Scientia Horticulturae 202 (2016) 107–110

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Short communication

Phytophthora infection in flooded citrus trees reduces root hydraulic conductance more than under non-flooded condition

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ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form 17 February 2016
Accepted 19 February 2016
Available online 27 February 2016

Keywords:
Flooding
Stomatal conductance
Water relations
Citrus
Sour orange

ABSTRACT

Phythophthora infections in citrus trees may result in poor tree health. Infections are very common under wet conditions. However, the interaction of *Phytophthora* and flooding conditions has yet to be studied in citrus. In this study, *Phytophthora* was inoculated into the soil of potted grapefruit trees, and trees were either well-watered or flooded for six weeks; then, these trees were compared with trees without *Phytophthora* inoculation under the same irrigation regimes. *Phytophthora* reduced root hydraulic conductance in citrus even though the propagule count was very low when root hydraulic conductance was measured (at the end of the experiment). In the presence of flooding, *Phytophthora* significantly reduced root hydraulic conductance compared to non-flooded citrus trees inoculated with *Phytophthora* alone. Flooding reduced stomatal conductance and increased tree mortality more than *Phytophthora*, but *Phytophthora* decreased the number of leaves per tree and tended to decrease tree growth more than flooding.

1. Introduction

Phytophthora species cause economic losses to a wide range of horticultural crops, including fruit tree species such as citrus, nut and deciduous trees (all species of stone and pome fruits). *Phytophthora nicotianae*, *Phytophthora palmivora*, and *Phytophthora citrophthora* are the most damaging soil borne fungi that attack citrus by causing root rot, foot rot, gummosis of the trunk, and brown rot of fruit in trees on susceptible rootstocks (Graham and Feichtenberger, 2015). Citrus rootstocks vary widely in resistance to *Phytophthora*, and the use of resistant rootstocks together with chemical control methods and cultural practices such as water management is necessary for managing *Phytophthora*-induced diseases (Graham et al., 2014).

Citrus are primarily grown between 40 north-south latitude, including tropical and subtropical regions. Many of these regions are under the influence of climatic events that increase the risk of floods such as active hurricane seasons and the effects of El Niño Southern Oscillation cycle in the American continent, and typhoons and the East Asian monsoon in Asia. Even without considering the presence of *Phytophthora*, waterlogging events cause small and large air pores in the soil to become filled with water, resulting in depleted O_2 levels in the soil. Soil hypoxia is known to cause rapid decreases in stomatal conductance (g_s), triggered by root hormonal signals, and in root hydraulic conductance in citrus and other trees (Islam and Macdonald, 2004; Rodríguez-Gamir et al., 2011).

The interaction of *Phytophthora* root rot and flooding has been studied in some species such as avocado (Reeksting et al., 2014) or oak tree species (Robin et al., 2001). In avocado, the effects of *Phytophthora* on overall gas exchange were greatest when trees were flooded (Reeksting et al., 2014). Also, oak trees growing in *Phytophthora*-inoculated soil medium declined more rapidly in waterlogged than in well-drained sites (Robin et al., 2001). Free water in the soil is necessary for the production, release, and motility of *Phytophthora* zoospores; however, waterlogging and hypoxia also have a direct effect on the reduction of mycelial growth (Kong and Hong, 2014).

The effects of flooding on water relations have been extensively studied in citrus in the last decades and include reductions in g_s (García-Sánchez et al., 2007) and root hydraulic conductance (Rodríguez-Gamir et al., 2011). Waterlogging has also been consistently related to incidence of *Phytophthora* root rot of citrus (Graham and Feichtenberger, 2015). Nevertheless, the effect of

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http://dx.doi.org/10.1016/j.scienta.2016.02.031
0304-4238/

Table 1
Effect of flooding and *Phytophthora* inoculation treatments on mean (n = 7) root hydraulic conductance (K, $mL\,s^{-1}\,MPa^{-1}$), stomatal conductance (g_s, $mmol\,H_2O\,m^{-2}\,s^{-1}$) four and six weeks after the treatments started, and efficiency of the photosystem II (F_v/F_m, adimensional).

	(K)	(g_s)		(F_v/F_m)
		Week four	Week six	
Flooding treatment				
No flooding	2.07 a[z]	156.6 a	198.7 a	0.83 a
Flooding	1.49 b	197.2 a	125.6 b	0.81 a
Phytophthora inoculation				
Without *Phytophthora*	2.09 a	198.6 a	171.0 a	0.83 a
With *Phytophthora*	1.47 b	155.1 a	153.3 a	0.82 a
Flooding × *Phytophthora*				
No flooding without *Phytophthora*	2.32 a	163.4 a	193.8 a	0.83 a
No flooding with *Phytophthora*	1.81 b	149.7 a	203.6 a	0.83 a
Flooding without *Phytophthora*	1.85 ab	233.8 a	148.1 ab	0.82 a
Flooding with *Phytophthora*	1.14 c	160.6 a	103.0 b	0.81 a

[z] Within each column, different letters indicate significant differences at $P \leq 0.05$.

Table 2
Effect of flooding and *Phytophthora* inoculation treatments on mean ($n = 7$) propagule count at week four and at the end of the experiment.

	Propagule count/g soil	
	Week four	Week six
Flooding × *Phytophthora*		
No flooding without *Phytophthora*	–[z]	–
No flooding with *Phytophthora*	5.7 b[y]	8.6 a
Flooding without *Phytophthora*	–	–
Flooding with *Phytophthora*	19.8 a	1.7 b

[z] *Phytophthora* was not detected in treatments where it was not inoculated.
[y] Within each column, different letters indicate significant differences at $P \leq 0.05$

Table 3
Effect of flooding and *Phytophthora* inoculation treatments on mean ($n = 7$) mortality (%), total plant dry weight (TPDW, g), root, stem, and leaf DW (g), leaf area (cm^2), leaf mass per area (LMA, $mg\,cm^{-2}$), and shoot to root ratio (S/R).

	Mortality[z]	TPDW[y]	Root DW	Stem DW	Leaf DW	Leaf number	Leaf area	LMA	S/R
Flooding treatment									
No flooding	7 b	129 a	59.5 a	63.3 a	21.4 a	103 a	20.7 a	10.6 a	1.6 a
Flooding	43 a	142 a	48.1 a	61.5 a	21.3 a	115 a	19.0 a	10.4 a	1.8 a
Phytophthora inoculation									
Without *Phytophthora*	21 a	142 a	60.3 a	68.5 a	23.7 a	124 a	18.4 a	10.5 a	1.7 a
With *Phytophthora*	29 a	128 a	47.2 a	56.2 a	19.0 a	94 b	21.3 a	10.5 a	1.7 a
Flooding × *Phytophthora*									
No flooding without *Phytophthora*	0 a	154 a	63.8 a	69.0 a	21.7 a	105 ab	19.2 a	10.9 a	1.7 a
No flooding with *Phytophthora*	14 a	127 a	55.1 a	57.5 a	21.2 a	102 ab	22.2 a	10.2 a	1.5 a
Flooding without *Phytophthora*	43 a	132 a	56.8 a	68.0 a	25.7 a	143 a	17.7 a	10.1 a	1.6 a
Flooding with *Phytophthora*	43 a	127 a	39.4 a	55.0 a	16.9 a	87 b	20.3 a	10.7 a	1.9 a

[z] The effect of flooding and *Phytophthora* on tree mortality was studied by performing a Chi-square analysis. Separate analyses were performed to evaluate the effects of flooding, *Phytophthora* inoculation, and the four treatment combinations on tree mortality.
[y] Mean separation for the effects of flooding, *Phytophthora* and their interaction on total plant, root, stem and leaf DW, leaf number, leaf area, leaf mass per area and shoot to root ratio was performed using a LSD test. Within each column, different letters indicate significant differences at $P \leq 0.05$

Phythopthora and its interaction with flooded conditions in water relations in citrus has not been studied. Thus, the goal of this study is to understand the response of grapefruit trees grafted onto sour orange rootstock to *Phythopthora* and flooding conditions. We hypothesized that the concomitant presence of *Phytophthora* under flooding conditions can affect in a different way soil-tree-atmosphere water relations that only *Phytophthora* or flooding condition.

2. Materials and methods

2.1. Plant material and growth conditions

This experiment was conducted between May and August 2014 at the Texas A&M University-Kingsville Citrus Center, in Weslaco, Texas. On May 16, similar-sized three-year-old disease-free grapefruit trees (*Citrus* × *paradisi* Macf. cv. Rio Red) grafted on sour orange (*Citrus aurantium* L.) from the Citrus Center nursery were transplanted into 30-cm tall, 2.4 L pots. These pots were filled with a commercial soil potting mixture (Metro-Mix 300, Sun Gro, Bellevue, WA) with an average bulk density of 232 $kg\,m^{-3}$, containing vermiculite, composted pine bark, Sphagnum peat moss, coarse perlite, bark ash, starter nutrient charge and slow release nitrogen, and Dolomitic limestone. Trees were thoroughly watered immediately after transplanting and placed in a greenhouse with open sides. During the experiment, maximum temperatures ranged from 27 to 38 °C, minimum temperatures were between 22 and 27 °C, and relative humidity values ranged between 33 and 97%. All trees were watered every three days based on tree evapotranspiration (ET_c; calculated gravimetrically every week by weight difference) until the beginning of the treatments.