disease severity (mean ± SE) of plants treated preventively 3 weeks before flooding with fungicides, biofungicides, fertilizer
872 or host plant defense inducers at 1-, 3-, or 7-days of flooding in trials 1 (top) and 2 (bottom). For root rot disease severity, each plant
873 was evaluated using a scale of 0−100% roots affected. Control treatments included the non-treated, inoculated and non-treated, non-
874 inoculated plants. Letters above the error bars represent significant differences in disease severity (α=0.05, Fisher's LSD test).



875 **Fig. 2.** *Trichoderma* (mean ± SE) colony counts on *Trichoderma*-selective medium at 1-, 3-, or 7-days of flooding in preventative application 1 week (top) and 3 weeks (bottom) before flooding. RootShield Plus^{+}-treated plants, undiluted root samples, as well as dilutions of 10^{-2} and 10^{-4}, were plated on *Trichoderma*-selective medium, and the colonies were counted after 10 days of incubation. Letters above bars represent significant differences in the number of *Trichoderma* colonies within flooding durations and trials (α=0.05, Least Squares Means).



880 **Fig. 3.** Disease severity (mean ± SE) of plants treated preventively 1 week before flooding with fungicides, biofungicides, fertilizer or
881 host plant defense inducers at 1-, 3-, or 7-days of flooding in trials 1 (top) and 2 (bottom). For root rot disease severity, each plant was
882 evaluated using a scale of 0−100% roots affected. Control treatments included the non-treated, inoculated and non-treated, non-
883 inoculated plants. Letters above the error bars represent significant differences in disease severity (α=0.05, Fisher's LSD test).



884 **Fig. 4.** Disease severity (mean ± SE) of plants treated curatively with fungicides and host plant defense inducers at 1-, 3-, or 7-days of flooding in trials 1 (top) and 2 (bottom). For root rot disease severity, each plant was evaluated using a scale of 0−100% roots affected. Control treatments included the non-treated, inoculated and non-treated, non-inoculated plants. Letters above the error bars represent significant differences in disease severity (α=0.05, Fisher's LSD test).