Outbreak of *Phytophthora cinnamomi* causing severe decline of avocado trees in southern Turkey

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Summary

Since the summer of 2017, severe decline symptoms have been observed on 10- to 25-year-old avocado trees in almost all commercial orchards planted in the Mediterranean coastal region of Turkey. Young, newly planted trees in infected orchards were also affected by the disease. Affected trees showed wilting, leaf discoloration, defoliation and severe dieback. Some trees were completely desiccated. Although fine roots of symptomatic trees usually were decayed, reddish brown cankers also occurred on taproots and lateral roots, of heavily infected trees. The pathogens were isolated from necrotic root and soil samples of symptomatic trees, using selective medium and soil baiting, and were identified based on morphological features and DNA sequences. One isolate each of *Phytophthora cryptogea* and *P. palmivora* were identified, while all other isolates were *P. cinnamomi*. In addition, a subcortical fan-shaped mycelium, characteristic of *Armillaria* spp. was observed in the crown of a symptomatic tree and identified as *Armillaria gallica* by DNA sequences. Pathogenicity of *Phytophthora* isolates was tested by stem inoculation on avocado seedlings. Two months after inoculation, canker lesions developed on stems of seedlings inoculated by any of the three *Phytophthora* spp.. In contrast, collenchyma callus formed over the wound points on control plants over the same time period. This is the first report of *P. cinnamomi, P. cryptogea, P. palmivora* and *A. gallica* causing root rot of avocado trees in Turkey. In addition, *P. cryptogea* and *A. gallica* are reported for the first time associated with disease on this host. Due to the severe symptoms and widespread occurrence, *P. cinnamomi* should be considered a potential threat to avocado cultivation and natural ecosystems of this region of Turkey.

1 Introduction

Avocado (*Persea americana* Miller) is a tree species native in Guatemala, Central America and Mexico (Henao et al., 2017). It is a significant and nutritious fruit crop grown in both the tropical and subtropical regions in many parts of the world (Menge et al., 2012). World production of avocados in 2017 was estimated at approx. 6 million tonnes with the highest production in Mexico. other important avocado producing countries include Dominican Republic, Peru, Indonesia, Columbia, Brazil, Kenya, Venezuela, Chile, the United States (California), China and Guatemala

(FAOSTAT, 2019). Avocado production is currently increasing in Turkey, such that export of this fruit have begun.

Phytophthora cinnamomi is the most important Oomycota species damaging forest trees and is also destructive in woody ornamentals and orchard crops including avocado (Robin et al. 2012). Avocado root rot caused by *P. cinnamomi* has long been known as the main disease of this crop throughout the world (Zentmyer, 1980; Erwin & Ribeiro, 1996). The pathogen has reduced production in many areas of the world, becoming the major limiting factor in production in Australia, California, Mexico, South Africa and Spain (Ploetz et al., 2002; Perez-Jimenez 2008). In Mexico, the pathogen has been present in all the main avocado production areas with incidence varying between 5 and 90%, depending on the region (Perez-Jimenez 2008). California avocado groves were affected by the disease with incidence of 60 – 70%, and estimated annual losses of over $30 million (Coffey, 1992; Erwin & Ribeiro, 1996). In Eastern Australia, the pathogen is wide-spread, seriously affecting avocado production (Pegg et al., 1987). In South Africa, the number of infected orchards increased rapidly once the crop was introduced, and by the early 1970s, the disease was estimated to affect 20% of all trees (Milne & Chamberlain, 1971). In the Andalusian region of Spain, 40% of avocado orchards were invaded by *P. cinnamomi* (Perez-Jimenez et al. 2005). Approximately half of the avocado orchards established in the Canary Islands of Spain are affected by the disease (Rodriguez-Padron et al. 2018). In Israel, the pathogen was first isolated from avocado in 1982, and the number of orchards infested over subsequent years increased (Perez-Jimenez 2008).

Apart from *P. cinnamomi*, several other *Phytophthora* species, including *P. cactorum*, *P. citricola*, *P. citrophthora*, *P. heveae*, *P. nicotianae* and *P. palmivora*, have been reported worldwide affecting avocado trees (Erwin & Ribeiro, 1996). Recently, *P. citricola* isolates known to cause avocado trunk canker, were renamed *P. mengei* (Hong et al., 2009). More recently, avocado orchards were surveyed in the Canary Islands and *Phytophthora* species, including *P. cinnamomi, P. multivora, P. niederhauserii, P. nicotianae,* and *P. palmivora* were obtained from the roots of symptomatic trees or orchard soils (Rodriguez-Padron et al., 2018). The most frequently isolated species was *P. cinnamomi,* whereas the most virulent species was *P. niederhauserii* in that study.

In periodic observations since the summer 2017, decline symptoms due to root rot were observed on 10- to 25-year-old avocado trees in commercial orchards in Mediterranean coastal parts of Turkey, where almost all avocados in the country are produced. The aim of the work reported here was to identify the causal agents of the root rot and decline symptoms on avocados, including evaluations of pathogenicity in controlled environment tests.

2 Materials and Methods

Sampling and isolations

Commercial avocado orchards of Turkey are located in the Alanya and Gazipaşa districts of Antalya province, and the Anamur district of Mersin province in southern Turkey (Fig. 1). This region, located between 36° and 37° north, has a sub-tropical climate and almost all avocado production in Turkey is centered there. Avocado orchards in this region were surveyed for plants with symptoms of root rot in 2018 to 2019. During the surveys, wilting, leaf discoloration, defoliation and severe dieback symptoms, sometimes resulting in tree mortality, were frequently observed in the orchards (Fig. 2). Fine roots of symptomatic trees were rotted. Reddish brown cankers formed on taproots and lateral roots of some heavily infected trees. Root and soil samples were collected from the roots of a single symptomatic tree in each of 23 different orchards. In addition, fan-shaped mycelium under the bark of the lower stem of a declined tree was observed in a single orchard (Fig. 2). Wood tissue including the mycelium was also sampled from that tree.

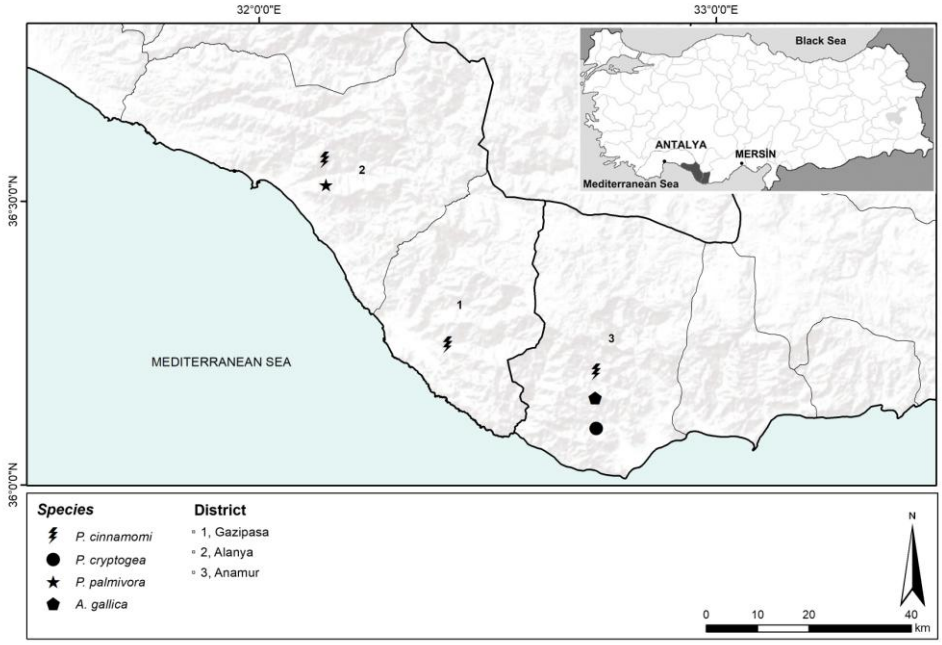

Figure 1. Distribution of *Phytophthora* spp. Alanya and Gazipaşa districts of Antalya province, and Anamur district of Mersin province.

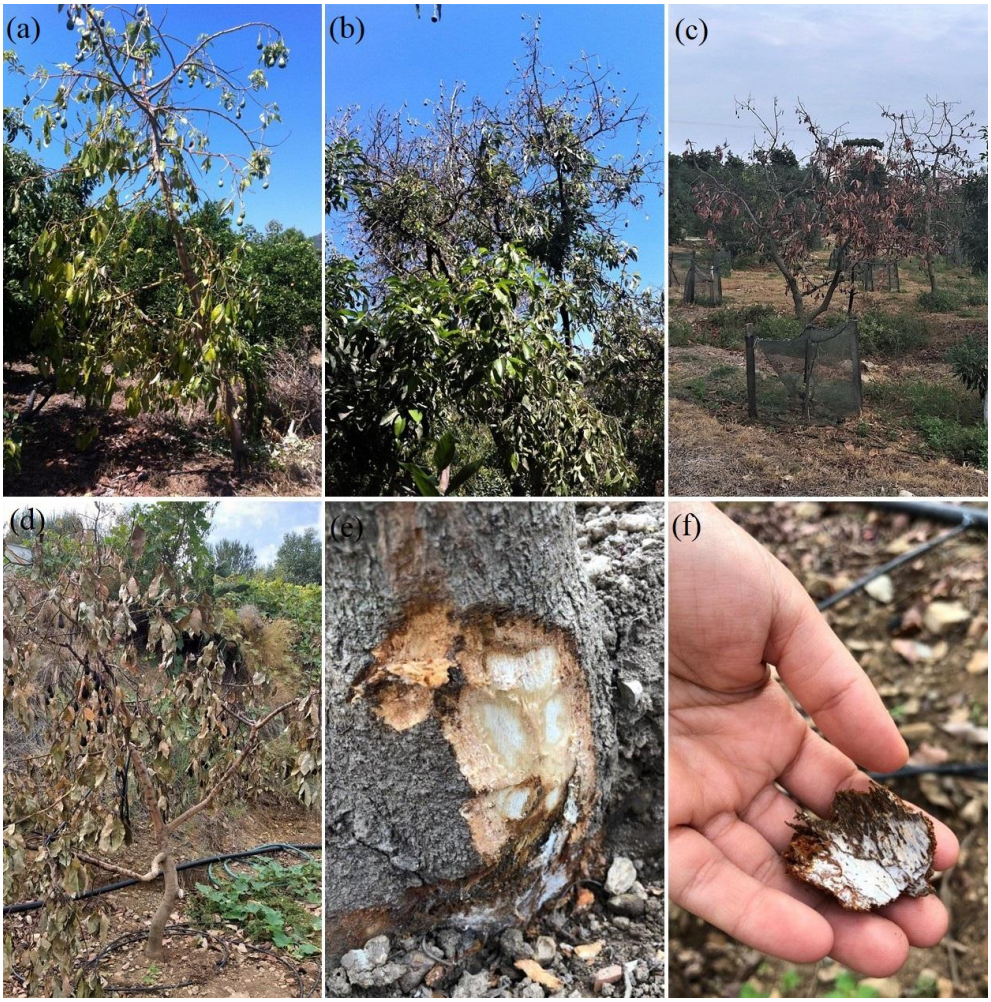

Figure 2. Wilting and defoliation (a); dieback (b); and decline (c) symptoms of *Phytophthora* spp; decline symptom (d) and fan shaped mycelium of *Armillaria* sp. (e-f) on avocado trees.

Necrotic roots of symptomatic avocado trees were washed in running tap water and air-dried. Small pieces of tissue, 3 – 5 mm^3 were excised from the lesion margins from taproots, fine roots and stem bases and placed onto PARP semi selective medium (Jeffers & Martin, 1986) without further surface sterilisation (Fig. 3). Cultures were incubated at 20–22°C in the dark and any hyphal growth emerging examined after 2–3 days under a light microscope. Single hyphal tips of emerging colonies with coenocytic hyphae having wide branching angles were excised and transferred to carrot juice agar (CA: 200 ml boiled carrot juice, 800 ml distilled water, 20 g agar) or V8 juice agar (200 ml clarified V8 juice, 800 ml distilled water, 20 g agar) to obtain pure cultures.

Soil samples were taken 1–1.5 m from stem bases at a depth of 10–30 cm beneath the soil organic horizon. Soil was not used in isolation attempts when at least one isolate of *Phytophthora* sp. was obtained from the root or collar tissues of a tree. Approximately 500 mL of each soil sample was flooded with distilled water. The organic material floating on the water surface was removed with cheesecloth. Young leaves of avocado cv. Topa Topa were floated on the water as baits and the traps maintained at room temperature. Leaves on which dark or brownish lesions appeared after 3–5

days at 22–24°C were cut into small segments (5 mm^2) and placed onto PARP medium (Fig. 3). Cultures were incubated and subcultured as described above.

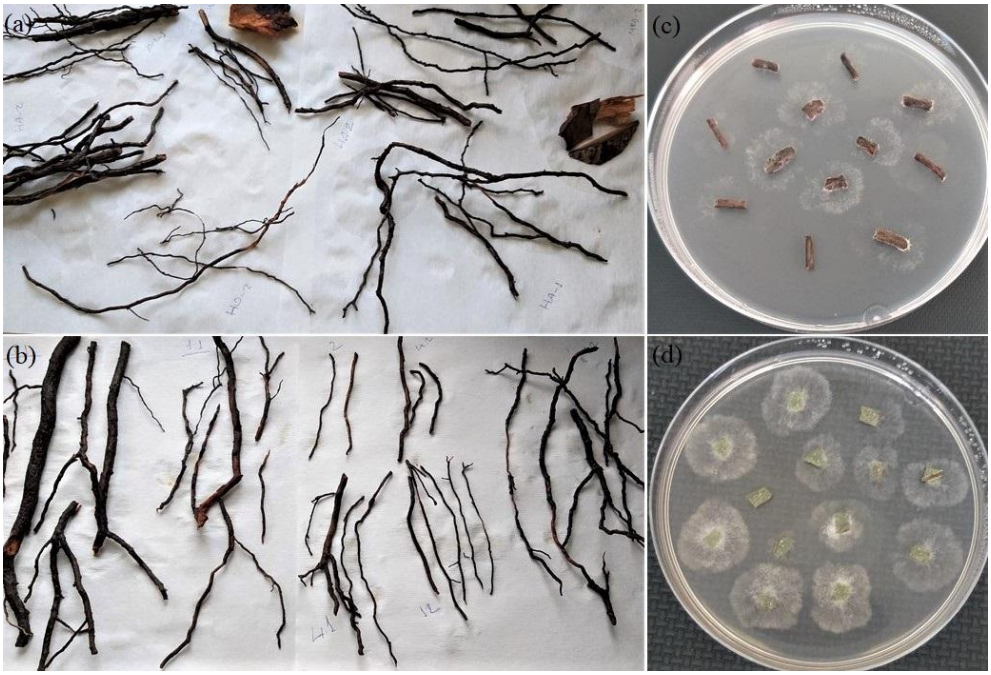

Figure 3. Necrotic root tissues obtained from avocado trees (a-b); *Phytophthora* isolations from root pieces (c) and leaflets in bait (d).

Identification of Phytophthora *spp. and* Armillaria *sp.*

Isolates of *Phytophthora* spp. were identified on the basis of morphological characteristics and by molecular analysis of the ITS region of the rDNA. Morphological identification was based on colony morphology, and microscopic structures such as hyphal swellings, chlamydospores and morphological features of sporangia (Erwin & Ribeiro, 1996; Gallegly & Hong, 2008). When half the surface of CA or V8 juice agar in Petri dishes was covered by a colony, 5-mm-diameter agar disks were cut from the growing edge were placed in 6-cm-diameter Petri dishes previously flooded with 7 ml rain water to induce the formation of sporangia. Colony morphology was described on CA, CMA, malt extract agar (MEA), potato dextrose agar (PDA) and V8A. The ability of the isolates to grow at 35°C was determined on CA and PDA after incubation for 5 days.

Morphological identification was confirmed by ITS sequences of rDNA. Internal transcribed spacer (ITS) regions of ribosomal DNA (rDNA) of 6 isolates of *Phytophthora* spp. were amplified using the universal primer pairs ITS-6 (5'-GAAGGTGAAGTCGTAACAAGG-3') and ITS-4 (5'-TCCTCCGCTTATTGATATGC-3'); for the single isolate of *Armillaria* sp., ITS-1 (5'-TCCGTAGGTGAACCTGCGG-3') and ITS-4 (5'-TCCTCCGCTTATTGATATGC-3') were used. In addition, the translational elongation factor 1-α (EF 1-α) gene region of an isolate of *Armillaria* sp. was amplified using primers EF595F (5'-CGTGACTTCATCAAGAACATG-3') and EF1160R

(5'-CCGATCTTGTAGACGTCCTG-3') (Maphosa et al., 2006). Mycelium of *Armillaria* sp. used in this work was taken directly from wood tissues.

PCR products were separated in 2% agarose gels, stained with safe DNA dye and visualized under UV light. Sequence analysis was carried out by GENOKS (Ankara, Turkey). Sequences were subjected to BLAST searches on GenBank (http://www.ncbi.nlm.nih.gov) to find the closest matches.

For phylogenetic analysis, the sequences generated in this study (ITS) were supplemented with additional sequences of *P. cinnamomi, P. cryptogea, P. palmivora* and *A. gallica* obtained from GenBank (Table 1). Evolutionary history of the isolates was inferred using the Neighbor-Joining method (Saitou & Nei, 1987). Evolutionary distances were computed using the Maximum Composite Likelihood method (Tamura et al., 2004) and presented in units of the number of base substitutions per site. Evolutionary analyses were conducted in MEGA7 (Kumar et al., 2016).

Table 1. Accession numbers of isolates obtained from GenBank used in construction of phylogenetic trees.

Species	Culture accesion No.	GenBank accession
P. cinnamomi	Pc06Bb	MN960453
P. cinnamomi	PN2035	MH236250
P. cinnamomi	508435	MN135945
P. cinnamomi	TARI 94006	GU111594
P. cinnamomi	AR-1	MH777152
P. cinnamomi	133	KP070662
P. cinnamomi	1873	KU961906
P. cinnamomi	CMW33386	GU799635
P. cryptogea	Carrai7II	KP070719
P. cryptogea	9	MG712918
P. cryptogea	PC01	MH401205
P. cryptogea	1072	EU200283
P. palmivora	CPR22	KU308392
P. palmivora	PPG8	KY475630
P. palmivora	Pp43-Wera-leaf	KP183963
P. palmivora	176PC	HQ237479

Pathogenicity tests

Pathogenicity of four isolates of *P. cinnamomi* and one isolate each of *P. cryptogea* and *P. palmivora* was tested by stem inoculation on avocado seedlings. Five one-year-old avocado seedlings cv. Topa Topa for each isolate were inoculated with 4-mm agar plugs from five-day-old cultures grown on V8A. Five seedlings were inoculated with sterile agar plugs as controls. All inoculations were sealed with moist, autoclaved cotton wool and wrapped in aluminum foil to prevent drying. Plants were kept in a greenhouse at 18–20±1°C and watered as required. Four weeks after inoculation, the outer bark was removed and canker lesions measured. Symptomatic tissue was excised from the margin of the canker and plated onto PARP to re-isolate the pathogen. Canker lengths on stems were subjected to analysis of variance (ANOVA), based on a completely randomized design, and means separated using the Tukey Test.

3 Results

Isolation and identification

Nineteen *Phytophthora* isolates were obtained from necrotic root tissues of 11 symptomatic trees and 8 soil samples. All but 4 orchards surveyed were found to be infested with *Phytophthora* spp. (82.6%). Based on cultural, morphological and molecular characteristics, isolates were identified as *P. cinnamomi* (17 isolates), *P. cryptogea* (1) and *P. palmivora* (1) (Table 2; Fig. 4). *Armillaria gallica* was isolated from the single symptomatic tree in an orchard in Anamur district of Mersin province, which had a mycelial sheath under the bark of the lower stem; *P. cinnamomi* was isolated from the soil in this same orchard. ITS (MT229426) and EF 1-α (MT239054) sequences of the *A. gallica* isolate, and r DNA ITS sequences of 6 *Phytophthora* spp. isolates (MH219917–MH219918, and MN833031–MN833034) were loaded into GenBank. The phylogenetic tree obtained using ITS sequences of *Phytophthora* spp. obtained in the present study and sequences deposited in GenBank is shown in Figure 5.

Table 2. Morphological and cultural characteristics of *Phytophthora* isolates obtained from avocado orchards in Turkey.

	P. cinnamomi	***P. cryptogea***	***P. palmivora***
Sexuality	Heterothallic	Heterothallic	Heterothallic
Sporangia			
Shape	Mostly ovoid, rarely ellipsoid and obpyriform	Usually ovoid and obpyriform, rarely ellipsoid	Mostly ovoid, rarely obpyriform
Papillae	No	No	Yes
Total range (µm)	44.3–82.5 x 32.4–45.7	42.8–62.0 x 28.3–38.7	38.8–57.9 x 28.5–42.4
Length/breadth mean (µm)	52.3 x 36.6	50.9 x 32.4	48.1 x 33.5
Length/breath ratio	1.43	1.57	1.44
Internal proliferation and nesting	No	Yes	No
Caducity	Non-caducous	Non-caducous	Caducous with short pedicel
Chlamydospore	Yes	No	Yes
Maximum temperature growth	<35°C	<35°C	<35°C
Colony pattern	Rosette on PDA	Petaloid on CMA and MEA	No

The most commonly isolated species was *P. cinnamomi*, found in 17 orchards, whereas *P. cryptogea* and *P. palmivora* were obtained from two other orchards. *Armillaria gallica* was detected in only one tree. *Phytophthora palmivora* was isolated only from soil, and *P. cryptogea* only from roots, while *P. cinnamomi* was isolated from both necrotic root and stem tissues, and from soil samples.

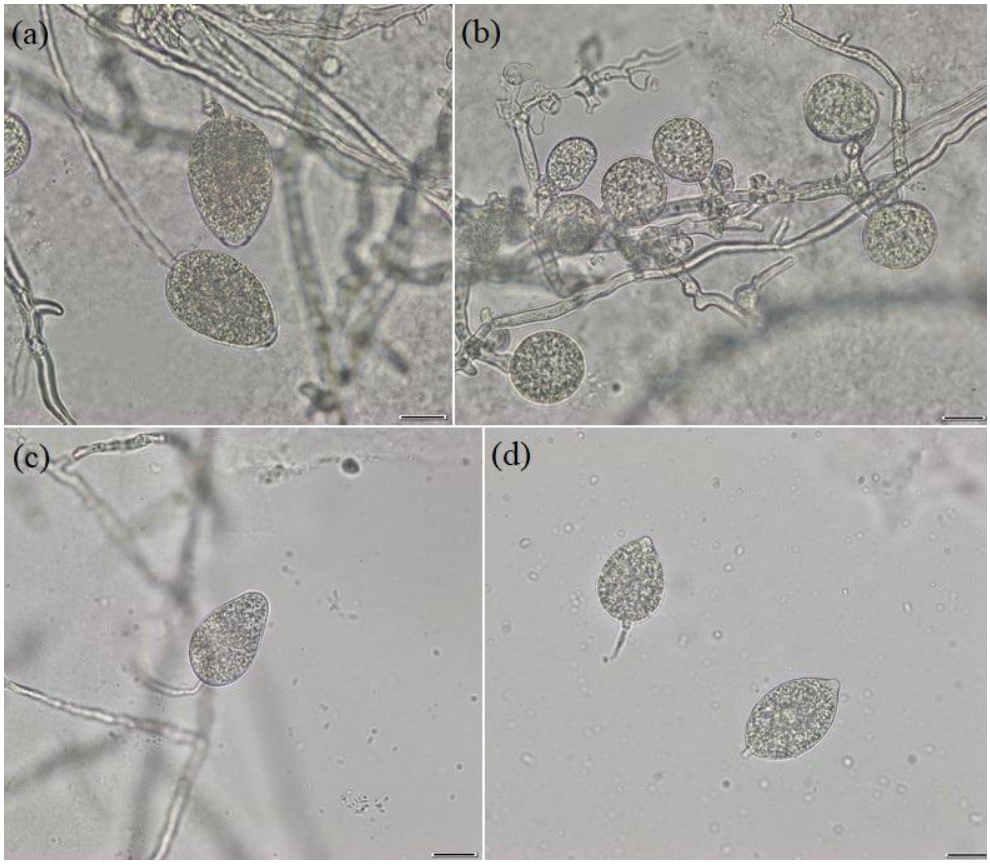

Figure 4. Sporangia (a) and chlamydospores (b) of *Phytophthora cinnamomi*; sporangia of *Phytophthora cryptogea* (c) and *Phytophthora palmivora* (d).

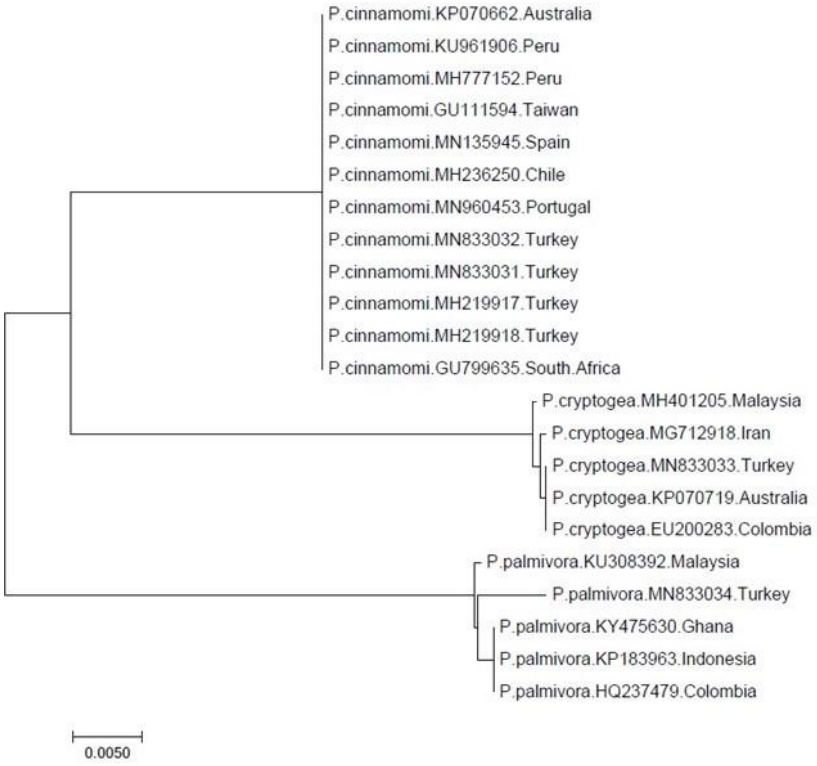

Figure 5. Dendrogram showing genetic relatedness of *P. cinnamomi* (4 isolates), *P. cryptogea* (1 isolate) and *P. palmivora* (1 isolate) isolated from roots of avocado planted in the south of Turkey, compared against sequences of eight isolates of *P. cinnamomi*, four isolates of *P. cryptogea* and four isolates of *P. palmivora* from GenBank (Table 1).

Pathogenicity test

Lesions between 1.4 – 5.4 cm in length appeared on stems inoculated with *Phytophthora* spp. (Table 3). In contrast, collenchyma callus of healthy appearance was produced over wound points over the same time period on control plants (Fig. 6). The inoculated *Phytophthora* spp. were re-isolated from symptomatic tissues. Lesion lengths were found to be significantly different ($P<0.05$) (Table 3). Data showed that *P. cryptogea* and three isolates of *P. cinnamomi* were in the same group, whereas *P. palmivora* and one isolate of *P. cinnamomi* were in a separate group.

Table 3. Stem canker length averages of seedlings inoculated with six isolates of *Phytophthora* spp. obtained from avocado orchards in Turkey

Isolate	GenBank accession	Min-max necrosis length (cm)	Necrosis length averages (cm)	
P. cryptogea	MN833033	3.5 – 5.4	4.32	A*
P. cinnamomi	MN833031	2.2 – 4.5	3.74	AB
P. cinnamomi	MH219918	2.5 – 4.1	3.42	ABC
P. cinnamomi	MH219917	2.2 – 4.5	3.32	ABC
P. cinnamomi	MN833032	1.7 – 3.4	2.62	BC
P. palmivora	MN833034	1.4 – 2.5	2.14	C

CV (%)=0.24; R^2=0.52

*Means followed by the same letter are not statistically different according to Tukey test (P≤0.05)

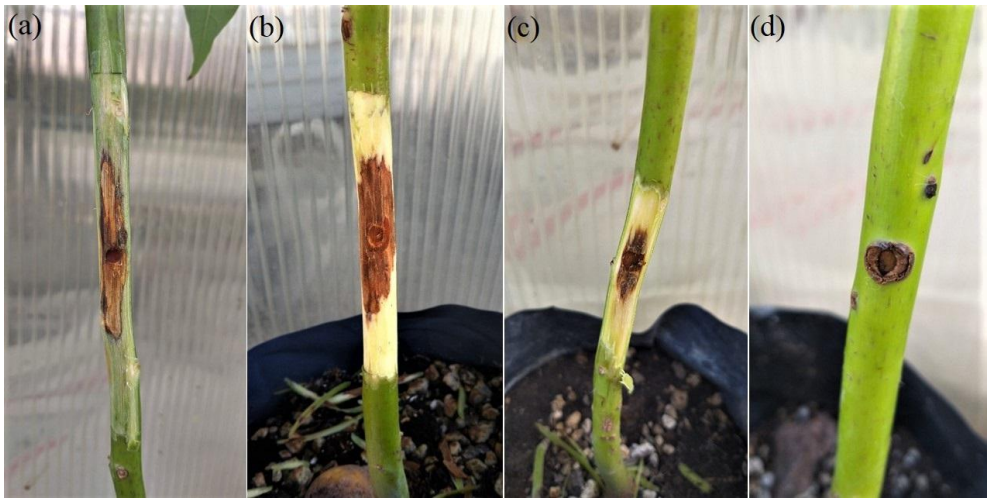

Figure 6. Stem inoculation test: lesions caused on avocado plants by *Phytophthora cryptogea* (a), *P. cinnamomi* (b), *P. palmivora* (c) and no lesion on control (d).

4 Discussion

This paper presents the first report of *P. cinnamomi, P. cryptogea* and *P. palmivora* causing avocado root rot in Turkey. It is a widespread disease in southern Turkey, such that at least one of the *Phytophthora* spp. was isolated from all but four of the avocado orchards surveyed. It is not surprising that *P. cinnamomi* was the most frequently isolated species. It is known that *P. cinnamomi* is the most destructive and widely distributed pathogen of avocados (Zentmyer, 1980; Coffey, 1992; Erwin & Ribeiro, 1996; Ploetz et al., 2002; Rodriguez-Padron et al., 2018). The fact that *P. cinnamomi* is the main species responsible for one the most severe plant disease epidemics

known, dieback of jarrah (*Eucalyptus marginata*) dominated forests in Western Australia clear demonstrate the exceptionally destructive nature of this pathogen (Podger, 1972; Shea et al., 1983; Erwin & Ribeiro, 1996).

Although *Phytophthora cinnamomi* was first found in Papua New Guinea (ref?), it is considered highly adaptable and certainly causes major problems in warm temperate climates (Crandall et al., 1945; Zentmyer, 1980; CABI, 1991; Balci et al., 2007). Extensive work in American oak forests occurring above the 40ºN latitude failed to find *P. cinnamomi* in soils (Balci et al., 2007). Cold winter temperatures are unfavorable climatic condition its survival (Zentmyer, 1980; Brasier & Scott, 1994; Balci & Halmschlager, 2003). Similarly, *P. cinnamomi* was obtained from various Turkish coastal regions with temperate climates. For instance, it was isolated from rhizosphere soil in oak forests (Balci & Halmschlager, 2003), and from soil around the roots of symptomatic chestnut trees (Akıllı et al., 2012, 2019) in temperate regions of Turkey. In addition, *P. cinnamomi* caused root rot of walnut (Kurbetli, 2013) and Protea spp. (Tok & Avcı, 2015) in subtropical parts of Turkey.

This work showed that, in addition to *P. cinnamomi,* other *Phytophthora* species such as *P. cryptogea* and *P. palmivora,* are also present in avocado orchards in Turkey although these species appear to be less widespread. *Phytophthora cryptogea*, one of the first *Phytophthora* species identified, has a very wide range of hosts (Erwin and Ribeiro, 1996), is reported for the first time associated with avocado in this work, although it was previously reported in orchards of several fruits, including apple, kiwifruit and sweet cherry in Turkey (Kurbetli & Değirmenci, 2011; Kurbetli & Ozan, 2013; Kurbetli, 2014). It may be widespread in fruit orchards in Turkey, but it was found in only one avocado orchard in this study.

The *Phytophthora* isolates obtained from avocados here produced extending lesions on stems of avocado seedlings, but it was surprising that the stem cankers caused by *P. cinnamomi* did not progress as expected. Lesion lengths on plants inoculated with *P. cinnamomi* were not significantly different from those caused by *P. cryptogea*. Some *Phytophthora* species, such as *P. quercina*, were not effective in causing stem lesions of oak in pathogenicity tests (Balci and Halmschlager, 2003; Bianco et al. 2003). Similarly, *Phytophthora megasperma* isolated from kiwifruit, almond and sour cherry failed to cause cankers in stem inoculations on the same hosts (Kurbetli & Ozan, 2013; Kurbetli et al., 2016, 2017). These species were highly pathogenic, however, when inoculated onto root systems of oak, almond and sour cherry plants (Jung et al., 1999; Kurbetli et al., 2016, 2017). Had root inoculations been carried out in the present work, it is possible that *P. cinnamomi* would have proved to be much more aggressive than *P. cryptogea* or *P. palmivora* on avocado.

Phytophthora palmivora was the least pathogenic species in this work although Rodriguez-Padron et al. (2018) reported that it showed high pathogenicity in stem inoculations on avocado.

It was interesting that the fan-shaped mycelium observed on the lower stem of a symptomatic tree in an orchard infested with *P. cinnamomi* was of *Armillaria gallica* identified by both ITS and EF-1α sequences. Compared to rDNA sequences, the EF-1α gene appears to better resolve closely related *Armillaria* species, such as *A. gallica* and other related species, and this gene presents a valuable diagnostic tool for the genus (Maphosa et al., 2006; Hasegawa et al., 2010; Klopfenstein et al., 2017; Heinzelmann et al., 2019). *Armillaria gallica* behaves as a saprotroph or rarely as an opportunistic pathogen (Tsykun et al., 2012; Heinzelmann et al., 2019). It is known that certain symptoms, such as necrotic collar lesions at the stem base of ash (*Fraxinus* spp.) caused by *Hymenoscyphus fraxineus* may be secondarily invaded by *Armillaria* species, which can further reduce host health and accelerate decline (Husson et al., 2012; Chandelier et al., 2016; Marçais et al., 2016; Enderle et al., 2017).

This study has increased knowledge of *Phytophthora* species associated with avocado crops, with the first report of *P. cryptogea* from avocado, and the isolation of the previously described avocado pathogens *P. cinnamomi* and *P. palmivora*. However, further investigation is required to clarify the involvement of *Armillaria* and *Phytophthora* species other than *P. cinnamomi* in avocado decline in Turkey.

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