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RESEARCH

Within orchard spatial distribution of mature avocado trees mortality

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Abstract The growth and development of mature, fruit bearing, avocado trees in Menashe Heights region of Israel was retarded from the late-2000s. As time passed the trees decayed gradually, leaves dropped off and eventually the trees died. This process usually spanned 2 to 4 years. The objectives of the study were to: (i) map the spatial distribution of symptomatic avocado trees, (ii) evaluate the potential role of topography in contributing to tree mortality, and (iii) estimate the extent of the tree mortality phenomena in the orchards. On April 2020 we mapped eight sub-units of avocado orchards. In each sub-unit we recorded the state of each tree. We estimated the topographic elevation of each tree using a digital elevation model (DEM). The relationship between the topographic elevation of the trees and the incidence of damaged trees were calculated using a logistic regression. Analysis of the spatial distribution of declining and dying trees reveled that they were not randomly distributed in the orchard and were more abundant in the lower zones of the orchards. Close observations of these zones revealed that the soil in these areas was soaked with water during the winter. Accordingly, we hypothesize that due to limited oxygen supply, root growth and water uptake were impaired, resulting in a negative feedback loop that increases soil water content, reduces aeration, and impairs roots' ability to absorb oxygen. Such conditions could make the roots more susceptible to soil-borne fungi that had damaged the roots of trees, causing them to deteriorate and eventually die.

Keywords Abiotic stresses · Climate change · Excess water · Pathology · *Persea Americana*

Introduction

Avocado (*Persea americana* Mill. family Lauraceae) is the fastest growing crop in Israel (with annual growth of about 10%) in the last decade and currently it is cultivated in an area of approximately 10,000 ha. One of the avocado production areas is the Menashe Heights region. The current production area in that region is relatively small (about 200 ha in total) but since this region is suitable for avocado production (temperate temperatures and annual precipitation of 625 mm), the cultivated area is planned to tripled in the next few years. From the late-2000s avocado growers in Menashe Heights region observed that the growth and development of mature, fruit bearing

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trees was retarded. As time passed tree growth rate declined gradually, leaves dropped off and eventually the trees died. This process usually spanned 2 to 4 years. At first the phenomenon was limited to individual trees in few orchards but in recent years the extent of the problem increased and today it has expanded to many orchards throughout the region. In the last decade, about 40% of the orchards in this region were uprooted and replanted because of this phenomenon and today about 15% of the trees show various levels of decline growth rate. Examination of the rooting system of symptomatic trees revealed that the roots were severely impaired. Their biomass was markedly reduced as compared to near-by asymptomatic trees and the few roots that remained bare brown to black sunken lesions which coalesce to destroy the roots.

Tree decline can result from abiotic factors, such as excess water, which may result conditions of anoxia in the root zone (Yalin et al., 2017) or from biotic factors, such as soil borne fungi. Root rot of avocado trees, the cause of avocado tree decline, may result from soil borne pathogens including: *Rosellinia necatrix* (Pérez-Bueno et al., 2019), *Phytophthora cinnamomi* (Kurbetli et al., 2020), *Fusarium* spp. (Olalde-Lira et al., 2020), *Verticillium albo-atrum*, *V. dahlia* (Ramírez-Gil & Morales-Osorio, 2021) and *Macrophomina* sp. (Shu et al., 2019). Avocado tree decline may also result by fungi that are not associated with root damage, such as species that belong to the Botryosphaeriaceae family (i.e. *Lasiodiplodia* spp., *Neofusicoccum* spp., *Diplodia mutila* and other) (Rodríguez-Gálvez et al., 2021). At different times of the year, roots from symptomatic trees were sent to the Israeli Plant Protection and Inspection Service (IPPIS) for diagnosis and identification of injurious pests. Although no *P. cinnamomi*, Rosellinia spp. or Verticillium spp. could be detected, the results revealed that the roots were colonized by Cylindrocarpon spp., Fusarium spp., Botryosphaeria spp. and Macrophomina spp. *Cylindrocarpon* is part of the nectriaceous fungi (Nectriaceae, Hypocreales).

The long term goal of the study was to identify potential cause(s) of the declining and dying of mature avocado trees in Menashe Heights region. The underlying hypothesis was that excess of water is the driving force for trees mortality either by the anoxia condition in the root zone or by weakening the natural resistance of the avocado trees and predispose soil borne fungi that had colonized their roots. The specific objectives of the current study were to: (i) map the spatial distribution of symptomatic avocado trees in Menashe Heights orchards, (ii) evaluate the potential role of topography in contributing to tree mortality, and (iii) estimate the extent of the tree mortality phenomena in the orchards.

Material and methods

The study area

Menashe Heights region is located in the north-west part of the country close to the Carmel Mountains, about twenty km from the Mediterranean Sea (Fig. 1). This is a relatively hilly region (150 to 300 m above sea level) and avocado orchards are located on the hill-tops, slopes of the hills and in the valleys between hills. Differences in altitude within one orchard commonly exceed 30 m. The soil is shallow, ranging from 30 to 50 cm overlying limestone bedrock. It has a clay texture with 60% clay, 18% silt and 22% sand particle distribution. Saturated paste solution of the soil has pH of 6.9 ± 0.2 and electrical conductivity of 0.8 ± 0.2 dS/m. The soil is poorly drained and, under conditions of excess water, prone to conditions of anoxia in the root zone.

The main avocado cultivar grown in Menashe Heights region is Hass, but cvs. Reed and Ettinger are grown as well. The rootstock are Degania 117, Degania 3 and Fairchild. Trees are spaced 4 m within rows and 7 m between rows. Trees in all orchards are irrigated with fresh water periodically in quantities defined by daily evapotranspiration measurements. Fertilization is applied via the irrigation water as recommended to avocado growers in Israel. The current study was performed in avocado orchards located in the center of Menashe Heights region in two collective farmes (Kibbutzim): Ramat Hashofet and Ramot Menashe. Avocado orchards in these Kibbutzim are divided into small sub-units off which we sampled eight sub-units, four in Kibbutz Ramat Hashofet and four in Kibbutz Ramot Menashe (Fig. 1). These sub-units will be identified here after as RH1 to RH4 and RM1 to RM4. The total number of trees in the eight avocado sub-units ranged from 329 to 1423.

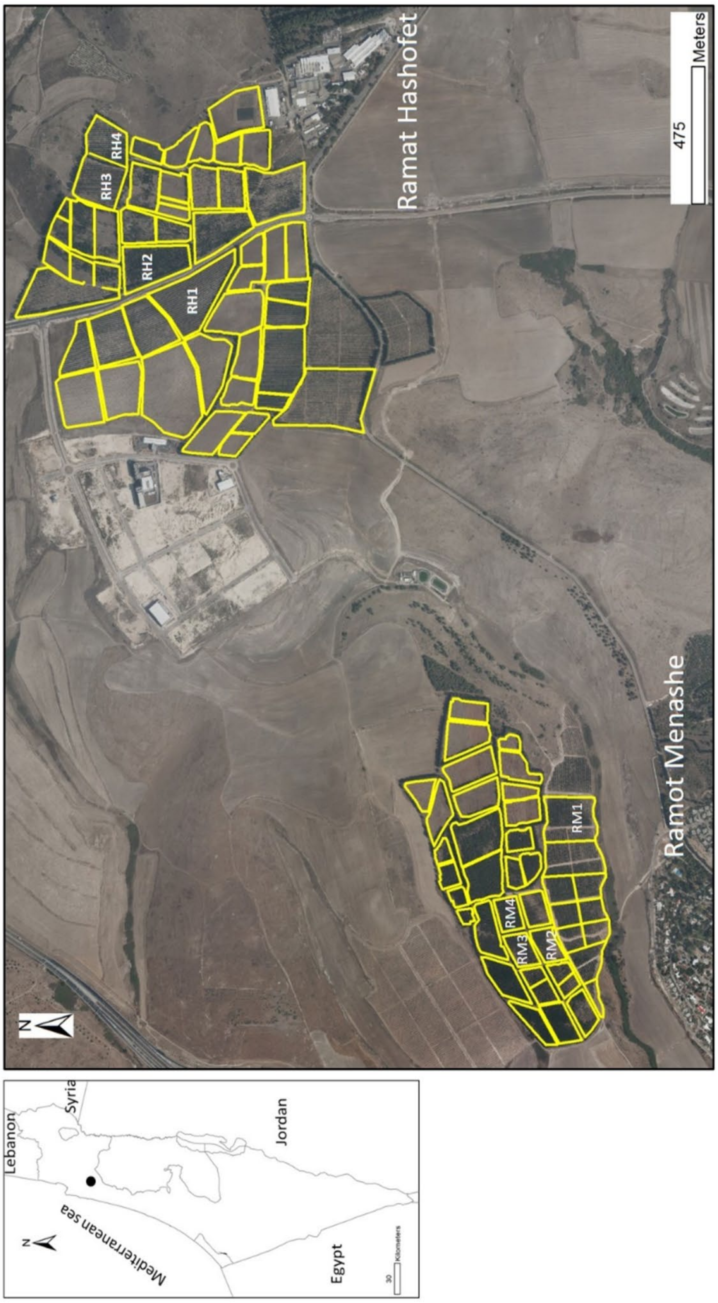

Fig. 1 The study area location demarcated with blank point (left) and the locations of the eight studied orchards (right)

Spatial distribution of symptomatic avocado trees in Menashe Heights region

On April 2020 we mapped eight sub-units of avocado orchards in Menashe Heights region (Fig. 1). In each sub-unit we recorded the state of each tree using a 5 level scale (Table 1). As these were commercial orchards and growers attempted to cope with the phenomenon, some of the affected trees were severely pruned prior to our assessment. Some of these trees remained damaged but in others growth was resumed, new shoots developed and the leaves were dark green. These trees were classified in category 4 since they were severely damaged before pruning. In this study, we refer to trees in categories 3, 4 and 5 as "damaged trees". According to the growers, all uprooted trees in the sampled orchards suffered from the phenomenon described above, and they were uprooted because their growth was deteriorated or because they had died.

To determine if the damaged trees were indeed scattered in the lower zones of the orchards, we estimated the topographic elevation of each tree using a digital elevation model (DEM, obtained from the Survey of Israel) with a resolution of 33×33 m using ArcGIS 10.5 (ESRI, Redlands, CA, USA). Then, we calculated the incidence of damaged trees at each topographic elevation, as: $DIi = Di / Ni \times 100$, where, DIi is damage incidence (%) in topographic elevation i, Di is the number of damaged trees in topographic elevation i, and Ni is the number of trees in topographic elevation i. Data were used to calculate the relationship between the incidence of damaged trees (DIi, the dependent variable; in %) and topographic elevation (i; independent variable; in m above sea level) for each of the orchards sampled. A logistic regression equation was fitted to the data and a P value was calculated using the SigmaPlot software (Systat Software Inc., USA):

$$Y = a/\left(1 + \exp\hat{}\left(-\left(X - X_o\right)/b\right)\right)$$

where Y is the damage incidence (%) in topographic elevation i; a is the asymptote; X_o is the inflection point of the curve and b is the slope of the tangent line at the infection point.

Results

Spatial distribution of symptomatic avocado trees in Menashe Heights region

The incidence of damaged trees varied as well, ranging from 0.6% and 87% (mean ± standard deviation: 41.6 ± 31.9%) (Fig. 2). Seven of the orchards were located in slops of hills and the differences in topographic elevation between the lower and upper parts of the orchards ranged from 5 to 25 m (mean ± standard deviation: 14.6 ± 7.6%). In each of these orchards, the incidence of damaged trees in the lower zone (mean ± standard deviation: 81.1 ± 15.0%) was significantly higher ($P < 0.0001$) than the incidence of damaged trees in the higher zone (mean ± standard deviation: 22.6 ± 19.8%), as determined by the χ^2 test. The correlation coefficients of the relationships between the incidence of damages trees and the topographical elevation exceeded 0.6 in six of the orchards and was significant in four (Table 2 and Fig. 3). In sub-unit RH4 the difference in topographic elevation between the lower and upper zones of the orchard was only 2 m, the incidence of damaged trees was low and there was no relationship between the

Table 1 The rank scale used to visually classify the severity of symptoms of each surveyed tree

Description	Rank
Asymptomatic trees: trees with abundant new growth and normal dark green leaves	0
Initial damage: trees lacking new growth, but there was no apparent leaf shedding and the contacted leaves had dark green color	1
Intermittent damage: leaf shedding was noticeable and the color of some of the leaves was light green	2
Moderate damage: significant leaf shedding, lateral shoots became completely shed, most leaves were light green	3
Severe damage: retarded growth, most branches lost their leaves, detached leaves turn yellow	4
Dead or uprooted tree	5

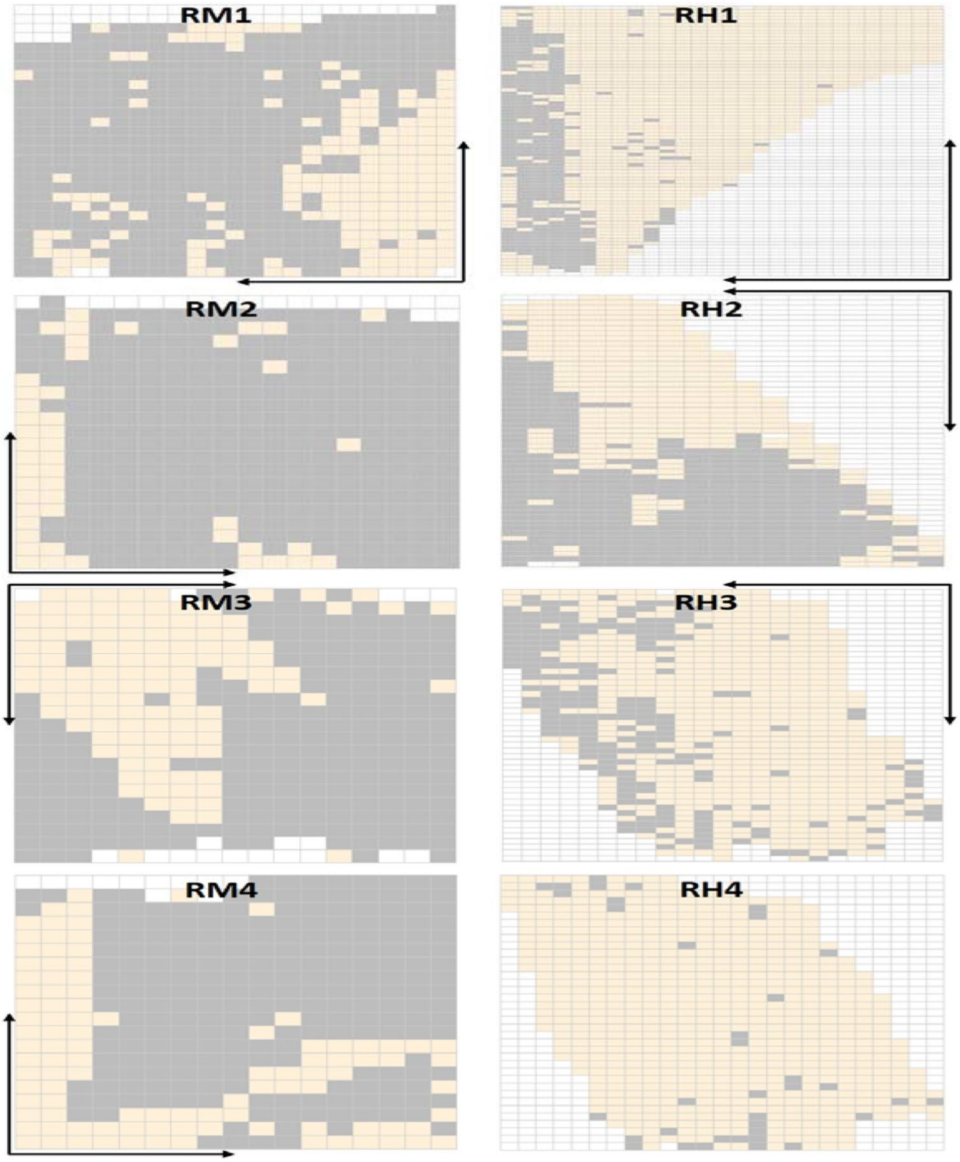

Fig. 2 The distribution of damaged trees in the eight orchards. Each tile denote either a damaged tree (gray) or not damaged tree (yellow). White tiles denote absent trees. Black arrows denote the direction of the slope in the sub-unit of the orchard

incidence of damages trees and the topographical elevation (Table 2 and Fig. 3).

Discussion

The spatial analyses showed that declining and dying avocado trees in Menashe Heights was not randomly distributed in the orchard as declining and dying trees were more abundant in the lower zones of the orchards. Close observations of these zones revealed that the soil in these areas was soaked with water during the winter (Fig. 4). In orchards situated on slopes, water tend to accumulate at the bottom of the slope. This is where the soil is the deepest and has the greatest moisture reserve. Soils in the Menashe Heights region are poorly drained clayey soils and under situations of excess water, prone

Table 2 The total number of trees, the incidence of damaged trees and the topographical elevation in the eight orchards in Menashe Heights region

Kibbutz	orchard code	No. of trees	Incidence of damaged trees (%)			Correlation coefficient (R^2)[b]
			Lower zone	Upper zone[a]	Average	
Ramot Menashe	RM1	620	80.6	42.1*	71	0.69*
	RM2	358	100	41.2*	87	0.16
	RM3	339	83.3	0*	64	0.89*
	RM4	329	85.7	46.2*	7	0.78
Ramat Hashofet	RH1	1422	52.4	2.1*	21	0.63*
	RH2	620	74.9	18.8*	55	0.87
	RH3	785	100	3.1*	27	0.83*
	RH4	659	6.7	5.7	0.6	No relationship

[a] Significant difference ($P < 0.0001$) in the incidence of damaged trees between the lower and the upper parts of the orchards, as determined by the χ^2 test

[b] The correlation coefficients of the relationships between the incidence of damages trees and the topographical elevation. Asterisks denote for significant regression at $P < 0.005$

to conditions of anoxia in the root zone. Yalin et al. (2017) described the substantial role of oxygen deprivation in avocado grown in clayey soils irrigated with treated wastewater. The poor physiological functioning of the roots due to limited oxygen supply results in less root growth and lower water uptake, which in turn raises soil water content, reduces root-zone oxygen availability, and further hinders tree growth. Accumulations of ethylene and CO_2 further suppress or alter root growth and development. When saturation persists, anaerobic respiration occurs, and nitrite and the reduced forms of iron (Fe^{2+}) and manganese (Mn^{2+}) may accumulate to injurious levels. Eventually, hydrogen sulfide (H_2S) may also accumulate, killing plant roots (Evans & Fausey, 1999). Given these effects on plant root metabolism, plants tend to develop a smaller, more superficial rooting pattern in excess water (Zhang et al., 2004), which in turn has implications for nutrient demand and the plant's response when temperature raises later in the growing season (Jackson & Drew, 1984). The effects of excessive water conditions on membrane processes may also reduce the ability of plants to absorb inorganic nutrients (Barrett-Lennard, 2003). Growers at Menashe Heights have tried to reduce the irrigation quantity. The trees' decline ceased at first, but after some time the symptoms returned. Abiotic stresses pre-exposure can also increase host susceptibility to pathogens (Atkinson & Urwin, 2012). For example, a large majority of published studies referred to a positive association between drought and disease, i.e. disease favored by drought or drought and disease acting synergistically on tree health status. Canker/dieback diseases, caused by pathogens belonging to the genera *Botryosphaeria*, *Sphaeropsis*, *Cytospora* and *Biscognauxia* (*Hypoxylon*) are intensified after drought periods (Desprez-Loustau et al., 2006). Interactions with other abiotic stresses and species-specific and genetic effects, related to host or pathogen, have also been reported. Desprez-Loustau et al. (2006) reviewed 117 scientific articles on the subject, focusing on the mutual effects of different endophytic pathogens. In most of the studies where the pathogens caused cankers and tree mortality, the abiotic stress and the pathogens acted synergistically.

Avocado are cultivated in the Menashe Heights region since mid-1980s. One may wonder why the phenomenon of tree declining and dying was initiated only in the late-2010s. It might result from two gradual changes taking place over time, both related to the water condition of the trees. The first, changes in the frequency of substantial rain events. Whereas the annual rainfall quantity did not change much between 2001 and 2010 and 2011–2020 (606 and 655 mm/year on the average in these periods, respectively; $P = 0.266$), the number of substantial rain event (more than 50 mm of rain in one event) increased by 37.1% (3.5 and 4.8 events/year on the average; $P = 0.04$) (data from a weather station situated in Kibutz Ein Hashofet which is located inside

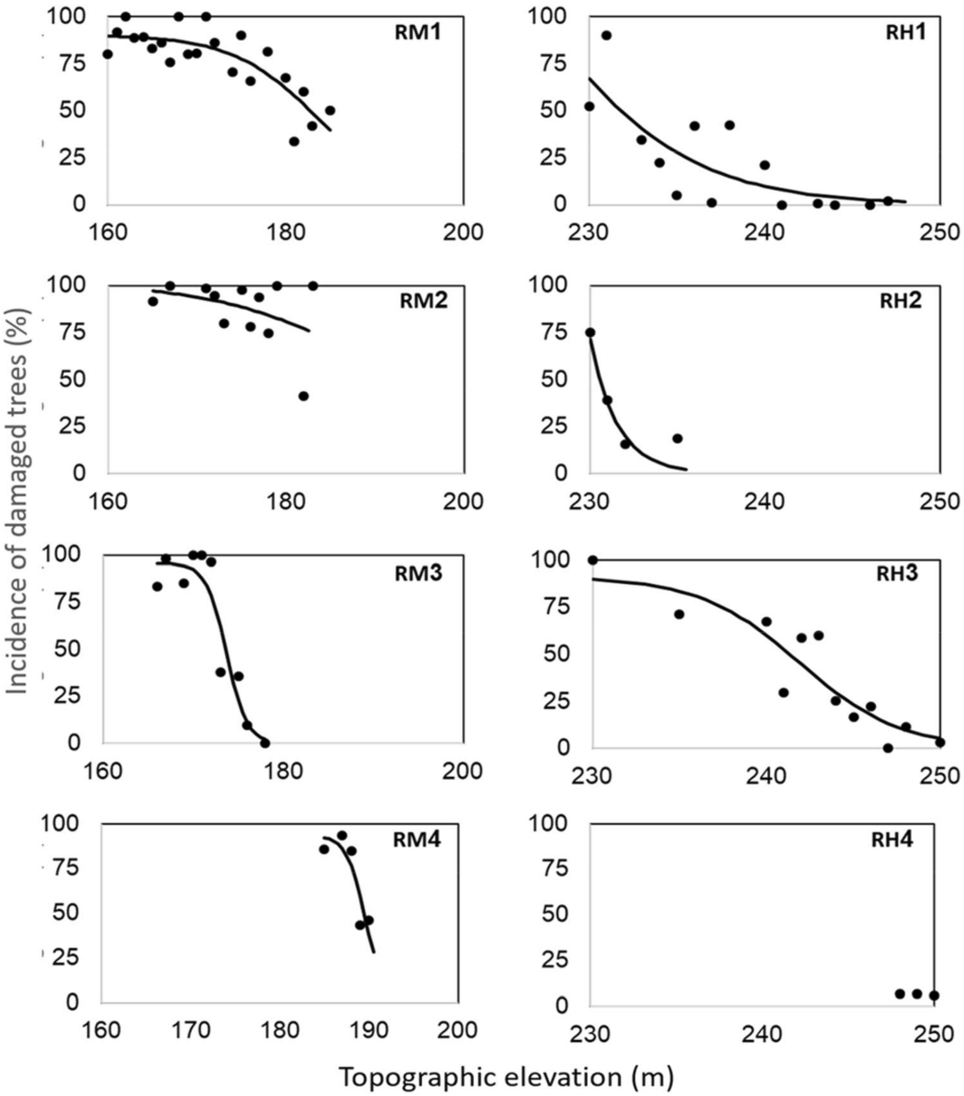

Fig. 3 The relationship between the topographic elevation of the trees and the incidence of damaged trees in eight avocado orchards in Menashe Heights region

the study area and operated by the Israeli Meteorological Service). This is part of a phenomenon that might be linked to climate change that reflects a change in the rainfall distributions and thus the tendency for increase in the number of heavy rainfall days during autumn and early winter (Alpert et al., 2008). The second, changes in irrigation practices. Whereas, mini-sprinklers installed beneath the tree canopies were used for irrigation before the early 2010s, by early-2010 growers shifted to drip irrigation. As time passed, drip irrigation became more and more common and currently is used in all orchards. In rainless periods, mini-sprinklers were used at frequency of 2–3 times a week enabling soil to dry between irrigations. However, drip irrigation is activated daily and the soil is kept moist continuously (Liao et al., 2008). As indicated above these two changes may have pose a negative effect on the roots and the development of the trees.

In conclusion, results of the study support the assumption that the phenomenon of avocado tree decline and death in Menashe Heights was caused by damage to the normal development of the rooting system by water excess accumulating at the lower areas

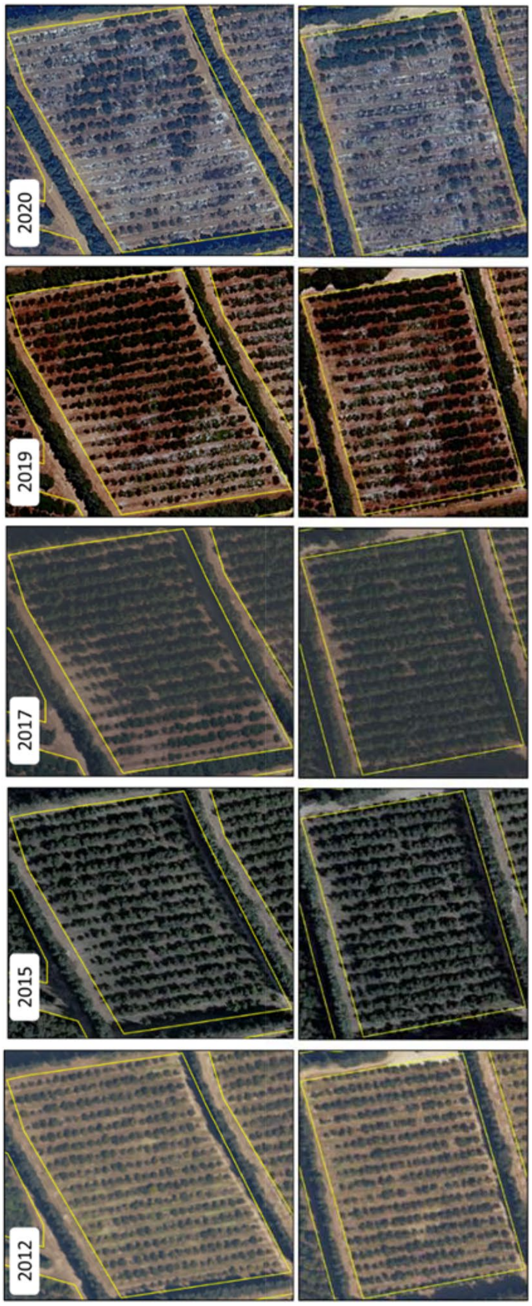

Fig. 4 Avocado tree decline and death in Menashe Heights demonstrated in two orchards, RM3 (upper photos) and RM4 (lower), from 2012 to 2020

of the orchards. This condition can lead to anoxia in the root zone resulting in damage to the roots or due to root rot by soil fungi thriving in the stressed trees (Bedard-Haughn, 2009).

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Authors' contributions Lior Blank, David Ezra and Dani Shtienberg conceived the ideas and supervised the study. Lior Blank, David Ezra, Helena Kasnov and Dani Shtienberg analyzed the data. Lior Blank, David Ezra and Dani Shtienberg wrote the initial draft of the manuscript. All authors contributed to the writing of the manuscript and approved the final version.

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Data availability Not applicable.

Declarations

Ethics approval and consent to participate All ethical aspects are considered.

Consent for publication The authors declare consent for publication.

Competing interests The authors declare that no competing interests exist.

Conflict of interest The authors have not found any potential conflicts of interest.

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