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Effects of Tuff and Compost Trenches on Some Physico-chemical Properties of a Clayey Soil Following Long-term Irrigation of an Almond Orchard with Secondary Treated Wastewater

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إهداء

أهدي رسالة الماجستير

إلى أطهر قلبين في حياتي... والديَّ العزيزين

إلى إخوتي.... سندي وعضدي ومشاطري
أفراحي وأحزاني

إلى جميع من تلقَّيتُ منهم النصح والدعم

أهديكم خلاصة جُهدي العلمي

إن إنهائي عملي لم يكن ليتم لولا دعمكم
وأتمنَّى أن ينال رضاكم

List of Abbreviations

FW	Fresh Water
TWW	Treated Wastewater
COM	Compost
TUF	Tuff
DOC	Dissolved Organic Carbon
TOC	Total Organic Carbon
SUVA	Specific Ultraviolet Absorbance
VWC	Volumetric Water Content
SAR	Sodium Adsorption Ratio
ESP	Exchangeable Sodium Percentage

Abstract

Long-term irrigation with treated wastewater (TWW) has been a major cause to a decrease in yields, especially in orchards planted on clayey soils. The possible reasons for the negative effects of TWW are their sodicity and salinity that lead to drastic changes occurring in soil chemical and physical properties. These changes reflect on the soil hydraulic conductivity and the osmotic potential which decreases the water percolation and limit plant water uptake, respectively. In turn, these changes reduce the oxygen capacity in the roots' zone, where the latter undergoes periods of oxygen shortage. Thus, impaired aeration in the root zone will consequently limit the roots respiration and adversely affect the root's and plants' growth.

Many studies investigated the effects of long- and short-term irrigation on clayey soils, yet only a few introduced the soilless media as agro-technical methods to cope with salinity, sodicity and aeration issues in orchards.

We hypothesized that introducing tuff and compost trenches to orchards grown in clayey soils and irrigated with TWW will (i) help the soil to sustain the soil properties in a way similar to that of orchards irrigated with FW, and (ii) improve the soil permeability to air and water by modifying the bulk density of the soil in addition to decreasing the sodium adsorption ratio (SAR) of the soil solution and soil exchangeable sodium percentage (ESP).

Based on that, the main research objective was to evaluate some chemo-physical soil properties following the use of different water qualities and the application of tuff and compost trenches (as agro-technical methods), introduced for mitigation of the build-up of high salinity and sodicity levels in clayey soils subjected to a long-term irrigation with secondary TWW. The specific objectives were to study the effects of the treatments on: (i) salinity, sodicity and DOM characteristics in the soil profile at the end of the irrigation and rainfall seasons, (ii) spatial distribution of salinity, sodicity and dissolved organic matter (DOM) characteristics around the drip line, (iii) aggregate stability in the soil profile and its spatial distribution at the end of the irrigation season, and (iv) dynamics of in situ soil water content and aeration.

For meeting the above-described objectives aeration trenches were installed along both sides of the trees' rows, in a commercial almond orchard, planted on a clayey soil (Grumusol) near the Sea of Galilee, Israel, and irrigated with TWW since 2013. The trenches, 30 cm deep and 25 cm wide,

were filled with either tuff or cattle manure compost. Thus, in the field we had four treatments: (i) and (ii) irrigation with TWW (TWW) and fresh water (FW), respectively without having trenches, (iii) and (iv) irrigation with TWW with having tuff (TUF) and compost trenches (COM), respectively. Each treatment had five replicas organized randomly in a block design. The orchard was irrigated with a trickle irrigation system, composed of two driplines along both sides of each tree row and placed on the soil surface, except for the compost treatment (COM), where the drip laterals were buried in the compost trenches at a 20 cm depth, to ensure homogeneous wetting and aeration of the compost trenches. The effect of the treatments (water quality and agro-technical methods) on soil properties, were examined by conducting some chemical and physical analyses of soil samples in the laboratory. Soil samples were collected following the irrigation and the rainy seasons (Fall and Spring, respectively) for two consecutive years (2018 and 2019), from two locations relative to the drippers (dripper- adjacent and between trees) and up to a depth of 90 cm. The chemical analysis of the soil samples included composition of the soil solution (EC, Cl, Na, Ca, Mg, K, DOC, and UV_{254}), while the physical analysis included measurements of soil aggregate stability (AS). Volumetric water content (VWC) and the oxygen content were monitored continuously by in-situ sensors, that were installed at a depth of 35 cm below the driplines. Additionally, VWC sensors were also installed between trees.

The results showed that soil profiles located between trees were, in most cases, only partially wetted out of the dripper’s wetting zone, therefore, for all the soil layers up to a depth of 90 cm, the salinity, sodicity and most of the ions concentrations were low. Additionally, those soil profiles were of high AS and DOM characteristics (DOC, UV_{254} and SUVA). Conversely, dripper adjacent soil profiles were generally of significantly higher salinity and sodicity, low DOM and AS, high VWC and limited aeration depending on the treatments type and depth. Additionally, pH and DOM were comparable for all the treatments at any given depth (up to 90 cm).

Soil samples that were collected following the rainy season (Spring), were of lower salinity indicators, and higher pH relative to soil samples collected in Fall, due to leaching by the rainfall. The sodicity indicators did not change much in the Spring, relative to soil samples collected in fall, because of the dilution of the soil solution by the rainfall, and reducing the concentrations of Ca+Mg, which exacerbates the effect of the adsorbed Na, especially when the soil is of low calcite content.

Following an irrigation season (Fall), dripper adjacent soil profiles, at a depth of 0-30 cm, were of significantly low salinity indicators in TUF and FW, while COM and TWW increased the salinity. In COM we suggested that the subsurface driplines in addition to the TWW quality to be the reason for the increased salinity. At this depth, SAR was completely dependent on the water quality, thus all treatments that were irrigated with TWW, were of significantly higher SAR than that of FW. At a depth of 30-60 cm, a trend was noted whereby the trenches treatments could mitigate the salinity, thus they were intermediate between FW and TWW, while TWW treatment was of significantly higher salinity than that of FW. Yet, the SAR was not affected by any treatment. Furthermore, at the bottom soil layers (60-90 cm), the treatments were comparable in most of the measured chemical parameters. That, despite the relatively high DOC in COM and the low Ca+Mg concentrations, a combination that is expected to lead to an increase in SAR.

Results of the AS analysis were controlled completely by the water quality treatments; thus, up to a depth of 60 cm, FW treatment was of significantly higher AS than that of all the treatments that were irrigated with TWW. While at a depth of 60-90 cm, all the treatments were comparable.

In an attempt to get an additional indication of the soil sodicity condition, we developed a modified USSL 1954 relationship, to estimate our soil's ESP. Our Gapon coefficient deviated by 38% from that of the USSL (0.009 vs 0.0145), leading to estimated ESP values of ~5. Since the estimation of ESP was based on the estimated SAR of the saturated soil paste, the dependence of the estimated ESP on the treatments was similar to that of SAR.

The measured values of AS at a depth of 0-30 cm, were inversely associated with the ESP at this depth, inasmuch as it was controlled by the water quality. Thus, treatments that were irrigated with TWW were of significantly lower AS and higher ESP than those of FW. Likewise, at 30-60 cm, the AS, again, was controlled by the water quality, but it could not be associated with the ESP at this depth, as similar to the SAR, the ESP was controlled by the trench type.

The moisture and oxygen content sensors were placed at a depth of 35 cm (5 cm under the trenches), the moisture sensors showed higher water contents for TWW and TUF, than for COM and FW. While the oxygen sensors showed a lower oxygen content for TWW than for the rest of the treatments. I suggest that the high salinity in TWW increased the osmotic potential in a way that it limited the plant water uptake. Therefore, a larger water content in the root zone in TWW treatment was expected, probably because of the poor hydraulic conductivity (HC) caused by impairing the soil AS. Moreover, the interpretation for the high water-content in the soil below the TUF trenches, can be related to the transition from a high HC in tuff to lower HC in the clayey soil under the trench. Additionally, the daily irrigation practice in the TUF treatment (opposed to the rest of the treatments) maintained higher water content in the soil usually, an inverse relationship exists between the water content and the oxygen content; thus, a higher water content leads to a lower oxygen content. However, in TUF this was not the case, whereby the oxygen sensors showed high oxygen content, despite the high water-content, which was ascribed to the close distance of the oxygen sensor to the tuff trench, which enhances the oxygen diffusion to the sensor's proximity. We noted that despite the deteriorated chemical and physical properties of COM (high sodicity and low AS up to a depth of 60 cm), this treatment was of optimal water uptake, and oxygen content. I assume that it can be ascribed to the well-developed root zone in the compost trench and probably to positive effect of the subsurface driplines. The reduction in oxygen levels in TWW were sharp, and the recovery took longer time than in the rest of the treatments, which I refer to limited plant water uptake and impaired hydraulic conductivity.

I conclude that enhancing the water quality from TWW to FW, reduced salinity, sodicity, increased AS, and provided optimal oxygen content due to enhanced water leaching and plant water uptake. TUF reduced salinity, similarly to FW, yet it did not mitigate sodicity at 0-30 cm. Additionally, it did not improve the soil AS. The soil under the tuff trench was of high VWC, yet of optimal aeration. COM was similar to TWW in salinity, sodicity indicators and AS. However, it provided enhanced plant water uptake and leaching (low VWC) and optimal oxygen content. All the above conclusions are related to dripper adjacent soil profiles, while no significant effect was observed in soil profiles between trees. DOM characteristics (DOC, UV and SUVA) were comparable for all the treatments, in dripper adjacent soil profiles and between trees, where in the latter, DOM was significantly higher than in dripper adjacent soil profiles. The effect of the rain was prominent and decreased the effect of TWW, excluding SAR and ESP which were not affected significantly by the rains. Opposed to our hypotheses, the compost trenches did not improve the physico-chemical properties of the clayey soil profile. While the tuff trenches reduced only salinity, yet they did not improve sodicity indicators, furthermore, the trenches treatments did not improve the aggregate stability. However, both trenches treatments, similarly to the FW treatments, improved the oxygen content at a depth of 35 cm.

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1. Introduction

Irrigation with treated wastewater (TWW) is nowadays an optimal alternative for the dwindling freshwater (FW) resources, especially in arid and semi-arid areas, and in countries where the annual water consumption by the agricultural sector is large (reaches 70-80%) (Becerra-Castro et al., 2015; Feigin et al., 1991a, 1991b; Lado et al., 2012a; Mohammad and Mazahreh, 2003). Recycling of reclaimed sewage water, mainly through agricultural and landscape irrigation, eliminates ecosystems' contamination, and makes TWW a valuable resource (EPA, 2012; Hadas and Kislev, 2011). In Israel, about 75% of the reclaimed wastewater is recycled and used in agriculture, covering 50% of the irrigation water needed in agriculture (Israel Water Authority, 2015; Jueschke et al., 2008). Furthermore, adequate irrigation management with TWW can enrich the agricultural soils with macronutrients such as N, P, and K, and micronutrients, which makes this type of irrigation economical, as it allows to reduce the use of synthetic fertilizers (Adrover et al., 2012; Mohammad and Mazahreh, 2003; Sousa et al., 2011; Yu et al., 2012).

Many studies revealed that irrigation with TWW for a long term (>6 years) has negative impacts on both soil and plants' health (Assouline and Narkis, 2013; Lado et al., 2012a; Nemera et al., 2020; Suarez and Gonzalez-Rubio, 2017; Yalin et al., 2017). A notable exception is the study of Fine et al. (2006) who reported that irrigating crops like citrus and orchards with TWW has mostly increased the yields and been considered economically profitable. Among the studies that showed a decline in the agricultural yields following a long-term irrigation with TWW, the reduction in crops' yields was associated with a combination of factors, including irrigation water quality, amounts of TWW used, soil type, irrigation intervals and local climate (Lado et al., 2012a; Tarchouna et al., 2010; Yalin et al., 2017). However, it was also noticed that the reduction in crops' yields occurs particularly in clayey soils (Assouline and Narkis, 2013); for instance, orchards like avocados or citrus that were grown on clayey soils (Assouline et al., 2015; Assouline and Narkis, 2013; Nemera et al., 2020; Indira Paudel et al., 2018; Paudel et al., 2016b; Yalin et al., 2017). In addition, researchers observed differences in the response to salinity and sodicity among a variety of soil types; coarse-textured soils with high permeability were affected by the irrigation with TWW in deeper soil layers than fine-textured clayey soils due to the low cation exchange capacity in the former (Assouline et al., 2016; Lado et al., 2012a; Tarchouna et al., 2010).

1.1. Treated wastewater (TWW)

The conventional sewage treatment (secondary/biological) majorly removes the organic suspended solids and reduces pathogens, while only minimal removal of dissolved inorganic ions is achieved (Feigin, 1991). Therefore, secondary treated wastewater (TWW) relative to freshwater (FW) is of high salt concentrations that were added during the industrial and domestic water use, also due water loss to evaporation during treatment, which eventually are transferred and deposited in the soil profile through agricultural irrigation. Additionally, compared to FW, TWW is of high pH levels, Cl and Na, besides the high concentrations of suspended and dissolved organic matter, plant nutrients, and trace elements (Assouline et al., 2016; Becerra-Castro et al., 2015; Jueschke et al., 2008; Lado et al., 2012a; Levy et al., 2014; Tarchitzky et al., 1999; Wallach et al., 2005). In Israel, recent regulations of the Ministry of the Environmental Protection require that tertiary TWW, is used for agricultural irrigation, and should contain less than 10 mg/l of BOD and TSS.

The TWW chemical properties may differ depending on the source of the sewage and the treatment plant (Assouline and Narkis, 2011), and consequently the composition of the soil solution will change (Lado et al., 2012a; Lahav et al., 2010). For instance, sewage water based on desalinated water is of relatively lower salinity, yet the addition of sodium to tap water in domestic/ industrial uses is by far the highest among the other ions dissolved in the water, which increases the sodium adsorption ratio (SAR) of this water (Lahav et al., 2010). Therefore, relatively to FW, TWW will be of a lower quality with respect to salinity and sodicity (Assouline and Narkis, 2011; Lado et al., 2012a; Levy et al., 1999; Suarez and Gonzalez-Rubio, 2017).

1.2. Soil Salinity and Sodicity

Applying an adequate leaching fraction while using TWW in irrigation is necessary for leaching the salts downward the soil profile to reduce the accumulation of excessive salts and nutrients concentrations in the root zone (Martõ, 1999; Pedrero et al., 2010). When the soil solution osmotic pressure increases, the free energy of water decreases, thus reducing water availability to the plants (Mehuys, 1975). When soil solution salinity (expressed by electrical conductivity – EC) is beyond the plant's tolerance threshold, the roots' water uptake will decrease, which will lead to damage to plants and in some extreme cases to mortality (Assouline and Narkis, 2013; Mohammad and

Mazahreh, 2003; Nemera et al., 2020). A common parameter for salinity is expressed by the electrical conductivity; thus, according to the USSL Staff 1954, the soil is considered saline when the electrical conductivity of the saturated soil water extracts is at least 4 dS/m. Additionally, soil salinity is associated with high osmotic potential which also leads to constraining the plants' water uptake (Bernstein, 1975). Moreover, salinity is generally associated with high concentrations of Cl and Na, and often of B in the root zone that leads to toxic levels of those elements in the plants' organs (Bar-tal et al., 2015; Läuchli and Grattan, 2011; Mehuys, 1975; Indira Paudel et al., 2018; Paudel et al., 2016a; Suarez and Gonzalez-Rubio, 2017; Yalin et al., 2017). The impact of salinity on plants' physiology and performance is a major issue in basic research and agricultural production, yet it is out of the current research scope. However, in this study, we are interested in examining the chemo-physical properties of clayey soils, as they are expected to be influenced by long-term irrigation with TWW.

Plants can indirectly be affected by excess of Na concentrations in both the soil solution and on the soil exchange phase. As this excess relative to divalent cations can alter the soil's chemo-physical properties, to an extent where the soil structure is impaired thus leading to reduced air to water ratio which results in lower soil productivity and difficulty for cultivation (Curtin et al., 1994; Levy, 2011). The term sodic soils, however, involves the exchangeable sodium ESR (solid phase) and, the sodium in the soil solution (SAR), together with considering the total electrolyte concentration (TEC) (Levy, 2011). As SAR values of secondary TWW are usually higher than those of FW, sodicity risk is expected following the rise of the soil exchangeable sodium (Assouline et al., 2016; Levy et al., 2014). Soil sodicity is essentially evaluated by two main parameters: **(i)** the exchangeable sodium percentage (ESP), which accounts for the exchangeable Na fraction over the total cation exchange capacity (CEC), which is usually determined at pH 7 or 8.2, and expressed in percentages as shown by eq. [1] (Levy, 2011).

$$\mathbf{ESP = 100 * \frac{[Na_{ex}]}{CEC}} \qquad \mathbf{(1)}$$

(ii) The sodium adsorption ratio (SAR) which gives a measure of the Na fraction in irrigation water or soil solution, relative to divalent cations: Ca and Mg. SAR is expressed in units of $\sqrt{(meq/l)}$, and evaluated by eq. [6], following to conversion of the divalent cations concentrations to (meq/l) (Levy, 2011; Sposito et al., 2016).

Reflecting on this issue, Assouline et al. (2016), defined the term "the root zone water budget", where the ratio between the infiltration, drainage, and evapotranspiration is affected by the change in the soil chemo-physical properties, as a result of irrigation with TWW. The latter changes the dynamics of the three-dimensional water and its distribution in the soil thus, the water and nutrients availability, the plats roots, the soil microbiome, and the oxygen concentration are manipulated.

1.2.1. *Swelling, dispersion, and deflocculating of clays:*

The swelling of clays is mainly affected by the concentration and composition of the soil solution that is in contact with the clay particles. Clay swelling is estimated by the d-spacing, which separates between two structure units, with its value being determined by the type of the hydrated cations in the aqueous soil solution and their concentration (Amorim et al., 2007). Soils of 2:1 layer alumo-silicates (Montmorillonite, smectite, Illite) compared with 1:1 layer alumo-silicates (kaolinite, and amorphous minerals), are considered unstable when exposed to solutions of high SAR and low salt concentration (McNeal et al., 1966), due to the structural and charge characteristics (Barzegar et al., 1997; Kopittke et al., 2006).

Swelling of montmorillonites following introduction of water or electrolytes solution can be described by two mechanisms: (1) the swelling of the crystalline, which occurs due to hydrations of ions on clay platelets' surfaces, where the change of the crystalline volume is explained by osmotic phenomena, and (2) the expansion of the diffuse double layer (DDL), which occurs following water ingress, and the dissociation of the hydrated cations from the clay surfaces, into the aqueous solution, where the DDL is formed and separates between clay particles, as shown in Figure 1;

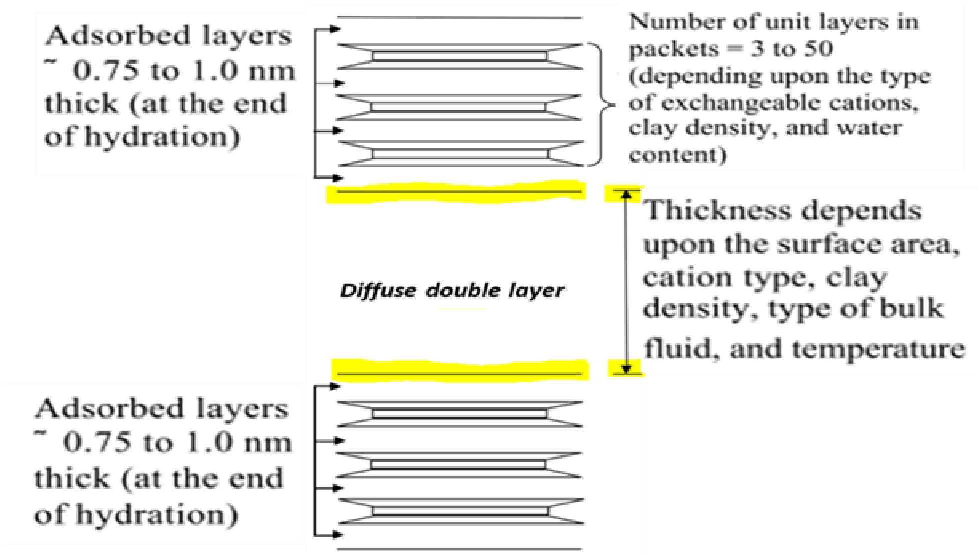

Figure 1. Schematic diagram of the unit layer arrangement, adsorbed layer, and the diffuse double layer for saturated montmorillonites (Schanz and Tripathy, 2009).

The swelling of clay particles reduces the soil's permeability and hydraulic conductivity, which is explained by the first mechanism proposed by Quirk and Schofield (1955): the swelling can simply block the soil conductive pores, completely or partially. While the second mechanism is attributed to the dispersion and deflocculating of the clay particles, an inevitable condition that is created when the attraction forces diminish to an extent of which the particles are separated and controlled by external forces, and that is when they get inside of the conductive pores to clog them and impair the diffusion of fluids through the conductive pores (Shainberg and Letey, 1984). Even though soil swelling is reversible, by the addition of flocculating electrolytes, soil dispersion is a partially reversible process, which creates sealed soil layers (Shainberg and Letey, 1984). Soils of high clay content are more vulnerable to the aforementioned phenomena, as the pore size in these soils is small, and the dispersed soil particles will not have to move far before they plug the pores (Shainberg and Letey, 1984).When montmorillonite clays (2:1 layers) are saturated with divalent cations like Ca and Mg, the aforementioned mechanisms are less likely to happen, as clay platelets exhibit flocculation due to strong attraction between Ca/Mg and the platelets surfaces, even in the presence of distilled water (Kopittke et al., 2006; Levy, 2011).

When introducing a small amount of sodium (exchangeable sodium percentage – ESP <15), to Ca-saturated clays in a mixed Na/Ca system, the swelling might be slightly affected, while by adding a large amount of sodium (ESP >15), a probable breakdown and intensive swelling of the flocculated clay tactoids will occur (Shainberg and Letey, 1984). Conversely, flocculation/dispersion is sensitive to the addition of small exchangeable Na amounts which is dependent on the Na concentration in the soil solution, furthermore, clay particles' dispersion is more likely to happen when the electrolyte concentration is below the flocculation value, the minimal electrolyte concentration that allows for flocculation (Shainberg and Letey, 1984). Swelling and dispersion are symptoms of sodicity, that are affected differently by the exchangeable sodium, thus clays particles disperse at lower ESP values, while swelling occurs only at higher ESP values (Shainberg and Letey, 1984). However, both phenomena are responsible for the change of the geometrical order of the soil's porous medium. Therefore, estimating the hydraulic conductivity based only on the soil's structure and the pore size distribution, will lead to overestimation (Shainberg and Letey, 1984).

The ionic strength of the soil solution, which can be expressed in terms of EC, is a substantial factor, which influences the DDL of the clay particles, and consequently impacts the soil physico-chemical properties, in a way where it can prevent clay swelling and dispersion, in spite of the high ESP values (He et al., 2013; Kopittke et al., 2006; Shainberg and Letey, 1984). Levy (2011) stated that the increase in the soil solution ionic strength increases the preference for Ca over Na by the platelets surfaces of expanding clay minerals, and the ESP decreases.

1.2.2. *Cations exchange, Gapon coefficient and ESP equations:*

The ion exchange equation according to Gapon which describes exchange reactions between Na and Ca, in soil solution and on the exchangeable soil phase is as follows (Shainberg and Letey, 1984):

$$\mathbf{Ca_{\frac{1}{2}}X + Na^{+} \leftrightarrow \frac{1}{2}Ca^{2+} + NaX} \qquad \mathbf{(2)}$$

Where the equilibrium constant (*K*) is derived as:

$$\mathbf{k} \quad = \frac{[\mathbf{Ca}^{2+}]^{\frac{1}{2}}\,(\mathbf{NaX})}{[\mathbf{Na}^{+}](\mathbf{Ca}_{\frac{1}{2}}\mathbf{X})} \qquad \mathbf{(3)}$$

Or the form:

$$\frac{\mathbf{E_{Na}}}{\mathbf{E_{Ca_{\frac{1}{2}}}}} = \mathbf{k} \quad \frac{[\mathbf{Na}]}{[\mathbf{Ca}]^{\frac{1}{2}}} \qquad \mathbf{(4)}$$

Where squared brackets indicate molar concentration of the cations in the solution, the parenthesis indicate the activity of the cations in the exchange phase, and they are assumed to be equal to their equivalent fractions.

With considering the Mg as a significant divalent cation on the exchanger and in the soil solution, the exchangeable sodium ration (ESR) can be given as (Shainberg and Letey, 1984):

$$\mathbf{ESR} = \frac{\mathbf{E_{Na}}}{\mathbf{E_{Ca_{\frac{1}{2}}}} + \mathbf{E_{Mg_{\frac{1}{2}}}}} = \frac{\mathbf{E_{Na}}}{\mathbf{CEC} - \mathbf{E_{Na}}} \qquad \mathbf{(5)}$$

and the sodium adsorption ratio (SAR) is described as (Shainberg and Letey, 1984):

$$\mathbf{SAR} = \frac{[\mathbf{Na}^{+}]}{\{([\mathbf{Ca}^{2+}] + [\mathbf{Mg}^{2+}])/\mathbf{2}\}^{\mathbf{0.5}}} \qquad \mathbf{(6)}$$

The cations units: meq/l

The relationship between SAR and ESR can be described using the empirical the empirical Gapon selectivity coefficient (K_G) as follows (Shainberg and Letey, 1984):

$$\mathbf{ESR} = \mathbf{k_G}\ (\mathbf{SAR}) \qquad \mathbf{(6)}$$

Since the exchangeable sodium and the sodium in the soil solution are affected by each other, an estimation of the soil ESR can be obtained from the SAR of the saturated soil paste and then the ESP. In case of employing diluted soil water extracts the ESP can be estimated by a linear model (Levy, 2011) as will be described later in the methods of the current study (section 4.4).

Ca and Mg in Eq. [4] and [5], are both considered as flocculation cations, Ca-saturated montmorillonite platelets revealed less swelling pressure relative to Na due to the strong electrical attraction between the Ca and the clays' surfaces charge (Levy, 2011). However, Mg according to Sposito el al., 2016 is a controversial issue, as the effect of Mg as a divalent cation on the soil structure and its hydraulic properties differs among different studies: some studies indicated similar influence for both Mg and Ca on maintaining soil structure, while others claimed a specific deleterious effect of the exchangeable Mg on soil stability and permeability (Keren, 1991), especially in non-calcareous soils. Furthermore, when the ESP values were high (i.e. $\geq$ 12 %) the hydraulic conductivity was decreased mainly by Na, and the effects of Mg were masked. Whereas in the case of relatively low ESP values (i.e. 3-8 %), the saturated hydraulic conductivity (K_s) in the case of Mg was only third of the K_s achieved when the exchangeable cation was Ca (Sposito et al., 2016). Furthermore, at constant SAR values, and Mg concentration larger than that of Ca, the relative K_s was significantly lower (Dontsova and Norton, 2001; He et al., 2013; METZGER et al., 1983).

As already mentioned, degradation of soil structure is in a close association with sodic conditions Many studies raised the question at what ESP value a soil is defined as sodic. According to the USSL Staff 1954 the definition of sodic soils has been ascribed to soils having ESP of 15 or higher. However, during the last decades it has been realized that this over-simplified definition does not include the combined effects of salinity (EC), soil organic matter (SOM) and a new irrigation water quality parameter termed the cation ratio of structural stability (CROSS) (Rengasamy and Marchuk, 2011), which considers the specific flocculation/dispersion ratio of each cation (Assouline et al., 2016; Sposito et al., 2016). For instance, McIntyre (1979) and Levy et al. (2005) suggested ESP >5 as a threshold for exhibiting a sodic behavior at TEC of 0.7 $mmol_c/l$, while Green et al., suggested ESP values of 20 and 10 for coarse and fine soil textures, respectively. It has been reported that soil permeability is best achieved at high EC values and low SAR values, such that already at low EC and low SAR values (i.e. 5 or 6) a non-sodic soil can turn into a sodic one (Levy et al., 1999 ; Assouline et al., 2016; Lado and Ben-Hur, 2010).

1.2.3. *Effect of rainfall on sodic soil:*

A relatively sodic clayey soil (i.e. Levels >6 for both SAR and ESP; Levy, 2012) is vulnerable to swelling, dispersion, and aggregates break down, in winter seasons rather than in irrigation seasons, because of the electrolytes dilution and leaching, which results in low ionic strength in the soil solution (Levy et al., 2014). In calcareous soils rain reduces soil sodicity, due to dissolution of lime during the rainy season that releases Ca to the soil solution. The latter is then preferably adsorbed to the soil clays in the upper soil layers, at the expense of exchangeable Na, which in turn moves to the soil solution, to eventually accumulate at deeper layers of the soil profile (Levy et al., 2014). Additionally, the hydraulic conductivity is adversely affected by clogging the soil water conducting pores, especially when the soil is exposed to high water energy or leached by rain water containing almost no electrolytes (Lado et al., 2012a; Leuther et al., 2019; Levy et al., 2005, 2014). The effect of the rain on reducing soil salinity following an irrigation season, was observed in many studies (Erel et al., 2019; Lado et al., 2012a; I. Paudel et al., 2018) observed the effect of the rain on reducing the EC and salts in general, but also notice that SAR, was not necessarily reduced.

The rain can substantially decrease the relative hydraulic conductivity in soil profiles irrigated with TWW, due to diluting the soil solution and amplification of the Na effect (Russo et al., 2020, 2015). Additionally, the effect of raindrops kinetic energy on mechanical mixing of the soil aggregates, leads to chemical dispersion and results in compaction of the soil layers and forming thin skin seals (Shainberg and Letey, 1984).

1.2.4. *Potassium (K) effect on soil physico-chemical properties:*

In general, monovalent cations create a wider hydrated shell than divalent cations, which causes soil particles dispersion and affects infiltration (Quirk And Schofield, 1955; Shainberg and Letey, 1984; Smith et al., 2014). High K content in TWW may result from the industry processes due to shifting Na- based cleansing products or animal diet to K-based products (Feigin et al., 1991a). Many studies showed the rise of the exchangeable potassium percentage (EPP) led to soil dispersion, low hydraulic conductivity, and soil erodibility (Auerswald et al., 1996; Rengasamy and Marchuk, 2011; Smith et al., 2014).

1.3. Soil pH:

The pH of the soil solution is a significant factor which controls the solubility of minerals (Afyuni and Bagheri, 2006), the mineralization of organic matter (Becerra-Castro et al., 2015), the type of the clay particles' electrical charge, and the interactions between the clay particles (edge/face) and organic matter, which might be either attraction (flocculation) or repulsion (dispersion) (Tarchitzky et al., 1993). Studies differed about the effect of the irrigation with TWW on the soil solution pH: in some studies, TWW increased the pH (Becerra-Castro et al., 2015; Lado et al., 2012a), while in others the pH was decreased (Afyuni and Bagheri, 2006; Becerra-Castro et al., 2015), mainly due intensified nitrification. TWW is rich with organic matter (OM) and CO_2 degases resulted from the decomposition of OM, they are expected to increase the water alkalinity, and to elevating its pH (Lado et al., 2012a; Suarez and Gonzalez-Rubio, 2017). In fact, Suarez and Gonzalez-Rubio (2017), established that both, water evaporation, and organic matter decomposition, can lead to increased alkalinity which causes $CaCO_3$ precipitation, and result in SAR increase. As the pH level may affect the soil chemical properties adversely, the suitability of the irrigation water is controversial. Suarez et al., (2017) indicated in their review the ability of high pH to decrease the saturated hydraulic conductivity at fixed EC and SAR. They also showed in their research that the increased pH from 7 to 8 reduced infiltration and aggregate stability either with or without dissolved organic C (DOC) and for all the SAR values they examined. In Israel, most of the clayey soils are considered calcareous due to the relatively high calcite content, therefore they are characterized with relatively high pH values that ranges between 7.5-8.2 (Singer, 2007), which contributes to the soil buffer capacity against the pH reduction.

1.4. Dissolved Organic Matter (DOM) and sodicity:

Irrigation with TWW is characterized by high dissolved organic matter (DOM), and may be expressed in terms of dissolved organic carbon (DOC). The dissolved organic carbon content (DOC) following irrigation with TWW, may increase in the upper soil layers (up to 20 cm) compared to soils irrigated with FW, and may get depleted in the subsoil (Assouline and Narkis, 2013; Jueschke et al., 2008) or could also remain unchanged (Borisover et al., 2012).

Barzegar et al., 1997 stated that the adverse effects of DOM depend on some factors, such as the clay mineralogy and its content in the soil, the composition of the organic matter (humic substances /aliphatic groups CH/ hydrophilic groups), the level of sodicity and the amounts of DOC (Suarez and Gonzalez-Rubio, 2017), besides the composition of the electrolytes in the soil solution. The latter has been emphasized by many studies (Barzegar et al., 1997; Lado et al., 2012a), where they noticed the influence of organic anions on decreasing the Ca activity, by complexation, which led to increased repulsion (dispersion) between the negatively charged clay particles. Additional studies indicated the importance of sufficient Ca amounts for preventing clay particles dispersion, by bridging them with the anionic organic colloids (Ali and Mindari, 2016; Robert et al., 2019; Tarchitzky et al., 1993). Furthermore, Suarez (1987), explained the effect of DOC decomposition on increasing the SAR of the soil, by releasesing CO_2, increasing the soil alkalinilty, and finally the percipitation of Ca as calcite, which exacerbates the SAR values (Suarez and Gonzalez-Rubio, 2017). Moreover, the insufficient ionic strength with a given ESP, create imbalanced ESP-EC ratio, which may lead the dissolved organic matter (DOC) to cause particle dispersion, thus, reducing the saturated hydraulic conductivity (Ks) of the soil (Metzger et al., 1983).

Many studies indicated the harmful effects of DOC, or its components - humic substances (MacCarthy et al., 1990; Nasonova et al., 2020) on the soil physico-chemical properties, that were summed in a reduction in the hydraulic conductivity and infiltration, poor drainage and decreased aeration, increased hydrophobicity, and creating preferable wetting paths (Lado and Ben-Hur, 2010; Suarez and Gonzalez-Rubio, 2017; Wallach et al., 2005). Wallach et al., (2005) studied the effects of DOC on soil hydrophobicity (water repellency), and stated that one of the reasons that led to creating a hydrophobic soil is the composition of the DOC, as it may contain aliphatic and amphiphilic groups (Bauters et al., 2000; Diamantopoulos et al., 2013; Wallach and Jortzick, 2008). Bernier et al., (2013) studied the effect of long- and short-term irrigation with TWW on the distribution of CH groups and hydrophilic groups, they found that compared to irrigation with FW, they did not find an indication to the advantage of TWW to contributing any of the mentioned groups to the soil, irrespectively of the mechanical composition of the soils they studied. Furthermore, they also observed the depletion of DOC in a clayey soil following five years of irrigation with TWW.

1.5. Use of trenches with highly porous media (tuff and compost):

Using soilless growing media is one of the solutions in agriculture in Mediterranean countries, where high quality irrigation water is limited, and the local soils suffer from pathogenic factors, excessive use of pesticides, and salinity (Baudoin et al., 2013). The use of soilless culture was accelerated following the ban of using methyl-bromide to replace the domestic pathogenic soils, since it is free of pests and diseases and can be easily sterilized (Jin and Jury, 1995).

Knowing the physical characteristics of the substrates/growing media, such as CEC, porosity, pore size, particle size, and bulk density, is crucial for estimating the water/air ratio, and the hydraulic conductivity of the growing media, which assists with regulating the irrigation practices (Baudoin et al., 2013; Raviv et al., 2019).

Growing media of highly continuous macro-pores distribution, enhances roots growth, gas interchange with the atmosphere, and high solutes infiltration and leaching (Scott et al., 1988). The physical properties of tuff have made it a popular substrate in Israel, thanks to its high porosity and hydraulic conductivity, which also provides aeration for the plant roots. The porosity of the tuff is higher than that of sand due to the tuff's inner micro-pores (Silber and Raviv, 1996).

Russo, et al. (2020) referred in their numerical study to the tuff trenches treatment as aeration trenches that also reduce the salinity peak as well as its accumulation under the irrigation laterals zone. Russo, et al. (2020) also found that the use of tuff trenches coupled with TWW irrigation, achieved EC, SAR and Cl concentration values close to FW treatment.

Compost is known to contribute to the soil fertility, as it enriches the soil with organic aggregating substances (Barzegar et al., 1997; Caravaca et al., 2002; Chenu et al., 2000), nutrients, and microbial diversity (Farrell et al., 2010). Composting of various organic wastes (i.e. cattle manure) results in reduced phytotoxicity and pathogenic factors in the organic material, stabilized N, and oxygen demand (Raviv, 2014, 2011). However, organic materials like compost decompose with time, hence, the physical characteristics of compost vary depending on the maturity stage, hindering its usage as a stand-alone growing medium (Baudoin et al., 2013; Marfá et al., 1998; Raviv et al., 2019). As the volume weight (bulk density) of composted cattle manure is relatively low compared with clayey soils and tuff, the material's quantity is affected by compression, which controls its physical and chemical characteristics. Organic substrates (growing media) compared with inorganic ones, are of low cost, high CEC, and usually of high alkalinity and salinity (Goldberg et al., 2020; Raviv et al., 2019). Direct analysis of soil moisture content in composted cattle manure medium against red tuff, showed very high water-content relative to tuff (Da Silva et al., 1998a).

Merging tuff with the soil was applied by Nemera et al, (2020), where they installed tuff trenches in an avocado orchard to mitigate the negative effects of TWW irrigation, and they found improvement in the physiological functioning of the trees. Furthermore, Rubio-Asensio et al., (2018) tested embedding coconut fiber substrate bags per tree, in a nectarine orchard, and they found improvement in nutrients and water use efficiency. Bar Yousef et al., (2000a), tested the effect of growing waxflowers in tuff pits in clayey soils, and they found improvement in the yield relative to the control treatments.

1.6. Soil Aggregate Stability

Soil aggregate stability (AS) is a property that describes the soil endurance against external forces and its ability to maintain the soil particles arrangement and porosity (Levy and Mamedov, 2013). As well, it affects soil fertility as maintaining AS improves the water dynamics in the soil, aeration, microbial activity, and eventually the growth of plants (Amézketa, 1999). AS provides sustainable agriculture, as it reduces the degradation of the soil and eliminates erosion derived pollutions (Amézketa, 1999). The measurement of soil AS, was found in correlation with physical soil properties, therefore it compensates for a tool for measuring a number of soil parameters such as erosive and crusting potential (Amézketa, 1999). The mechanisms involved in affecting the soil AS, are slaking (breaking of aggregates due to compressed air within the aggregate), dispersion and swelling (Amézketa, 1999). AS includes the stability of the macro and micro aggregates of the soil (Amézketa, 1999). Many factors affect the soil AS such as the agricultural practices, where tillage, continuous crops rotations, and soil sodicity destabilize the soil aggregates (Levy and Mamedov, 2013). Soil aggregates are susceptible to the chemical composition of the soil solution, thus the increase in sodicity (or ESP) and the decrease in salinity reduces the soil AS (Levy and Mamedov, 2013).

Since sodicity affects AS, irrigation with TWW definitely affects AS, due to high Na concentrations in TWW. Moreover, impaired AS was found related not only to SAR and ESP, but also DOM, and EC (Assouline and Narkis, 2013; Goldberg et al., 2020; Schacht and Marschner, 2015), clay content and aggregate size (Mamedov et al., 2017). The mechanisms by which AS is impacted, were described also by Le Bissonnais (1996), and were described by the disruption of aggregates due to swelling, air eruption during rewetting, particle dispersion by drop's energy, and by physiochemical factors (Chenu et al., 2000).

1.7. <u>Monitoring Soil Moisture Content:</u>

Monitoring the volumetric water content (VWC) or soil moisture, was conducted in the soil by many studies (Da Silva et al., 1998b; Polak and Wallach, 2001; Rahav et al., 2017; Tarchouna et al., 2010; Yalin et al., 2017) in a purpose to examine the water dynamics in the soils, and the availability of water to the rootzone, which also helps for regulating the irrigation patterns. The water in the soil is controlled by many factors such as water potential, and gravimetric forces, and the dynamics of water in the soil is affected by the physical structure of the soil, where large pores improve the water percolation and enhance the leaching of the soil (Voroney, 2018), in addition to the plants physiology, where high salinity in the soil solution leads to high osmotic potential and restrains the plant water uptake by the roots, which leads to the accumulation of water in the soil pores on the expense of oxygen, creating conditions of lack of oxygen (hypoxia) (Assouline and Narkis, 2013; Indira Paudel et al., 2018; Yalin et al., 2017).

Polak and Wallach 2001, studied the variations of moisture around the root zone in an orchard, by installing TDR sensors, at different depths (shallow and deep). They divided the stages of moisture content into four variations: (i) during the irrigation event, (ii) the sharp drop of water content by free drainage, which stops at field capacity, (iii) a combination of root uptake and free drainage, and (iv) moisture depletion by root uptake only. They found distinctive moisture variations for each depth, where at the topsoil layers (10-40 cm), they noted between subsequent irrigations events, a larger gap of soil moisture content than that at deep soil layers (40-70 cm). However, those variations might change when applying agro-technical methods and affect the water content in the soil.

1.8. Soil Ambiance Oxygen

The gaseous composition of the soil ambiance differs from that of the air above the soil, and it is largely controlled by roots' and soil microbes' respiration, climatic changes, biological and chemical organic matter degradations. All are processes that consume oxygen and, in turn, increase CO2 concentrations (Friedman and Naftaliev, 2012; Neira et al., 2015; Raviv et al., 2019). Soil air oxygen is essential for the plants' development, as it is involved in the biochemical growth processes. The soil's oxygen content ranges between 18-20 volumetric percent in pasture lands to 20.7 volumetric percent in tilled lands, when the total pores space are calculated based on the specific air-dried soil bulk density (Ben-Noah and Friedman, 2018; Jacobson et al., 2000).

The use of oxygen sensors for monitoring the oxygen levels was demonstrated by an abundance of studies (Assouline and Narkis, 2013; Clark et al., 2015; Friedman and Naftaliev, 2012; Yalin et al., 2017), where the sensors' locations were in proximity to the root zone, and at different depths. For instance, Friedman and Naftaliev 2012 found a correlation between the season, the age of trees, the soil texture, the water quality, the wetting pattern, the dimensional distance from the emitter, and the level of oxygen in the soil. Additionally, Yaline et al., 2017, found a reduced water tension accompanied by high water content that reduced the oxygen levels in plots irrigated with TWW rather than those irrigated with FW. Following the irrigation with TWW, CO_2 concentration is expected to rise at the expense of O_2, because of the decomposition of the OM in TWW, which reduces the oxygen concentration as well (Assouline and Narkis, 2013).

1.9. Measures for mitigating issues associated with TWW irrigation:

The emerging drop in crops' yields, associated with the deterioration of the soil fertility due to the long-term irrigation with TWW, drove agronomists and researchers to seek solutions for overcoming or adapting to the new conditions in the field. Many (Paranychianakis and Angelakis, 2008; Zekri and Parsons, 1992) studied new tolerant rootstocks, while others (Ben-Noah and Friedman, 2016; Ben-Noah et al., 2020; Zhu et al., 2019) aimed to solve soil aeration issues (hypoxia/anoxia) by active air injection into the rootzone. Others (Pitt et al., 2015) relied on mechanical methods for breaking the compacted soil aggregates and enhance the leaching of chloride and sodium. Additional studies examined chemical methods for overcoming soil sodicity like amending compost (Avnimelech et al., 1994) or gypsum (Aboelsoud et al., 2020; de Oliveira et al., 2016; Lebron et al., 2002; Vyshpolsky et al., 2010). Where additional studies (Nemera et al., 2020; Indira Paudel et al., 2018) considered enhancing the irrigation water quality.

1.10. Study motivation

Many studies reported the negative impacts of short- and long-term irrigation with TWW on the soil physico-chemical properties. However, to the best of our knowledge, we have not encountered studies that tested compost and tuff trenched simultaneously in orchards, and only a few studies investigated the physico-chemical properties, AS, moisture and oxygen in the soil following the use of compost and tuff trenches combined with TWW irrigation. Therefore, it is of interest to investigate how substrates brought from soilless agriculture, behave when embedded in the soil and whether they improve the soil properties near and below the trenches in an almond orchard.

2. Hypotheses

Introducing tuff and compost trenches to orchards grown in clayey soils and irrigated with TWW will (i) help the soil to sustain the soil properties in a way similar to that of orchards irrigated with FW, and (ii) improve the soil permeability to air and water by adding a medium of coarse texture in addition to decreasing the SAR of the soil solution and soil ESP.

3. The Research Objectives

The main research objective is to evaluate some chemo-physical soil properties following the use of different water qualities and the application of tuff and compost trenches (as agro-technical methods), introduced for mitigation of the build-up of high salinity and sodicity levels in clayey soils subjected to a long-term irrigation with secondary TWW. The specific objectives are to study the effects of the treatments studied on: (i) salinity, sodicity, and DOM characteristics in the soil profile at the end of the irrigation and rainfall seasons, (ii) spatial distribution of salinity, sodicity and DOM characteristics around the drip line, (iii) aggregate stability in the soil profile and its spatial distribution at the end of the irrigation season, and (iv) dynamics of in situ soil water content and aeration.

4. Materials and Methods

4.1. <u>Experiment Site and Design:</u>

The current research (2018-2020) was conducted in a commercial almonds (*Prunus dulcis*) orchard on a Grumusol soil (Dan, 1983; Singer, 2007) near the Sea of Galilee, Israel (32°46'58.8"N, 35°28'44.4"E) (Figure 2). The climate in the region is Mediterranean with average annual precipitation around 500 mm; actual annual precipitation values during the experiment are presented in Table 1. The main commercial almond cultivar (Um El- Fahem, grafted onto '677' root stock), was planted in rows between the rows of two different pollinating cultivars ('53' and '54') as shown in Figure 3, with distances between trees and tree rows being 5 and 7 m, respectively.

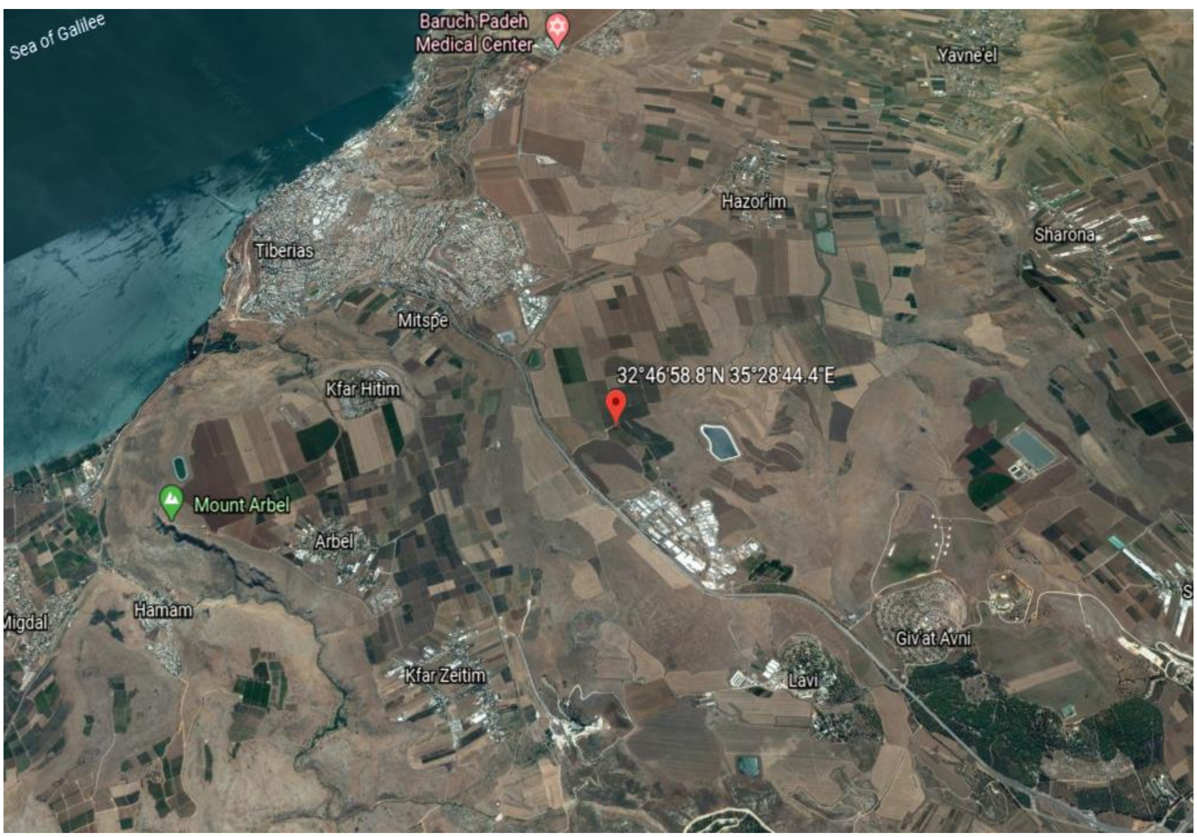

Figure 2. A satellite image of the experiment site location.

Table 1. Annual average precipitation at the experiment site.

Period of precipitation	Amount (mm)
8.10.2017 – 6.6.2018	450.7
21.10.2018 – 21.4.2019	686.6
15.10.2019 – 6.3.2020	481.7

Data was received from the meteorological station of the ministry of agriculture of Israel.

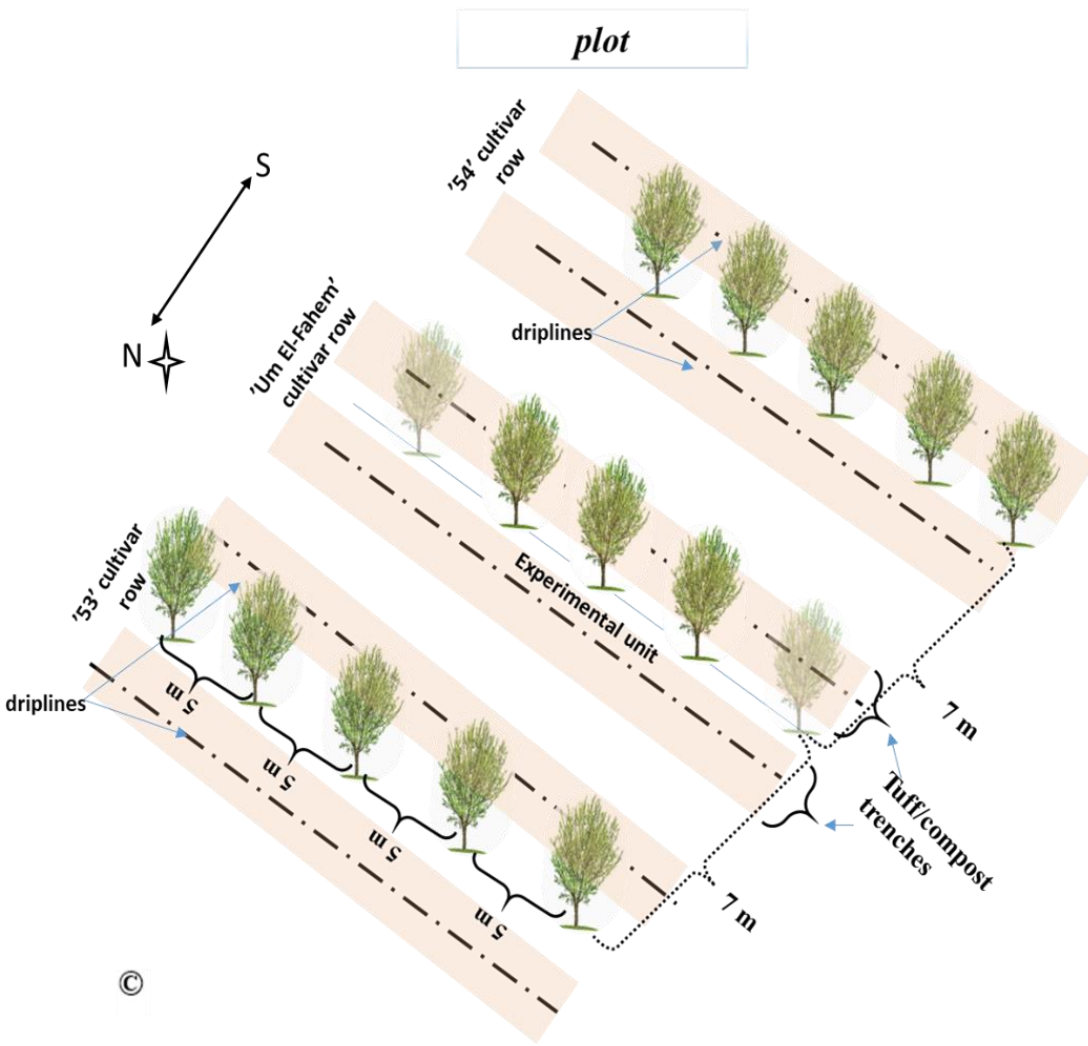

Figure 3. A scheme of an experimental plot, (a replicate out of 5) for each of the studied treatments. The driplines and the trenches locations, the distances between trees, and tree rows are shown

Table 2. Some basic properties of the soil (samples were collected in March 2017 – prior the start of the current study)

Parameter	Units	Soil Depth (cm)		
		15 cm	45 cm	75 cm
SP	%	95.28 (2.30)	102.55 (2.90)	101.68 (1.68)
Clay	%	64.60 (2.92)	65.13 (4.71)	70.13 (1.63)
Sand	%	11.47 (3.33)	9.47 (2.86)	6.47 (1.58)
Silt	%	23.93 (2.29)	25.40 (3.47)	23.40 (2.47)
Calcite	%	4.99 (0.66)	5.33 (0.39)	5.51 (0.35)
OM	%	2.02 (0.07)	1.60 (0.18)	1.23 (0.07)
CEC (meq/100 g)	meq/100 g	68.75 (2.47)	69.72 (1.95)	68.07 (1.87)
Exchangeable Ca	meq/100 g	68.65 (2.86)	63.72 (2.08)	67.10 (1.92)
Exchangeable Na	meq/100 g	1.8 (0.25)	2.6 (0.26)	2.4 (0.25)
Exchangeable K	meq/100 g	1.87 (0.32)	0.96 (0.07)	0.96 (0.12)
Exchangeable Mg	meq/100 g	10.68 (0.24)	11.45 (1.31)	9.53 (0.57)
Saturated HC (Ks)	m/ day		0.94	

Means calculated based on 4-6 replicates. SE are shown in parentheses.
SP= saturation percentage, OM = organic matter, CEC = cation exchange capacity, HC = hydraulic conductivity. CEC data from Dr. David Russo, personal communication.

The orchard was planted in 2013, in a clayey soil of increasing clay content downward the soil profile (Table 2). The soil is characterized by a relatively low mild persistent calcite content up to a 90 cm depth. The soil contains a relatively low organic matter content (Banin and Amiel, 1970), which decreases downward the soil profile, and CEC, SP and HC typical in of heavy fine-textured soils. The orchard has been irrigated with secondary treated wastewater (TWW) since 2013. In March 2017 one year before the beginning of the current study, soil samples up to 90 cm depth were collected by the orchard’s staff. The soil samples were delivered to the extension services laboratory in Tzemach near Kineret, where the soil solid phase and soil paste characteristics (Table 2) were determined, excluding cation exchange capacity (CEC) which was performed at our laboratory at Volcani center (ARO), using the sodium acetate extraction procedure. The experiment included four treatments, that were established in 2017 (one year prior to the start of the measurements presented in this M.Sc. Thesis), each in five replicates (plots) that were organized in a complete randomized block design. Each plot consisted of 15 trees aligned in three rows, where the center of the central row (5 trees of Um El – Fahem cultivar) constitute the measured unit (Figure 3). The examined treatments were: irrigation with domestic secondary treated wastewater (**TWW**), with trenches installed on both sides of the tree rows, filled with either **(I)** aerobically digested manure – compost (**COM**) – (Kibutz Sde Eliyaho compost company, 2005), or **(II)** with 0-8 mm equivalent radius of tuff (**TUF**) particles (Volcanic ash, scoria,Tuff Merom Golan, Israel, 1972). Irrigation with either **(III)** fresh water (**FW**) or **(IV)** treated

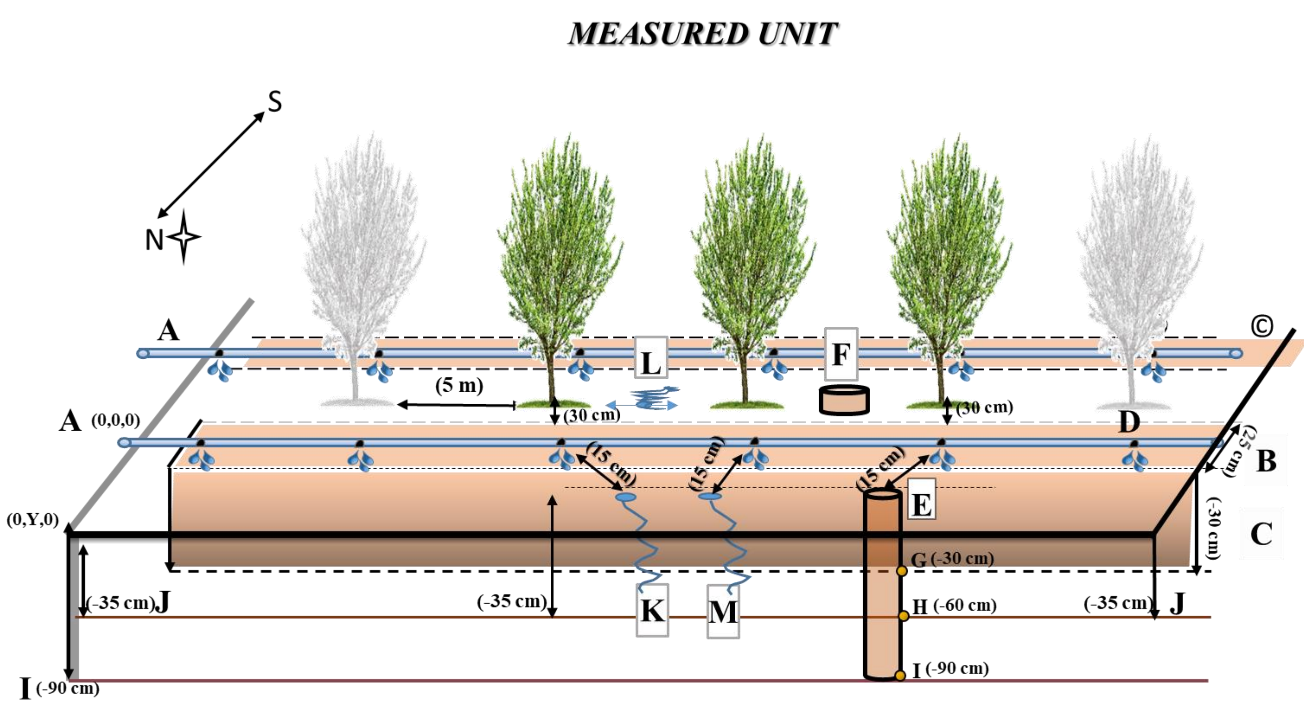

Figure 4. A scheme of the central tree row (Um El-Fahem cultivar) in an experimental plot. A – driplines on both sides of the trees row; B and C are width and depth of a tuff or compost trench, respectively. D – a dripper, E – the dripper adjacent soil sampling point, F – between trees soil sampling point, G, H, I – three soil sampling depths, J – oxygen and volumetric water content (VWC) sensors installation depth. K dripper adjacent -VWC sensor, L – between trees- VWC sensor. M – dripper adjacent oxygen sensor.

wastewater **(TWW)** without having installed trenches. The trenches depth and width of the trenches being 25 and 30 cm, respectively (Figure 4.B, Figure 4.C).

Some physical and chemical properties of the trenches fill (tuff and compost) are shown in Table 3 and Table 4.

Table 3. Selected properties of the tuff used for filling of the tuff trenches.

parameter	units	Value
Maximum particle diameter	mm	8 mm
Bulk density	g/ cm^3	1.091
porosity	m^3/ m^3	0.587
Saturation VWC (Θs)	m^3/ m^3	0.55
Residual VWC (Θr)	m^3/ m^3	0.08 m^3/ m^3
Saturated HC (Ks)	m/ day	105.4
Residual HC (Kr)	m/ day	0.01
CEC	$cmol_C$ / kg	2.85
Calcite%		0
OM%		0

VWC = volumetric water content, HC = hydraulic conductivity. OM = organic matter, CEC = cations exchange capacity.

Tuff data from Silber et al., 1994 and Wallach et al., 1992

Table 4. Selected properties, of the compost used for filling of the compost trenches in 2017.

Variable	Units	Values
Bulk density	g/ cm^3	0.656
porosity	m^3/ m^3	0.82
Dry Matter	%	63.7
Organic matter	% w/w	36.8
Organic carbon	% w/w	21.6
Total nitrogen	% w/w	1.74
C/N		12.4
Water Extracted by 10:1 water: compost		
pH		7.5
EC	dS /m	6.6
$N\text{-}NO_3^-$	mg/ l	1.8
$N\text{-}NH_4^+$	mg /l	30.7

Data were adapted from Sde Eliyaho database

4.2. Irrigation Management:

The irrigation of the orchard started every year, in Spring (March – April) towards the end of the rain season and ended in Fall (October – November), close to the start of the subsequent rain season. The total irrigation amounts by the end of the irrigation season were similar for all the treatments, as shown in Figure 5. The irrigation dose was determined by using the Penman and Monteith formula (with considering a crop factor). The orchard was irrigated with a trickle irrigation system, composed of two driplines placed on the soil surface along both sides of each tree row, except for the compost treatment (COM), where the drip laterals were buried in the compost trenches at a 20 cm depth, to ensure maximum wetting of the compost trenches. For all treatments, each lateral consisted of a set of drippers spaced 0.5 m apart with emitter discharge rate of 2.3 l/h. Irrigation water samples were tested for their chemical properties several times a year. The yearly averages of the irrigation water properties showed 3 to 4 times higher concentrations of Cl and Na in TWW than in FW, furthermore, the carbonates and pH were higher in TWW than in FW, in addition to higher NPK concentrations in TWW than in FW, as shown in Table 5. The different treatments in the orchard were fertilized by injecting different types and amounts of liquid fertilizers (ICL, 1946) through the irrigation system by 3/4” Tefen pump. The water qualities, FW and the TWW were separated at all levels (containers/laterals) as recommended by the regulations of the Israeli ministry of agriculture. The planned fertilizers’ NPK amounts (Figure 5) were based on the estimation of the NPK consumption by the trees and the amounts supplied with the irrigation water as presented in Table 6. The treatments that were irrigated with TWW, were fertilized with mineral nitrogen fertilizer (Oran 32), and the FW treatment was fertilized with complex mineral fertilizers as Tov in 2018 and Idiet in 2019.

Though the total irrigation amounts were similar, the irrigation intervals planned for each of the treatments were different, thus the TUF treatment was irrigated daily, the TWW and FW treatments twice a week, and the COM treatment once a week.

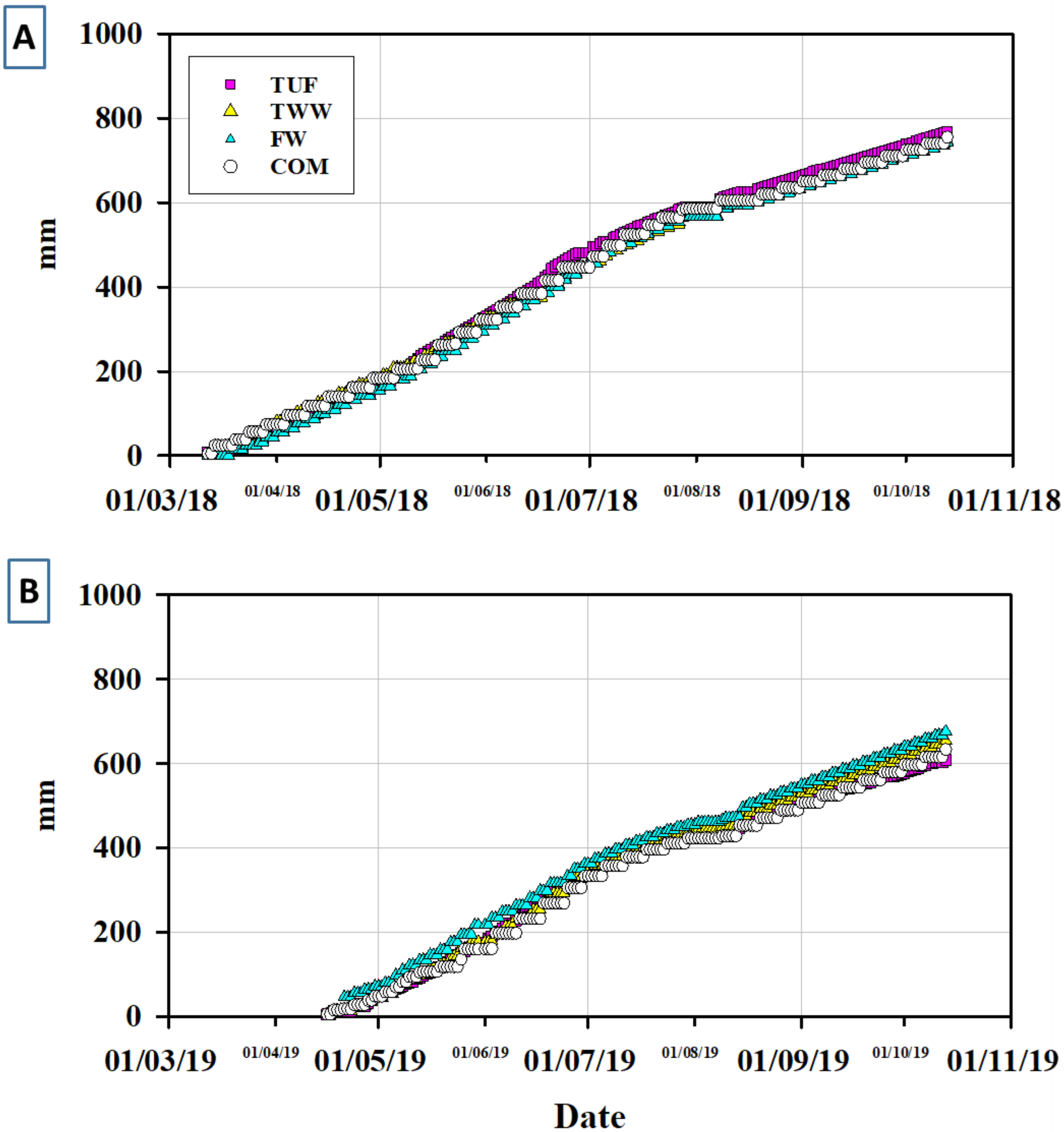

Figure 5. Periods of irrigation and cumulative irrigation water amounts given to the four treatments: TWW, FW, COM, TUF, during the years 2018 (A) and 2019 (B).

Table 5. Selected irrigation water properties in 2018 and 2019.

Year	2018				2019			
Irrigation water quality	TWW		FW		TWW		FW	
Parameter	Value	SE	Value	SE	Value	SE	Value	SE
BOD (mg/l)	10.14	1.55			14.00	1.41		
COD (mg/l)	31.15	7.28			37.00	4.50		
N-NH_4 (mg/l)	6.34	2.76			10.80	6.61		
N-Kjeldahl (mg/l)	17.09	3.27			13.45	6.81		
N-NO_3 (mg/l)	6.76	1.89	3.26	0.06	9.24	3.19	3.82	0.82
pH	7.93	0.15	7.15	0.15	7.88	0.07	7.30	0.00
SAR $(mEq/l)^{0.5}$	4.32	0.14	1.10	0.12	4.14	0.23	0.84	0.09
TSS 103-105 (mg/l)	6.16	1.54			9.45	2.81		
Soluble K (mEq/l)	1.21	0.07			1.16	0.02	0.06	0.00
soluble B (mg/l)	0.37	0.16	0.10	0.01	0.16	0.02	0.07	0.00
S (mEq/l)	2.34	0.77	0.40	0.01			0.33	0.03
CO_3 (mEq/l)	7.14	0.53	4.71	1.58			5.99	0.15
Total P (mg/l)	8.11	2.07			5.10	0.21		
Soluble P (mg/l)	5.57	1.00			3.76	0.27		
Cl (mg/l)	272.52	16.97	91.24	16.69	262.70	14.35	99.40	
Cl (mEq/l)	7.61	0.41	2.57	0.47	8.04	0.70	2.68	0.12
Mg (mEq/l)	2.62	0.32	2.47		3.02	0.37	2.34	0.20
EC (dS/m)	1.67	0.07	0.85	0.00	1.56	0.03	0.81	0.01
Na (mEq/l)	8.58	0.39	2.08	0.17	8.27	0.49	1.61	0.11
Ca (mEq/l)	5.36	0.34	4.411		4.22	0.11	4.47	
Ca+Mg (mEq/l)	7.89	0.36	7.18	0.30	7.43	0.52	7.47	0.47
HCO3 (mEq/l)	0.00	0.00					0.01	0.01

FW = fresh water; TWW = treated wastewater; EC = electrical conductivity; SAR = sodium adsorption ratio; TSS = total suspended solids; BOD = biochemical oxygen demand; COD = chemical oxygen demand.

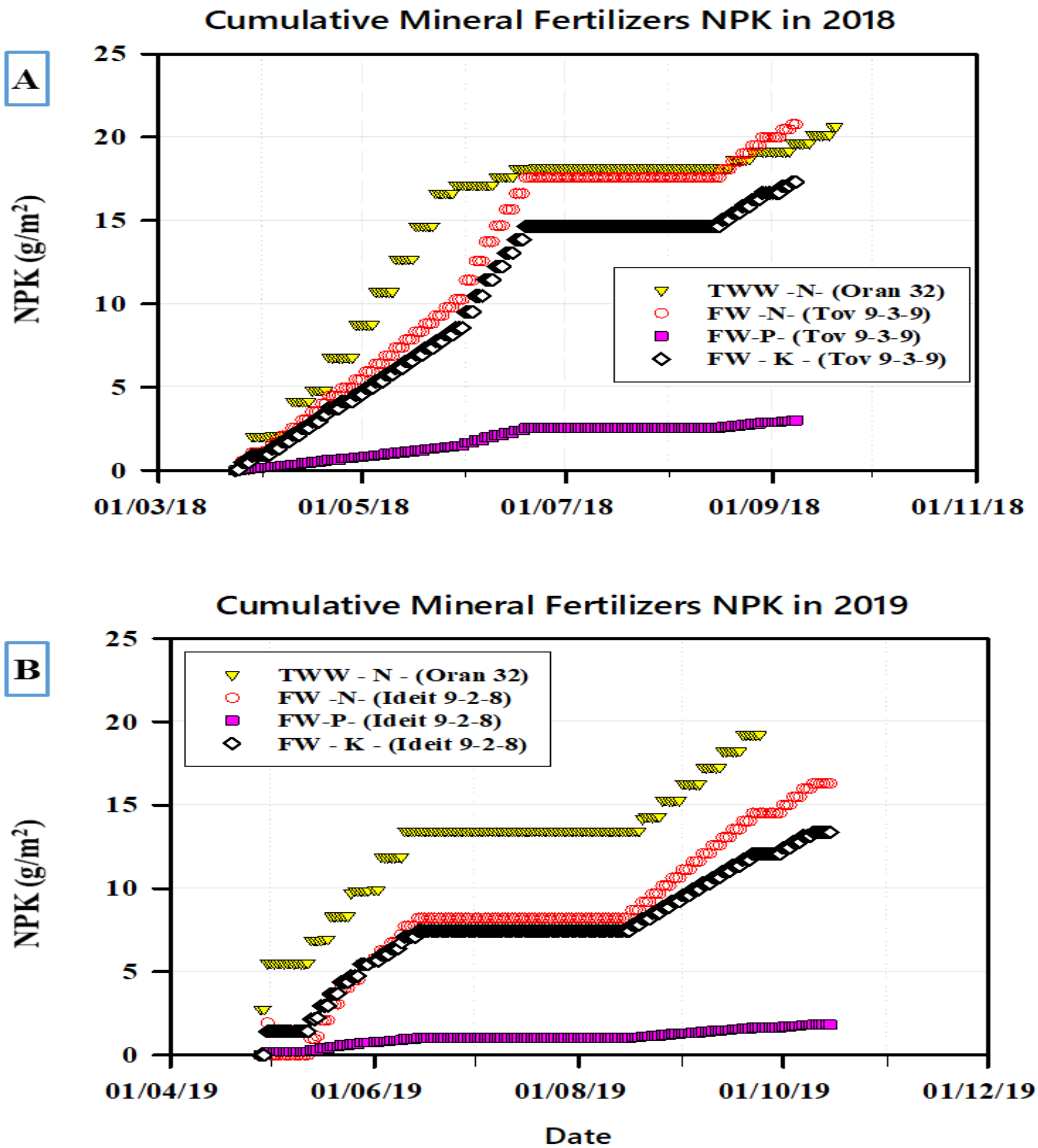

Figure 6. Fertilization durations and cumulative amounts of the mineral NPK elements, that were given to the treatments that were irrigated with TWW (TWW, COM and TUF) and the treatment irrigate with FW in the years 2018 (A) and 2019 (B).

Table 6. Calculated total amounts (g/m^2) of salts and nutrients contributed by the irrigation water up to the days of soil sampling in years 2018 and 2019.

Soil sampling dates	***May 24, 2018***				***October 24, 2018***				***April 18, 2019***				***September 25, 2019***			
Treatment	TWW	COM	TUF	FW	TWW	COM	TUF	FW	TWW	COM	TUF	FW	TWW	COM	TUF	FW
Irrigation water quality	TWW	TWW	TWW	FW	TWW	TWW	TWW	FW	TWW	TWW	TWW	FW	TWW	TWW	TWW	FW
Total water amount (mm)	**284**	**292.6**	**290.4**	**263.5**	**746.8**	**755.63**	**767.61**	**743.6**	**13.8**	**15.3**	**13.15**	**15.8**	**599.8**	**579.1**	**568.52**	**622.1**
K	13.4	13.8	13.7		35.13	35.54	36.1		0.62	0.7	0.6		27.2	26.2	25.74	
Cl	77.4	79.74	79.14	24.04	203.58	205.93	209.2	67.84	3.62	4.03	3.5	1.5	**158**	152.13	149.4	61.83
Mg	9.05	9.32	9.3	7.9	23.8	24.1	24.5	22.32	0.5	0.6	0.5	0.5	22	21.24	20.1	17.7
Na	55.8	57.5	57.03	12.52	146.7	148.4	150.6	35.33	2.6	2.9	2.5	0.6	113.6	109.7	107.7	22.93
Ca	30.5	31.41	31.2	23.3	80.2	81.13	82.42	65.72	1.2	1.3	1.1	1.4	50.72	49	48.1	55.72
N-NH4	1.8	1.85	1.84		4.73	4.79	4.86		0.15	0.17	0.14		6.47	6.25	6.14	
N-NO3	1.92	1.98	1.96		5.05	5.1	5.19		0.13	0.14	0.12		5.54	5.35	5.26	
Kjeldahl N	4.85	5	4.96		12.76	12.91	13.12		0.19	0.21	0.18		8.07	7.79	7.65	
Total - P	2.3	2.37	2.36		6.06	6.13	6.23		0.07	0.08	0.07		3.06	2.95	2.9	
Soluble -P	1.58	1.63	1.62		4.16	4.21	4.28		0.05	0.06	0.05		2.25	2.18	2.14	

4.3. <u>Soil Sampling:</u>

Soil samples were collected for chemical analyses (section 4.3.1) and aggregate stability measurements (section 4.3.2).

Throughout the current research period (2018-2020). The treatments in the field consisted of plots that were randomly organized in 5 blocks (each plot is one replicate of a treatment). The soil samples were taken from each plot twice a year: *May* and *October 2018*; *April* and *September 2019.* For each of the sampling dates, except for April 2019, soil samples were collected from two spots relative to the dripper, as demonstrated in Figure 4: (i) between two central trees, out of the drippers' wetting area, denoted as between trees soil sampling location (Figure 4. F), and (ii) in the dripper wetting area denoted as dripper-adjacent soil sampling location (Figure 4. E). At each sampling location, soil was collected from three depths (0-30 cm, 30-60 cm, 60-90 cm). In *April 2019,* soil samples were collected from dripper- adjacent spots only, and to a depth of 60 cm only. In the case of the TUF treatment, the samples at depth of 0-30 cm, were collected from dripper-adjacent spots yet next to the tuff trench, to avoid collection of the tuff stones; while at depths 30-60 cm and 60-90 cm, soil samples were collected from soil layers underneath the tuff trenches. Regarding the COM treatment, the soil sampling was performed, similarly to FW and TWW treatments. The collected soil samples were brought to the laboratory in Volcani center (ARO), air-dried (45°), and crushed to pass through a 2- mm sieve, and stored in plastic cans under a room temperature to be later analyzed for their chemical and physico chemical properties.

4.3.1. *Ex situ soil water samples – chemical and physico-chemical analyses*

For soil samples taken in 2018 and 2019, 2:1 (water: soil) soil water extracts were prepared for each soil sample, by mixing 15 gr of soil with 30 mL of deionized water, in 50 mL plastic tubes. The tubes were then shaken in a lab shaker for an hour, then centrifuged for at least 5 minutes at 4500 rpm centrifugation speed. The resulted supernatant was filtered with a relatively slow filter discs (#293; 1-2 µm Sartorius, Fisher Scientific, Thermo fisher scientific, Finland) and immediately thereafter, the electrical conductivity (EC) and pH were determined by a SevenCompact Duo S213-meter, pH/Ion dual channel benchtop meter (Mettler-Toledo India Private Limited), respectively.

The soil water extracts were then acidified with 0.04 ml of HCl 4%, prior to storage at 4^{o} C degrees for further analyses.

The concentrations of Ca^{2+} and Mg^{2+} in the extracts were determined by an atomic absorption spectrophotometer (Analyst 400, PerkinElmer, Waltham, MA, USA), following the addition of 1% $LaCl_3$, to prevent their precipitation as insoluble salts with phosphate ions.

Concentrations of Na and of K were determined by a Flame photometry (Sherwood M410; Sherwood Scientific Ltd., Cambridge, UK).

The concentrations of Na, Mg, and Ca were used to calculate the sodium adsorption ratio – SAR $\sqrt{(meq/l)}$ (Richards, 1954) by Eq. [8] following unit conversion from mg/l to meq/l.

Dissolved organic carbon (DOC), was determined in the previously mentioned supernatants, after additional filtration with filter discs of 0.45 µm pores diameter. The filtrates were analysed using a total organic carbon (TOC) analyzer by high-temperature catalytic oxidation (Shimadzu TOC-VCPN with a Shimadzu ASI-V auto-sampler, Kyoto, Japan). In this study the DOC represents the water extractable organic carbon (WEOC).

These filtrates were also used for measuring *UV_{254nm},* by a Thermo Fisher spectrophotometer (Genesys 10S, Germany), both the DOC (mg/l) and the UV_{254nm} analyses were determined at the same dilution ratio of the original water extracts, for calculating the *Specific Ultraviolet Absorbance (SUVA)* by the following equation:

$$\mathbf{SUVA} = \frac{\mathbf{UV}}{\mathbf{DOC}} * \mathbf{100} \qquad \mathbf{(8)}$$

4.3.2. *Aggregate Stability:*

Aggregate stability was determined for soil samples collected from dripper adjacent soil profiles up to 90 cm depth, and from soil profiles between trees at a depth of 0-30 cm, in September 2019. Prior to measurements, the <2 mm soil samples were first sieved to get the fraction between 0.5 and 1 mm by using two sieves (a 1 mm net on top of a 0.5 mm net). Aggregate stability was determined by using a modification of the laser diffraction (LD) technique, commonly used for particle size distribution (e.g., Levy et al., 2017). A Malvern Mastersize 3000 (Malvern Instruments Ltd., Southborough, MA, USA) with red light source: Max. 4mW He-Ne, 632.8nm and blue light source: Max. 10mW LED, 470nm, that measures particles in the range of 0.01 - 3500 µm, was used. Calculation of the size distribution of the measured particles was with Malvern software V5.0, based on theory developed by Mie in 1908 (Wriedt, 2009). Individual soil samples (0.2-0.4 g) of 0.5-1.0 mm aggregates were transferred to the fluid module containing deionized water and equipped with a mechanical stirrer. The variation in the amount of soil transferred to the fluid module depended on the need to satisfy the light transmittance requirements of the laser analyzer (~5-20% of light obscuration). The suspension was then subjected to 10 consecutive 1-min runs using a combined stirring and pump speeds of 1850 rpm, a level that prevents, on one hand, particles from settling out of the suspension and, on the other hand, the creation of air bubbles. Aggregate stability at the end of every 1 min run was estimated from the median size particle (Dx (50)); the greater the size of the median aggregate, the more stable the aggregates.

4.4. Estimation of soil echangeable sodium percentage (ESP):

Estimation of ESP is significant to get an additional indication of how sodic our soil might be. Moreover, to examine whether the different factors (treatment, depth, season, soil profile location) influence the soil ESP. That is possible by adapting the USSL Staff 1954 empirical correlation which is described as follows:

$$ESP = \frac{E_{Na} \cdot 100}{CEC} = \frac{100(-0.0126 + 0.01475\ SAR)}{1 + (-0.0126 + 0.01475\ SAR)} \qquad \textbf{(9)}$$

Developing the USSL 1954 ESP correlation was based on a large variety of soils, however comparing it with our modified ESP correlation will allow us to examine the validity of our calculated ESP. Determining the exchangeable Na, and the SAR of the saturated soil paste extracts, was performed on soil samples collected by the orchard's staff in *March 2017* and analyzed by the extension services laboratory in Tsemach (Table 7). While the CEC was determined at our department's laboratory, on soil samples collected in *September 2019*.

The soil samples belonging to March 2017, were collected from two locations: between the trees' rows, and between the trees in the row, up to 90 cm depth.

By drawing the ESR values vs the SAR data, the slope of the fitted linear line, is defined as the Gapon coefficient (k_G), as was suggested by the US Salinity Laboratory (1954).

In order to get SAR values on the basis of saturated soil paste extracts, the SAR obtained from the 1:2 soil:water (v:w) extracts (soil samples of 2018 and 2019), were converted by using Eq. [10]. This conversion considers multiplying the concentrations of the cations in the soil water extract by a dilution factor, which in our case is equivalent to 2; as the saturation percentage of the saturated soil paste is equivalent to 100 (SP % Table 2), and the soil water extracts were diluted by 2 (section 4.3.1).

$$\mathbf{SAR_{SOIL\ WATER\ EXTRACT} * \sqrt{2} = SAR_{SOIL\ PASTE\ EXTRACT}} \qquad \textbf{(10)}$$

Following the estimation of k_G, the estimation of ESP values for each of the soil samples, is given in the form of the equation proposed by the US Salinity Laboratory 1954 Eq. [11]:

$$\mathrm{ESP} = \frac{100\ (\mathrm{aX} + \mathrm{b})}{1 + (\mathrm{aX} + \mathrm{b})} \qquad \textbf{(11)}$$

a – k_G coefficient, X – SAR of saturated soil paste extracts.

b – the line intercept with axis Y (denotes ESR).

However, for estimating the soil ESP and using the conversion equation (Eq. [10]), a few assumptions must be considered:

1- All ions in the solution are in the form of free ions and not in complexes.

2- The system is found in equilibrium, with the same conditions before and after dilutions: CO2 pressure, and 25 C°.

Table 7. Selected soil pastes extract properties, of soil samples collected on 30.3.2017, before the start of the experiment.

parameter	Soil Depth (cm) 15	45	75
Ca (meq/l)	5.01 (0.57)	3.85 (0.26)	8.38 (1.63)
Ca+Mg (meq/l)	7.02 (0.704)	4.95 (0.33)	10.94 (1.93)
Cl (meq/l)	1.11 (0.07)	2.86 (0.56)	8.22 (1.95)
EC (dS/m)	0.80 (0.06)	0.95 (0.11)	1.75 (0.31)
K (meq/l)	0.28 (0.05)	0.11 (0.02)	0.13 (0.02)
Mg (meq/l)	2.01 (0.19)	1.26 (0.13)	2.56 (0.33)
Na (meq/l)	2.39 (0.32)	5.39 (0.75)	6.35 (1.08)
pH	7.47 (0.03)	7.50 (0.03)	7.33 (0.05)
SP %	95.28 (2.30)	102.55 (2.90)	101.68 (1.68)
SAR	1.32 (0.24)	3.38 (0.37)	2.74 (0.25)

Means calculated based on 4-5 replicates. Standard errors are shown in parentheses.

EC = electrical conductivity, SP = saturation percentage, SAR = sodium adsorption ratio.

4.5. **Field Sensors Measurements:**

4.5.1. *Soil moisture monitoring:*

TDT sensors are comparable to TDR (Time Domain Reflectometer) sensors (Time Domain Transmissometer) are used for measuring the soil moisture content, and it is based on the reflected electromagnetic signals transmitted. Volumetric water content, EC, and temperature of the soil at depth 35 cm, were monitored continuously by in-situ installed TDT sensors (Digital TDT® Acclima Inc., Meridian, Idaho, USA). These sensors are Digital Time Domain Transmission meters, that measure the permittivity of soils by determining the propagation time of an electromagnetic wave transmitted along a waveguide through the soil. The transducer can be commanded to produce both the bulk permittivity and the water content of the soil. The transducer also measured soil temperature. The permittivity and soil moisture measurements were corrected for temperature effects. The sensors were installed at a 35 cm depth, in the tree rows 15 cm from the dripline laterals (Figure 4. K), and in mid distance between the two central almonds trees (Figure 4. L). For comparing between the volumetric water content of the soil in the different treatments, a normalization of data was performed on the data of each sensor. Normalizing of the actual data transmitted by each sensor, was performed by locating the maximum value transmitted by each sensor, on a graph where it showed the activity of each sensor. The maximum value of each sensor on the graph, was considered a 100 percent volumetric water content (VWC).

4.5.2. *Soil Aambiance oxygen monitoring:*

Oxygen concentration in the soil pores was measured by means of a galvanic cell type sensor which linearly matches the oxygen content in an ambiance by voltage units (in mV). The oxygen sensors (KE-50, Figaro, Japan) were firstly plugged in a small container made of 50 ml plastic tube, and carefully sealed with silicon, allowing for only the wires to be out of the container, thus protecting the sensors from soaking in water in the field. Additionally, the container was perforated with small holes at the bottom allowing only for air entrance, as shown in Figure 7. Thereafter, the sensors were installed in the wetted area of the tree-adjacent dripper, 15 cm from the drip-line laterals (similar to the TDR sensors Figure 3.M), at 35 cm depth. The readings were calibrated to match 20 % oxygen as maximum oxygen content in the soil ambiance (50 mV maximum sensors' potential), by installing them at 35 cm depth in buckets filled with air-dried soil collected from the experimental site, and to match 0% oxygen by soaking the sensors in gaseous nitrogen.

Both the oxygen and the volumetric water content sensors were installed during July 2019. The sensors were connected to different data loggers (CR 1000, CR 3000, Campbell Scientific Inc.) and the data were transferred to the network and stored every 30 minutes.

Figure 7. KE-50 oxygen sensor sealed in plastic container. Electric wires and water suction tube are let out.

5. Statistical Analyses

All the statistical analyses were conducted by using JMP 15 (MP®, Version <15>. SAS Institute Inc., Cary, NC, 1989-2019).

5.1. **<u>Statistical analyses of the chemical analysis part:</u>**

As soil sample were taken from the same plots at different depths and different spots, a split plot ANOVA model (using a significance level $p < 0.05$) was used for each sampling date, with treatment as the main plot effect, depth and spot as sub-plot effects and plot nested within treatment as the random sub-plot factor. On dates where information was available, the random block factor was added.

Following the analysis of all the data by the complete above-mentioned model, the following specific models were defined.

For the comparison between the overall effect of the season on the measured parameters, an ANOVA model was used for each depth at spot b, with date of soil sampling and treatment and their interaction as fixed factors. (The data for the soil sampling location between-trees were not included, as they were not collected for April 2019.)

For the *September 2019* data (following the irrigation season), the ANOVA split plot model analysis was followed by analyses for each location separately: comparison of treatments for each depth, and comparison between depths for each treatment.

Post-hoc pairwise comparisons of depths within treatment or treatments within depth were performed by the Tukey-Kramer HSD test using a significance level $p < 0.05$.

Log transformation was performed on the values of the parameters where necessary, in order to normalize and to stabilize variances.

5.2. **<u>Statistical analysis of the Aggregate stability measurements:</u>**

Repeated measures ANCOVA (analysis of covariance), was conducted for each depth and location separately to compare treatments with treatment as a fixed factor, and two random factors: block, and plot which was nested within treatment and block. Log- transformed time was considered as the continuous factor. Post-hoc pairwise comparisons of treatment means were made by the Tukey-Kramer HSD test using a significance level $p < 0.05$.

- In a few cases we also used the student's t test.

5.3. <u>Statistical analysis of the sensors data:</u>

The oxygen and the volumetric water content (VWC) data were measured by the sensors every 30 minutes for different time frames through the years 2019 and 2020. Averages were calculated for each sensor, on each day, for two periods – before noon and after noon.

Treatments were compared for the day of irrigation only, where the ANOVA model (using a significance level $p < 0.05$) included treatment, sampling location, and period of day as fixed factors, and plot nested within treatment, as a random factor.

(The treatments were compared only for the day of irrigation)

Pairwise comparison between treatments was performed for each location separately by the Tukey-Kramer HSD test using a significance level $p < 0.05$.

6. Results

6.1. Establishing the ESP-SAR relationship

In order to be able to estimate soil ESP from existing SAR values, we determined the ESP-SAR relationship (Figure 8) for our field data based on the approach developed by the US salinity laboratory staff (1954) (for details see section 4.4). A linear regression was fitted for ESR as a function of SAR, using measured data from March 2017 sampling campaign.

6.1.1. *Estimation of Gapon coefficient, and developing the soil ESP equation:*

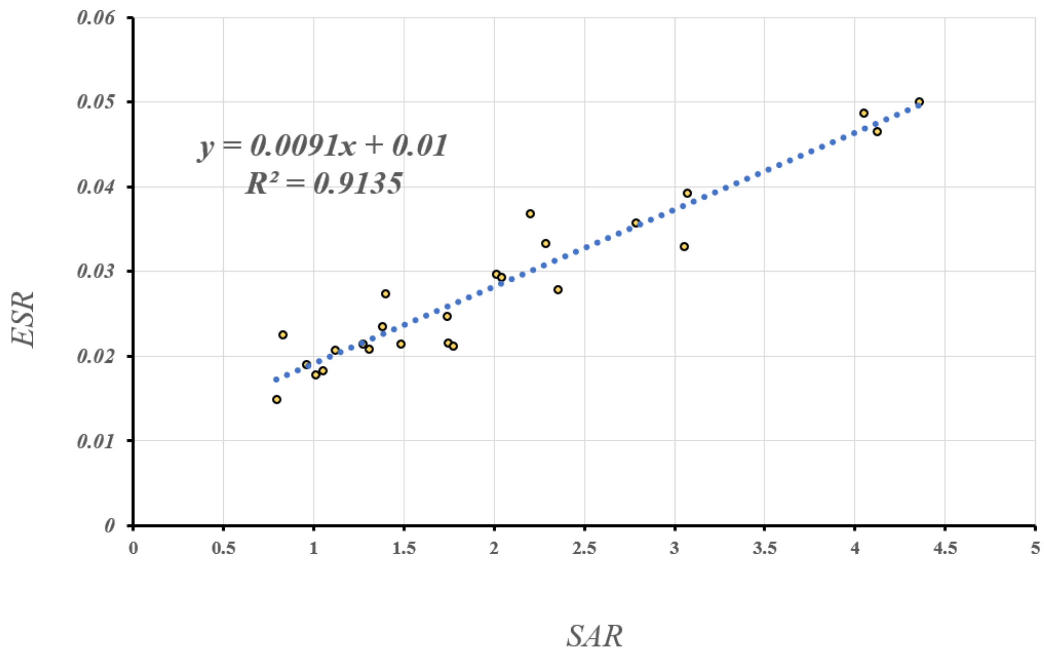

Figure 8. Exchangeable sodium ratio (ESR) vs. the sodium adsorption ratio (SAR) for data obtained from the soil analysis from the March 2017 sampling campaign. The slope of the fitted regression line is the Gapon coefficient (US salinity laboratory staff 1954).

The equation of the regression line obtained in Figure 8 is:

$$\mathrm{ESR} = 0.0091\ \mathrm{SAR} + 0.01 \qquad \textbf{(12)}$$

Where the slope of the line, 0.0091, is the Gapon coefficient.

Introducing the constants in Eq. [12] to Eq. [11], yields our modified "US salinity Laboratory 1954" empirical equation for calculating the ESP as follows:

$$\mathrm{ESP} = \frac{100\ (0.0091\ \mathrm{SAR} + 0.01)}{1 + (0.0091\ \mathrm{SAR} + 0.01)} \qquad \textbf{(13)}$$

ESP values were estimated using Eq. (13) using SAR values that were obtained in 1:2 soil:water extracts and then converted to SAR of saturated soil paste using Eq. [10], for soil samples collected in years 2018 and 2019.

6.2. Analyses on soil samples – Chemical analysis:

In order to address the main objective of the research we investigated the effects of water quality (FW vs. TWW) as well as the effects of two new agro-technical methods: tuff and compost trenches (TUF, COM) on some soil physico-chemical parameters of an almond orchard planted on a clayey soil. Chemical analyses of soil sampled along the soil profile, and at different locations relative to a given dripper enabled addressing the following specific objectives: investigating the effects of the treatments on (i) sodicity and salinity in the soil profile at the end of the irrigation season; and (ii) spatial distribution of salinity and sodicity around the trees. To this end I used the data of the soil samples in September 2019 because this was the latest sampling date in the current research and reflected the impact of 3 consecutive years of irrigation since the setup of the four treatments (since *2017*). The results exhibited similar trends to those obtained for samples taken on October 2018, therefore the 2019 results were considered typical to the end of the irrigation season.

6.2.1. *Between - trees vs. dripper - adjacent soil profile (September 2019)*

The measured parameters in this section are referred to dilute soil water extracts of soil samples collected from soil profiles located adjacent to dripper (Figure 4. E) or between trees (Figure 4. F). Differences in pH values between both sampling locations and treatments were insignificant (Table 8), therefore data are not shown.

Between trees the following measured parameters EC, Cl, Na, K, Ca+Mg, the calculated SAR and ESP, were significantly lower than those obtained from samples collected from dripper adjacent soil profiles (Figures 9, 29 in appendix, 11, 12, 13, 30 in appendix, respectively). In addition, the tested treatments did not have a significant effect on these parameters in soil profiles between trees. Conversely, DOC, UV_{254nm} and SUVA (Figures 14, 31 and 32 in appendix, respectively), showed significantly higher values in soil profiles located between trees than of those located adjacent to the dripper. In general, the treatments did not affect these parameters in soil profiles in both locations.

Table 8. ANOVA (Prob > F) of the soil solution composition variables, September 2019. Highlighted numbers are significant (p<0.05)

Variable	*Block*	*Treatment*	*Location*	*Treatment *Location*	*Depth*	*Treatment *Depth*	*Location *Depth*	*Treatment *Location *Depth*
df	**4**	**3**	**1**	**3**	**2**	**6**	**2**	**6**
pH	0.69	0.4543	0.2664	0.8498	0.1571	0.8595	0.1821	0.8224
EC	0.03	0.0185	2.46E-13	0.7696	0.5866	0.4083	0.2547	0.7327
Cl	0.38	0.001	2.23E-12	0.8507	0.6823	0.3284	0.1086	0.5336
Ca+Mg	0.11	0.8515	0.0003	0.2159	0.1989	0.7021	0.0008	0.6753
K	0.05	0.8259	0.0001	0.1346	6.53E-08	0.0966	0.0159	0.5089
Na	2.91E-06	1.53E-06	4.82E-21	0.02	2.96E-09	0.8892	0.571	0.2881
SAR	1.95E-05	0.021	2.48E-20	0.0003	1.17E-19	0.3797	0.3857	0.1249
DOC	0.108	0.3437	0.6503	0.5879	0.0418	0.8	0.7867	0.7972
UV	0.19	0.3408	0.0184	0.5858	3.99E-06	0.9123	0.0896	0.9018
SUVA	0.0034	0.8663	0.1863	0.4432	4.12E-06	0.4225	0.826	0.6798

EC= electrical conductivity, SAR= sodium adsorption ratio, DOC = dissolved organic carbon, SUVA = specific ultraviolet absorbance

The values determined for EC (Figure 9 B) and Cl (Figure 29B in the appendix) in dripper adjacent soil profiles, were distributed similarly, and significant differences were noted between the treatments (Table 8). Thus, in COM, EC and Cl were significantly higher than in TUF, at a depth of 15 cm. Furthermore, EC and Cl in TWW were significantly higher than in FW at a depth of 45 cm. For all the treatments, EC and Cl were comparable at a depth of 75 cm. A trend of decrease in EC and Cl was observed down the soil profile only in COM.

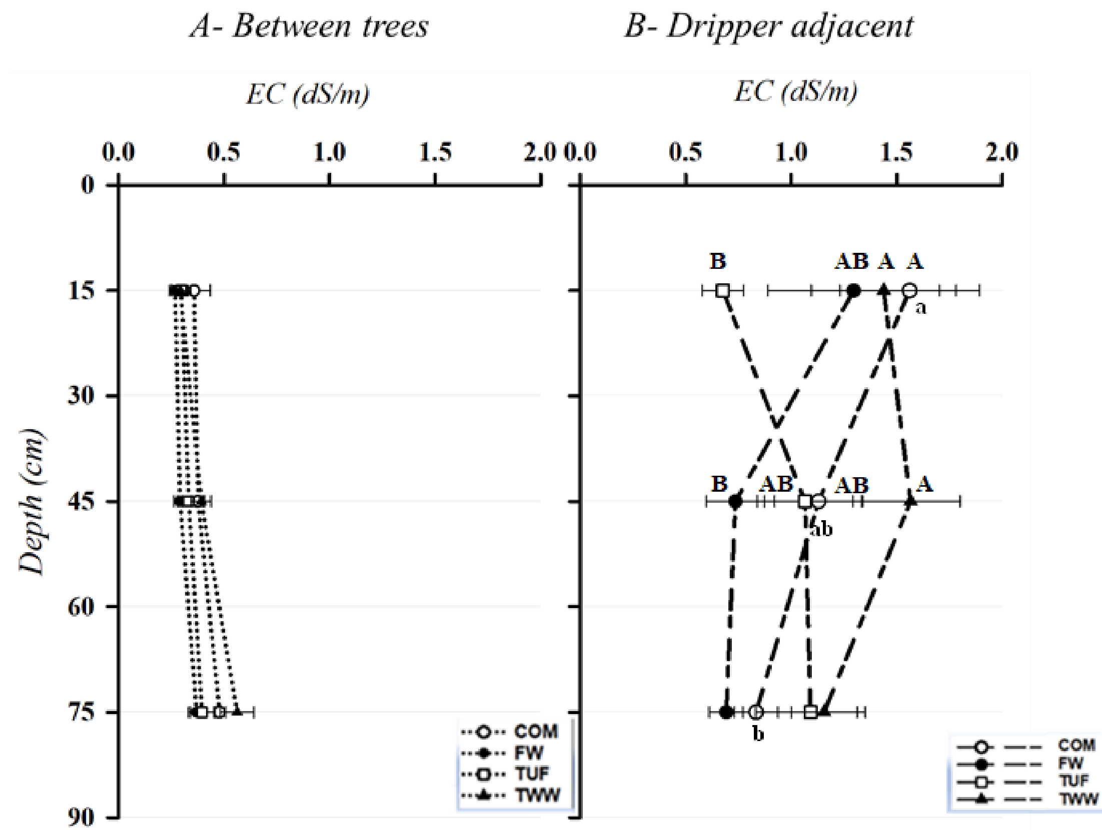

Figure 9. Effects of the soil profile location: A – between trees, B – dripper adjacent, treatments (COM, FW, TUF and TWW), and depth on average electrical conductivity (EC) of the soil water extract. Bars indicate two standard errors. Different uppercase letters on the curve, indicate significant difference (p < 0.05) between treatments at a given soil depth. Different lowercase letters on the curve, indicate significant difference (p < 0.05) between depths for a given treatment.

The Na concentration in dripper-adjacent soil profiles (Figure 10 B) was significantly higher in both COM and TWW (7.34 and 6.7 meq/l, respectively) than in FW (2.9 meq/l), at a depth of 0-60 cm, while its concentration in TUF was not significantly different than in any of the treatments, at the same depth. At a depth of 60-90 cm, the treatments were comparable. A trend of increase in Na concentrations down the soil profile was observed in FW and TUF treatments. Na concentrations between trees was significantly lower in TUF than in COM at a depth of 0-30 cm, with a trend of increase in Na concentrations down the soil profile observed in TUF.

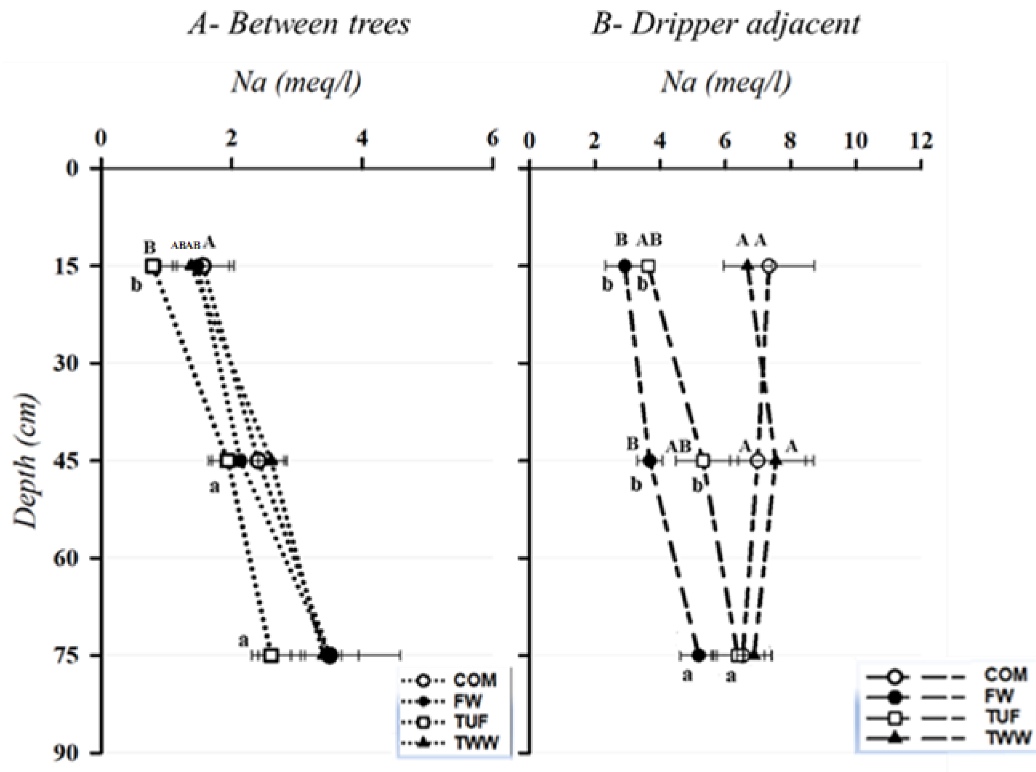

Figure 10. Effects of the soil profile location: A – between trees, B – dripper adjacent, treatments (COM, FW, TUF and TWW), and depth on average sodium concentration (Na) of the soil water extract. Bars indicate two standard errors. Different uppercase letters on the curve, indicate significant difference ($p < 0.05$) between treatments at a given soil depth. Different lowercase letters on the curve, indicate significant difference ($p < 0.05$) between depths for a given treatment. Note: Scales on X axis differ between soil profile locations.

The K concentrations in dripper-adjacent soil profiles (Figure 11. B) at depth of 0-30 cm were significantly higher in COM (0.39 meq/l) than in FW (0.16 meq/l). In TUF (0.212 meq/l) and TWW (0.25 meq/l), K values were similar and did not differ significantly from COM or FW. At a depth of 30-90 cm, HSD-Tukey ($p < 0.05$) did not show any significant difference between the treatments. A trend of decrease in K concentrations down the soil profile, was observed in COM and TWW. The concentrations of K between trees (Figure 11. A), was comparable between the treatments, with a trend of decrease in K concentrations down the soil profile.

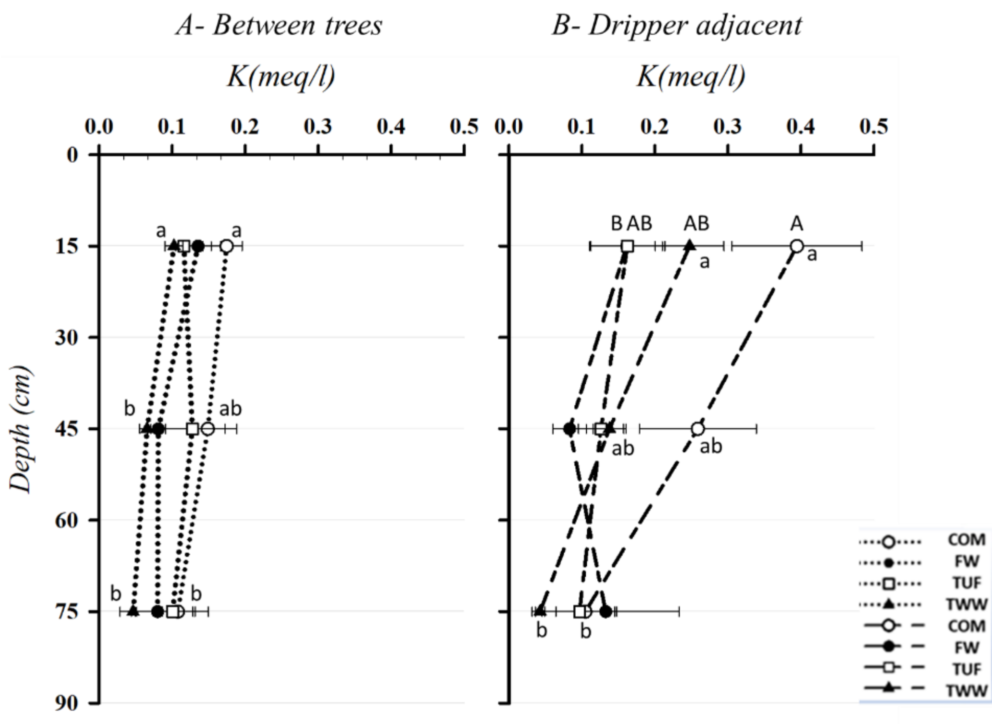

Figure 11. Effects of the soil profile location: A – between trees, B – dripper adjacent, treatments (COM, FW, TUF and TWW), and depth on average Potassium concentration (K) of the soil water extract. Bars indicate two standard errors. Different uppercase letters on the curve, indicate significant difference ($p < 0.05$) between treatments at a given soil depth. Different lowercase letters on the curve, indicate significant difference ($p < 0.05$) between depths for a given treatment.

In this study, the overall concentrations of Mg were remarkably lower than of Ca concentrations in both the dilute soil water extracts, and in the exchange complex (Table 2). Therefore, the effects of Mg on soil dispersion and swelling are considered fairly similar to those of Ca; hence, it was felt reasonable to sum it together with Ca. In dripper-adjacent soil profiles (Figure 12B), the Ca+Mg concentrations were significantly higher in FW (14.06 meq/l) than in TUF (4.66 meq/l), at a depth of 0-30 cm. At this depth, COM (10.9 meq/l) and TWW (9.58 meq/l) were similar and did not differ significantly from either TUF or FW. At a depth of 30-60 cm in this soil profile, TWW (9.91 meq/l) was significantly higher than FW (5.98 meq/l), whereas TUF (6.92 meq/l) and COM (6.51 meq/l) were similar and did not differ significantly from TWW and FW. The Ca+Mg concentrations at a depth of 60-90 cm were significantly higher in TUF (6.17 meq/l) than in FW (3.63 meq/l) and COM (3.7 meq/l), whereas the TWW treatment did not differ significantly from the rest of the treatments.

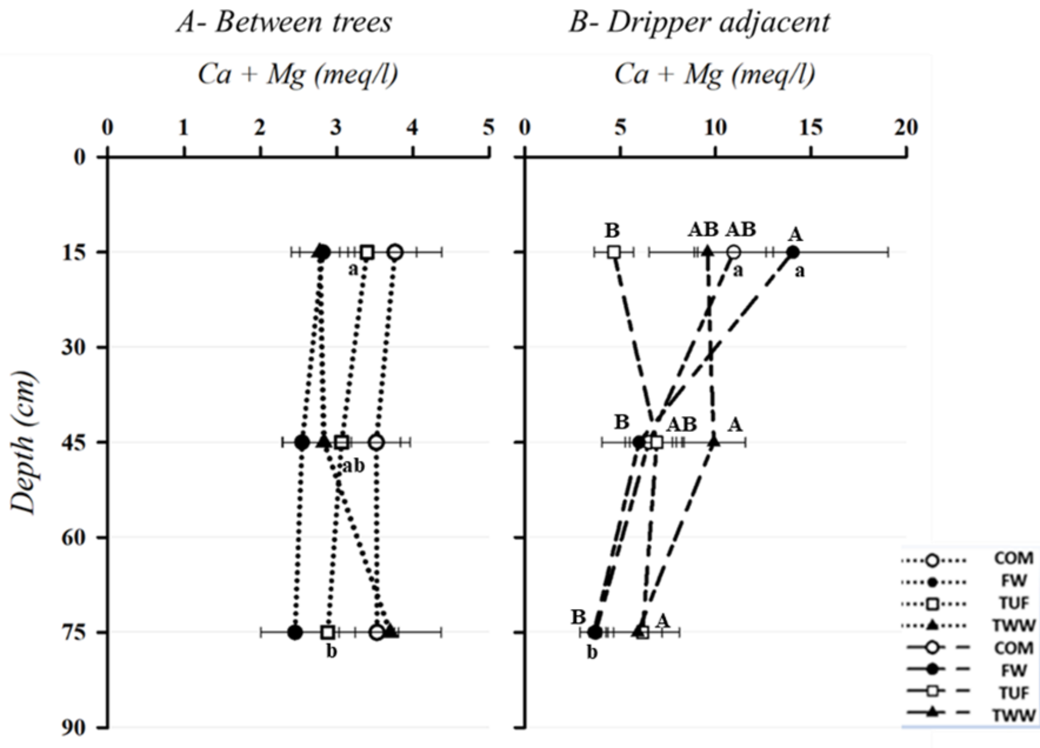

Figure 12. Effects of the soil profile location: A – between trees, B – dripper adjacent, treatments (COM, FW, TUF and TWW), and depth on the average Ca+Mg concentrations (meq/l) of the soil water extract. Bars indicate standard errors. Different uppercase letters on the curve, indicate significant difference ($p < 0.05$) between treatments at a given soil depth. Different lowercase letters on the curve, indicate significant difference ($p < 0.05$) between depths for a given treatment. Note: Scales on X axis differ between soil profile locations.

A trend of Ca+Mg decrease down the soil profile was observed in TUF between trees, and in COM and FW in adjacent to dripper soil profiles.

As opposed to the variation of the previously presented parameters (EC, Ca+ Mg, K, Cl) with depth in the soil profiles, we notice that similarly to Na (Figure 10 B), SAR values (Figure 13) increased with the increase in soil depth in both soil profile locations.

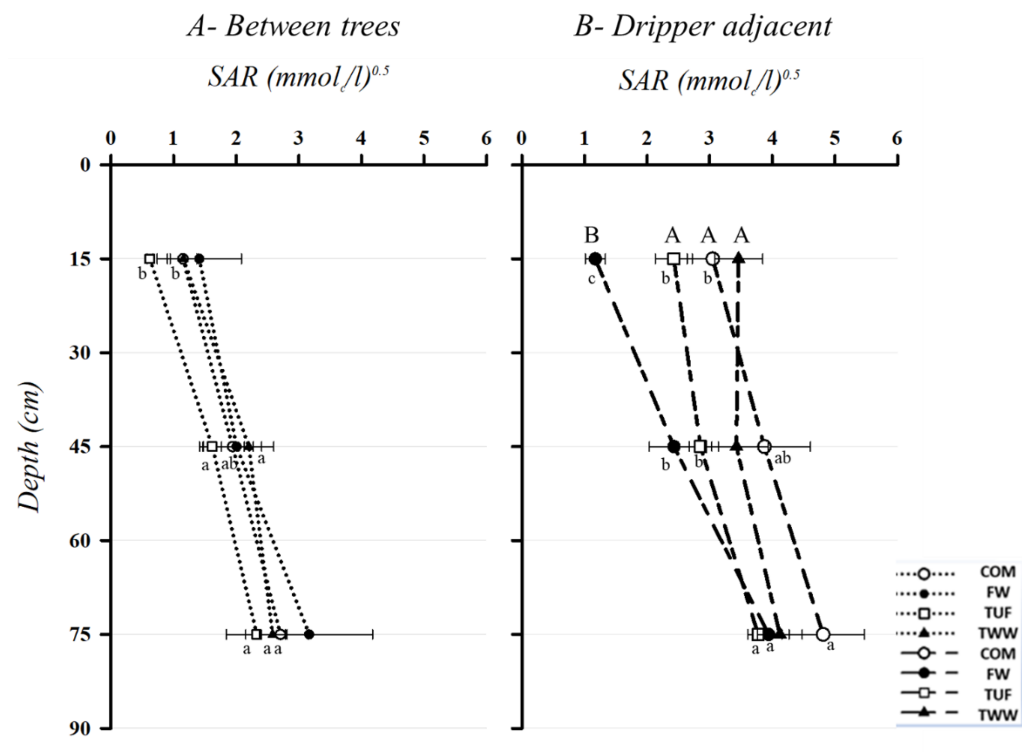

Figure 13. Effects of the soil profile location: A – between trees, B – dripper adjacent, treatments (COM, FW, TUF and TWW), and depth on sodium adsorption ratio (SAR)) of the soil water extract. Bars indicate two standard errors. Different uppercase letters on the curve, indicate significant difference ($p < 0.05$) between treatments at a given soil depth. Different lowercase letters on the curve, indicate significant difference ($p < 0.05$) between depths for a given treatment.

For samples collected from soil profiles located adjacent to the dripper (Figure 13B), at a depth of 0-30 cm, the SARs of TWW (3.46), COM (3.05) and TUF (2.43), were significantly higher than that of FW (1.17). At depths of 30-90 cm the differences between SARs of the treatments were not significant. However, by applying a less strict statistical test, Student's-t test, instead of HSD-Tukey ($p<0.05$), we noted that SAR of COM (3.9), was significantly higher than that of FW (2.4).

The ESP data were derived from the estimated SAR values (Figure 13), by applying Eq. [13], therefore the distribution of ESP (Figure 30 in the appendix) is identical to that of SAR, only with different values, which will be discussed later.

In dripper-adjacent soil profiles (Figure 14.B), a significant difference in DOC between treatments was observed only at a depth of 60-90 cm, where DOC in COM was significantly higher (32.97 mg/l) than in TWW (20.29 mg/l). A trend of decrease in the DOC down the soil profile was observed only in TWW treatment.

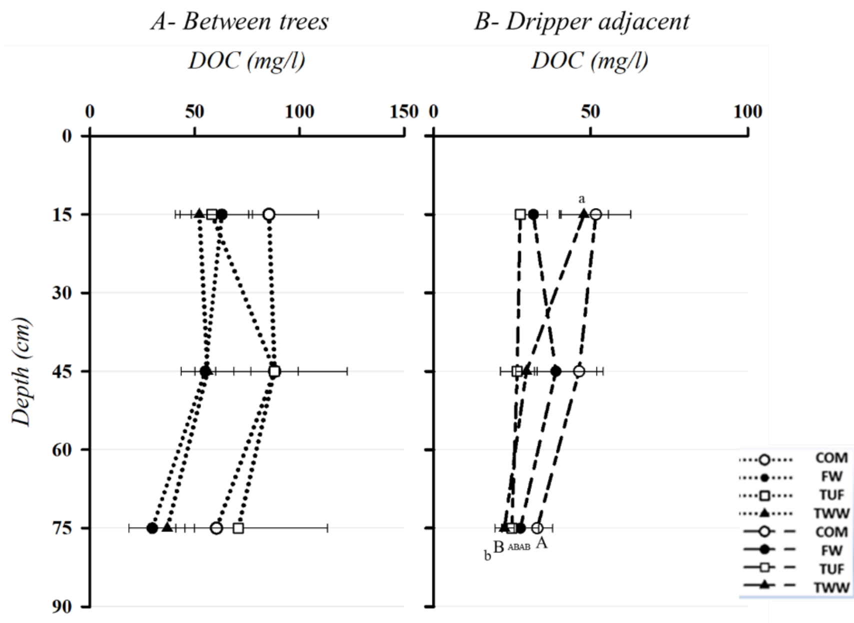

Figure 14. Effect of the soil profile location: A – between trees, and B – dripper adjacent, the treatments: COM, FW, TUF and TWW, and the depth in each treatment, on average dissolved organic carbon concentration (DOC) of the soil water extract. Bars indicate two standard errors. Each uppercase letter on the curve, indicates a significant difference ($p < 0.05$) between treatments at each soil profile location. Each lowercase letter on the curve, indicates significant difference ($p < 0.05$) between depths for each treatment. Note: Scales on X axis differ between soil profile locations.

In both soil profiles locations, the UV_{254nm} and SUVA (Figure 31and Figure 32, respectively in appendix) were comparable for all the treatments (Table 8), with a general trend of decrease with the increase in soil depth.

6.3. Aggregate Stability – physical analysis:

Aggregate stability (AS) measurements were conducted on soil samples, collected from dripper-adjacent soil profiles, at all the depths up to 90 cm (Figure 19. A, C and D), while for soil profiles located between trees, AS measurements were performed on soil samples at a depth of 30 cm only (Figure 19. B). AS measurements on part of the soil samples followed the analyses of Na, SAR and ESP, in cases where we observed significant differences and were interested in further indications as to the relations between chemical and physical properties of the soil. Hence, we did not perform AS analysis on soil samples that were not significantly affected by sodicity (i.e., between trees at depths >30 cm).).

The results indicated that differences in AS between treatments at a depth of 0-30 cm, in soil profiles between trees (Figure 19. B) were not significant.

At dripper adjacent soil profile, the curve for AS (expressed in terms of median aggregate size [Dx50]) under FW treatment, at a depth of 0-30 cm (Figure 19. A) was higher than the curves for the rest of the treatments (TWW, COM and TUF). However, results of the Tukey-Kramer HSD test using a significance level $p < 0.05$, did not show any significant differences in the curves between the treatments at this depth. Because of a significant difference in SAR values between water qualities at a depth of 0-30 cm, we decided to also employ the Student's-t test that showed that for FW the median aggregate diameter (Dx50) is significantly higher (115.8 micron) than that for TWW (93.19 micron). Though we rely on the Tukey-Kramer HSD test using a significance level $p < 0.05$, for analyzing our parameters, in this specific situation, the significance proven by the Student's-t test indicates that the treatments may have significant effects that the highly strict Tukey-Kramer HSD test rejected. Moreover, this apparent significant effect of FW on AS is supported by the results shown for the SAR/ESP values at an average depth of 15 cm, in dripper-adjacent soil profile (Figure 14, Figure 15. B) where the SAR and ESP of TWW were significantly higher than those of FW. Significant differences between the treatments were also observed at an average depth of 45 cm, where AS in FW was significantly higher (128.96 micron) than those observed in the rest of the treatments (TUF>TWW> COM) that did not significantly differ from each other.

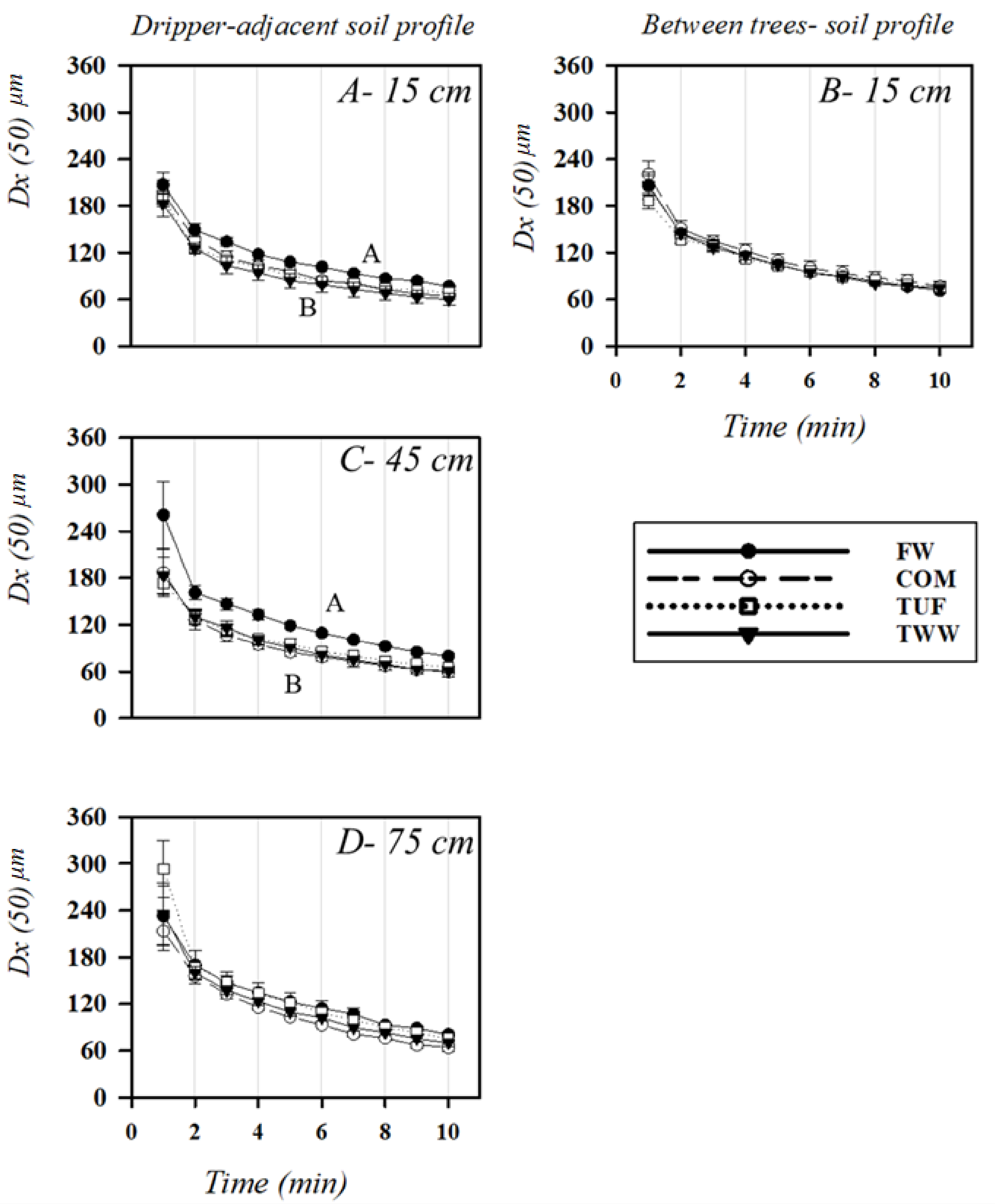

Figure 15. Effect of treatments: COM, FW, TUF and TWW on aggregate stability (expressed in terms of median aggregate size [Dx (50)] of the soil samples collected at average depths: 15 (A), 15(B), 45 (C), and 75 (C) cm, from soil profiles located adjacent to the dripper, except for (B) where samples were collected from soil profiles between trees, in September 2019. Bars indicate two standard errors. Uppercase letters indicate significant difference (p<0.05) between the treatments at each depth.

6.4. <u>Analyses on soil samples – Chemical analysis:</u>

As already mentioned in section 4.3, soil samples were collected in *May 2018* (Spring-018), *October 2018* (Fall-018), *April 2019* (Spring-019), and *September 2019* (Fall-019). Therefore, it is of interest to examine sampling date effects (seasons) on the chemo-physical properties of our clayey soil, together with the effects of water quality (FW and TWW) and the two tested agro-technical methods (COM and TUF).

6.4.1. *Change of parameters over seasons, at dripper-adjacent soil profiles.*

Following the previous results presented in section 6.2.1, we noticed that the major effects of water quality were in soil profiles located adjacent to the dripper. Thus, in order to examine the effects of climatic seasons, treatments, and soil depth on the studied attributes (salinity, sodicity and DOM characteristics), the averages of the analyzed parameters from each sampling date, each depth (up to 90 cm) and for each treatment (FW, TWW, COM and TUF), were pooled for dripper-adjacent soil profiles and shown in the following Figures. In Table 9 the statistical analysis did not consider the blocks effect, due to technical problems in the soil sampling campaign.

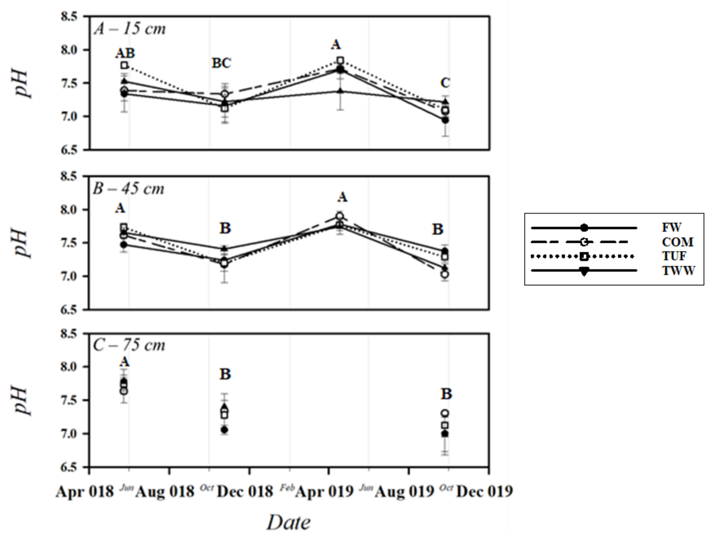

Figure 16. Effects of the season (soil sampling date) on the pH of the soil water extract of soil samples collected from dripper-adjacent soil profiles at three average depths: (A) 15 cm, (B) 45 cm and (C) 75 cm. Bars indicated standard errors. Each uppercase letter on the curve, indicates significant differences ($p <$ 0.05) between soil sampling dates at each depth. Note: in April 2019 soil was not sampled at 75 cm depth (C). Significant differences between the treatments in each date at each depth, will be mentioned in the descriptive text only.

In general, the parameters fluctuated among the seasons, being lower at Fall (following irrigation seasons) compared with Spring (following rainy season) (Figure 17, Figure 19, Figure 33 and Figure 34 in appendix). At a depth of 0-30 cm, the effect of the seasons was significant on all parameters but for K (Table 9). While at a depth of 30-60 cm, the effect of the seasons was significant on all the parameters but for SAR and borderline for in the case of K. And at a depth of 60-90 cm, the effect of the seasons was significant on some parameters (pH, EC, Cl, Ca+Mg, COD and UV).

Table 9. ANOVA (Prob > F) of the soil solution composition variables, in Spring 2018, 2019 and September 2018, 2019 (adjacent to the drippers). Highlighted numbers are significant (p<0.05).

Depth (cm)	Variable	df	pH	EC	CL	Ca+Mg	K	Na*	SAR*	DOC	UV	SUVA
0-30	Date	3	5.84E-05	9.6E-06	3.88E-08	5.66E-05	0.1807	9.7E-07	0.014	0.0023	7.4E-15	0.0034
	Treatment	3	0.6325	0.4201	0.0315	0.4209	0.0642	0.00019	0.000029	0.5224	0.1375	0.6197
	Treatment*Date	9	0.5606	0.9882	0.5168	0.8066	0.1106	0.36	0.93	0.4621	0.06537	0.1522
30-60	Date	3	6.1E-13	4.97E-11	3.08E-14	2.57E-11	0.0507	3.8E-06	0.18	1.38E-06	3.43E-23	4.51E-07
	Treatment	3	0.81	0.0097	0.0056	0.6679	0.0295	0.0016	0.00019	0.688411	0.161109	0.929303
	Treatment*Date	9	0.1006	0.5958	0.2446	0.0444	0.0083	0.76	0.31	0.729767	0.332947	0.982413
60-90	Date	2	3.03E-05	3.18E-07	1.07E-07	0.0378	0.4273	0.77	0.31	0.0011	2.74E-06	0.0656
	Treatment	3	0.7802	0.003516	8.37E-05	0.0069	0.5202	0.014	0.068	0.2867	0.5324	0.2649
	Treatment*Date	6	0.6789	0.172774	0.013448	0.256	0.8563	0.47	0.6	0.0824	0.9034	0.0628

Na* and SAR*, df = 2, statistical analyses excluded Spring 2018, at depths 0-30 and 30-60 cm, df= 1 at depth 60-90 cm.

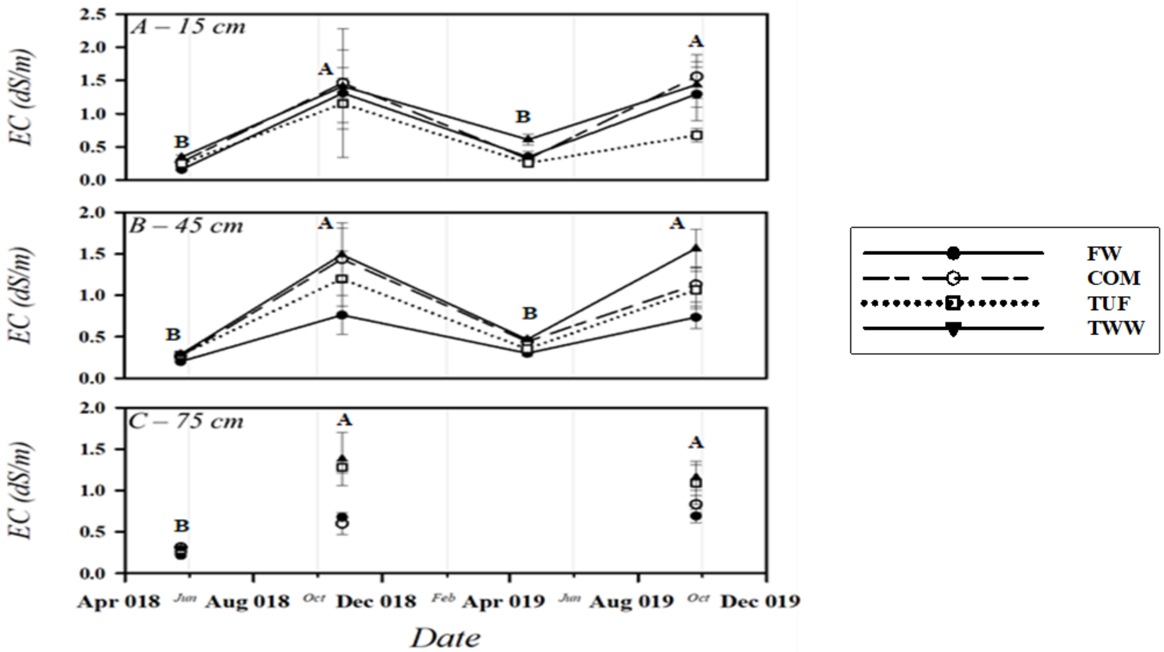

Figure 17. Effects of the season (soil sampling date) on the EC (dS/m) of the soil water extract of soil samples collected from dripper-adjacent soil profiles at three average depths: (A) 15 cm, (B) 45 cm and (C) 75 cm. Bars indicated standard errors. Each uppercase letter on the curve, indicates significant differences (p < 0.05) between soil sampling dates at each depth. Note: in April 2019 soil was not sampled at 75 cm depth (C). Note: Scales on Y axis differ between depths. Significant differences between the treatments in each date at each depth, will be mentioned in the descriptive text only.

Differences between the EC of treatments at 0-30 cm depth, were not significant. At a depth of 30-90 cm, the treatments had a significant effect on the EC. Unlike the EC, in Cl the differences between the treatments were significant at all soil depths.

The effect of treatments on Ca+Mg (Figure 27 in appendix) differed among the depths. At a depth of 0-30 cm, the effect of the treatments was insignificant, while at a depth 60-90 cm, there was a significant effect. At a depth of 30-60 cm, an interaction between the date and the treatment existed, therefore, data of each combination of date and treatment need to be compared (see section 6.2.1, Figure 12).

At all depths, the effect of treatments on Na (Figure 19), was significant (Table 9). In the case of K (Figure 18), the effect of the treatments was significant only at a depth of 30-60 cm. The effect of the treatments on SAR (Figure 20) was significant up to 60 cm. The effect of the treatments on ESP (Figure 35 in appendix) was similar to the SAR, as it was calculated based on SAR by applying Eq. [13].

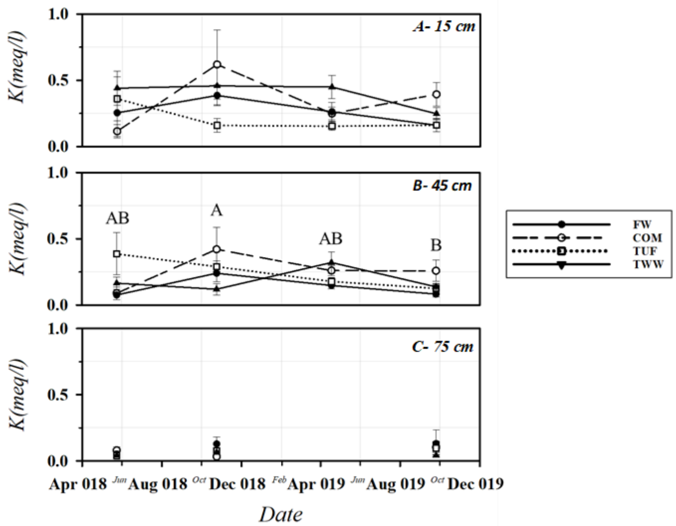

Figure 18. Effect of the season (soil sampling date) on the average Potassium concentration (meq/l), in the soil water extract, of soil samples collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Significant differences between the treatments in each date and at each depth, will be mentioned in the descriptive text only.

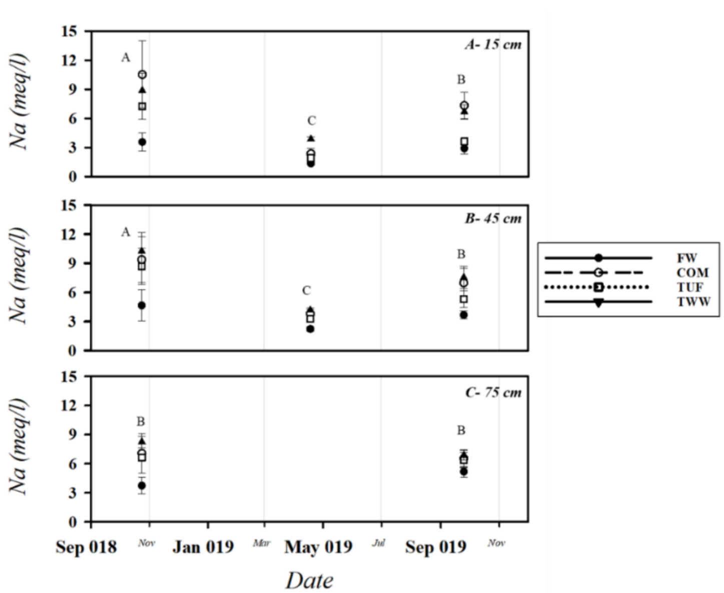

Figure 19. Effect of the season (soil sampling date) on the average Sodium concentration in the soil water extract, of soil samples collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Significant differences between the treatments in each date and each depth, will be mentioned in the descriptive text only

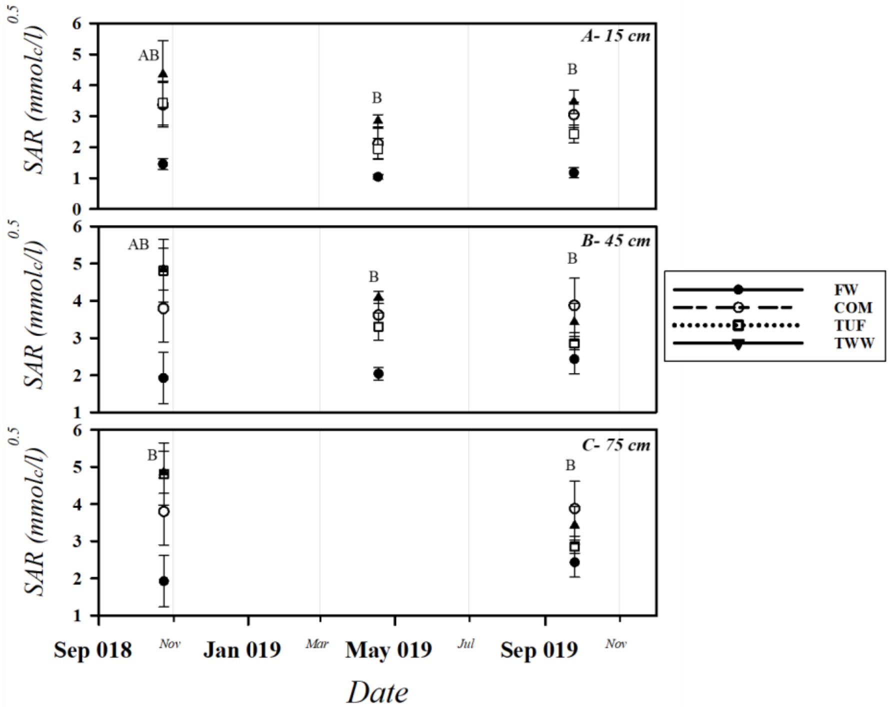

Figure 20. Effect of the season (soil sampling date) on the average Sodium Adsorption ratio - SAR (meq/l)$^{0.5}$, in the soil water extract, of soil samples collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference (p < 0.05) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Significant differences between the treatments in each date and at each depth, will be mentioned in the descriptive text only.

The effect of the treatments on the DOM characteristics (DOC, UV and SUVA, Figure 21, Figure 22, and Figure 23, respectively) was not significant (Table 9).

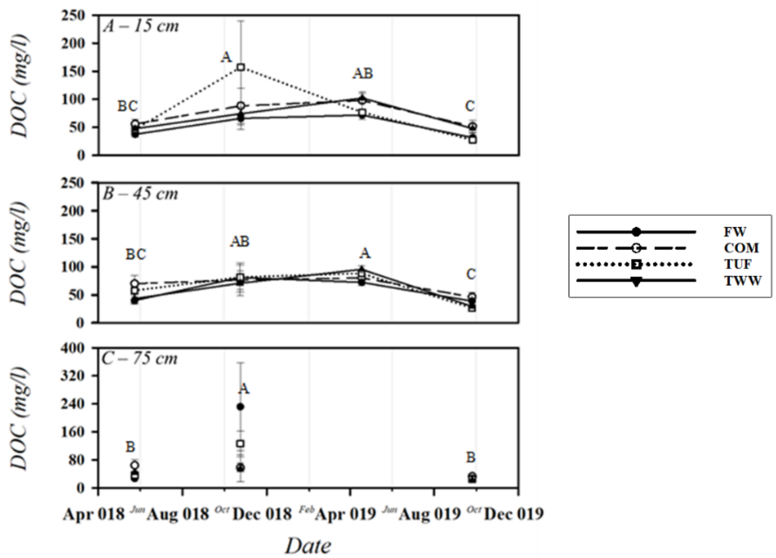

Figure 21. Effect of the season (soil sampling date) on the dissolved organic carbon (DOC), in soil water extracts of soil samples that were collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference (p < 0.05) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Scales on Y axis differ between depths.

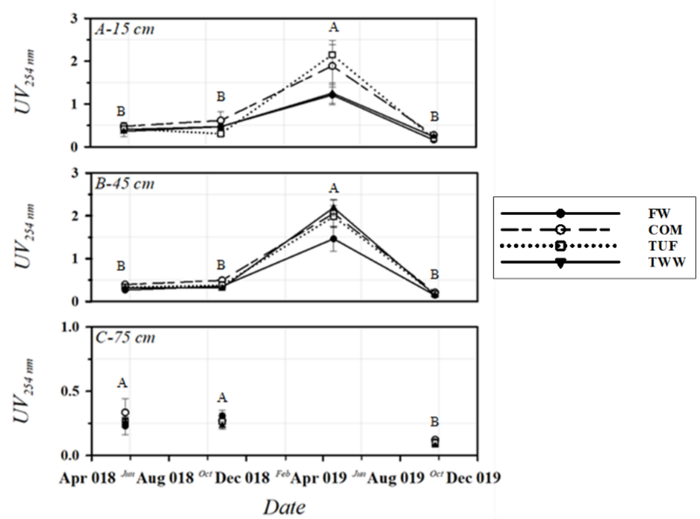

Figure 22. Effect of the season (soil sampling date) on the ultraviolet absorbance, in soil water extracts of soil samples that were collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Scales on Y axis differ between depths.

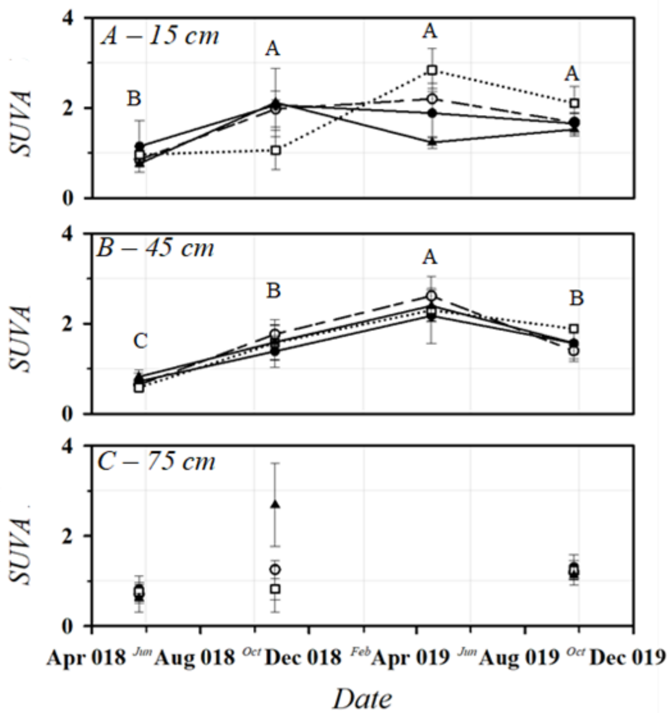

Figure 23. Effect of the season (soil sampling date) on the specific ultraviolet absorbance, for soil water extracts of soil samples that were collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Scales on Y axis differ between depths.

6.5. <u>Continuous oxygen and VWC measurements:</u>

6.5.1. *Volumetric Water content:*

In this section the daily irrigation amount (DIA), stands for the daily irrigation volume (DIV) as well.

The observed fluctuations in the volumetric water content (presented as normalized values) were affected by the amount of the daily irrigation, irrigation interval, and the treatments (water quality and agro-technical methods) (Figures 24 and 25).

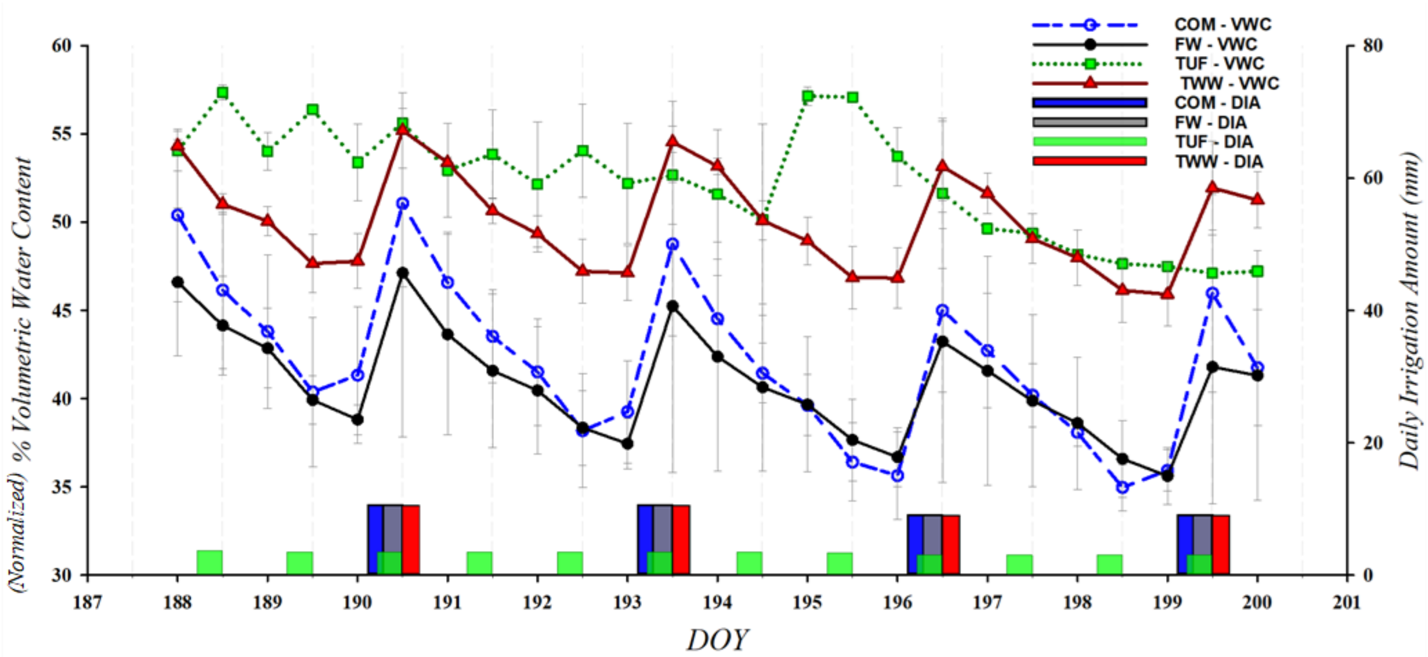

Figure 24. Effect of the treatment, and the daily irrigation amount on the normalized volumetric water content of the soil, in dripper adjacent soil profile at a depth of 35 cm. Each filled bar represents the amount of irrigation on that specific day. Bars on the curves of each treatment indicate standard errors. 7/07/2019 – 19/07/2019.

The daily irrigation volume (DIV) given to TWW, FW, and COM, were simultaneous and equivalent (10 mm/day), where the irrigation was applied twice a week. Moreover, all the treatments corresponded to irrigation events, where a rising trend in the normalized volumetric water content (NVWC) was observed following each irrigation, until reaching a peak (maximum point), followed by a trend of decrease, until reaching a minimum point, prior to the next irrigation event. However, the average NVWC monitored by the sensors at a depth of 35 cm, varied among the different treatments, whereby in FW and COM treatments the NVWC values were similar and relatively lower than those of TUF and TWW.

TUF was irrigated daily with a smaller volume of irrigation (4 mm/day), and its average NVWC was similar to that of TWW.

Additionally, the values of NVWC at the peaks (maximum) were higher in TUF and TWW than those in COM and FW. Furthermore, the minimum NVWC points in TWW that resemble the lowest moisture content following three consecutive days without irrigation, are higher than both the maximum and minimum points in FW and COM.

The difference between the maximum and minimum NVWC in each treatment (VWC gaps), represent the loss of water at a depth of 35 cm, which can be caused by plants' uptake, leaching, and matric potential. Those gaps seem to be larger in FW and COM than in TWW and TUF.

The given DIV in June 2020 (Figure 25) were larger than those given in July 2019 (Figure 24). The maximum NVWC peaks increased for all the treatments. Despite the partially overlapping NVWC curves of the treatments, FW and COM curves maintained lower NVWC values than those in TUF and TWW. The rise of the NVWC in the given treatments is synchronized with the irrigation timing and water percolation. The maximum NVWC values, were reached following the irrigation, are the highest in TWW and the lowest in FW. The gaps (max- min) in NVWC were not always larger in COM and FW than in TWW and TUF.

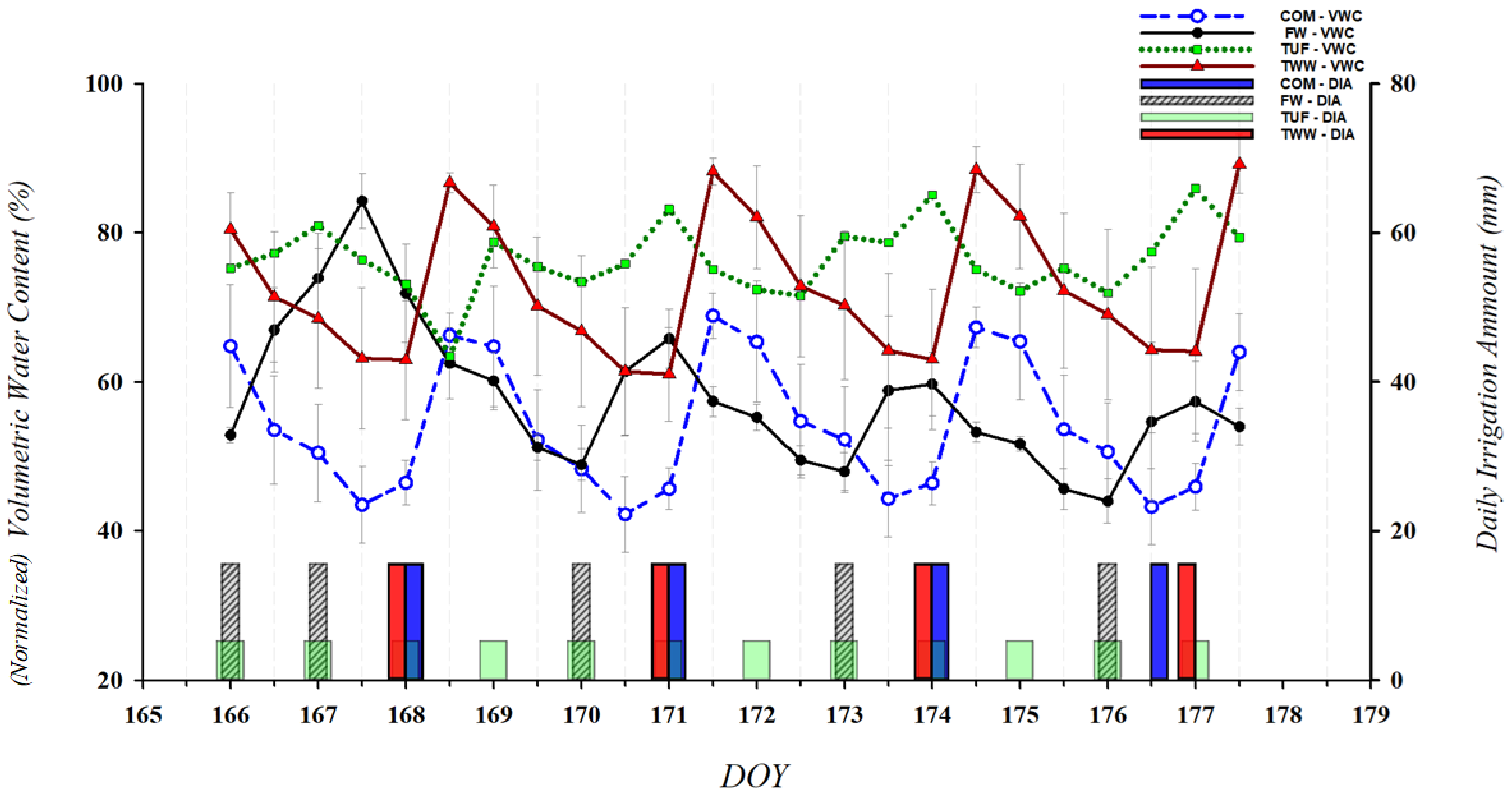

Figure 25. Effect of the treatment, and the daily irrigation amount on the volumetric water content of the soil, in dripper adjacent soil profile at a depth of 35 cm. Each filled bar represents the amount of irrigation on that specific day. Bars on the curves of each treatment indicate standard errors. Significant differences between the treatments (p<0.05) will be mentioned in the descriptive text only. Note: VWC averages are shown through the period 14/06/2020 – 25/06/2020 and presented as days of year.

The effect of the daily irrigation amount, and the treatment, on the soil oxygen content (O_2%) at a depth of 35 cm, between the dates 7/07/2019 – 31/07/2019, and 14/06/2020 – 25/06/2020 are shown in Figure 26 and Figure 27, respectively.

Corresponding with the increase in the VWC at a depth of 35 cm in July 2019 (Figure 24), the oxygen in soil pores is displaced with water, which reduces the oxygen content in the soil ambiance and in the root zone. The reduction in oxygen is the largest in TWW, whereas in COM, FW, and TUF, the curves were almost overlapping, and unlike the curve for TWW, the difference between the peaks and the pits, were minimal (Figure 26), indicating faster recovery in oxygen level in TUF, FW, and COM, and longer periods of oxygen deficiency in TWW.

As the given DIV was larger in June 2020 than in July 2019, we observed lower oxygen content in all the treatments (<18%) (Figure 27), especially in TWW, where the minimum oxygen contents were lower than 15%. COM treatment exhibited the highest oxygen content among the studied treatments, while oxygen curves for TUF and FW, are almost overlapping. The difference between the peaks and pits, in the oxygen curve of the TWW treatment are larger than those of the TUF, COM and FW, which indicates a fast recovery in soil oxygen level in those treatments, compared with TWW.

6.5.2. *Oxygen content in soil ambiance*

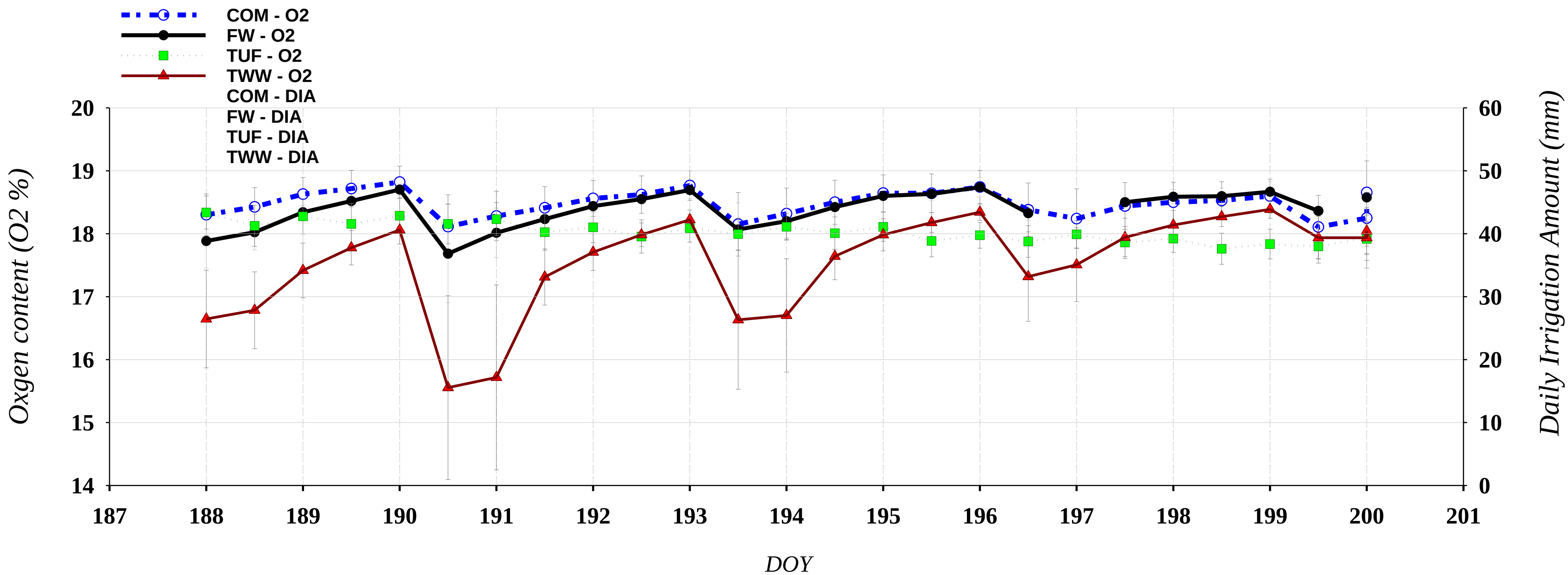

Figure 26. Effect of the treatment, and the daily irrigation amount on oxygen content in the soil ambiance, in dripper adjacent soil profile, at a depth of 35 cm. Each filled bar represents the amount of irrigation on that specific day. Bars on the curves of each treatment indicate standard errors. Significant differences between the treatments (p<0.05) will be mentioned in the descriptive text only. Note: the daily oxygen content averages are shown through the period 7/07/2019 – 31/07/2019.

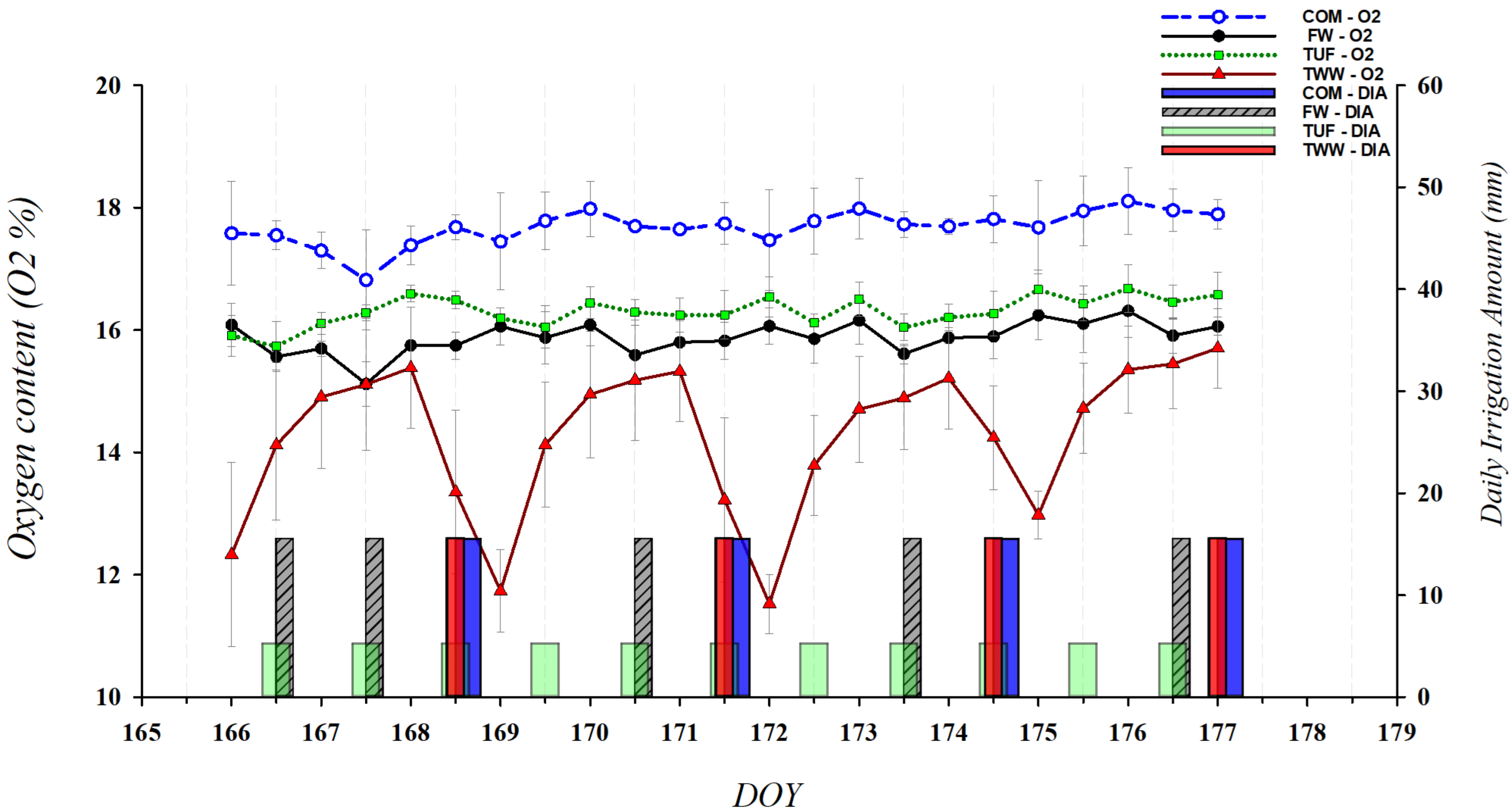

Figure 27. Effect of the treatment, and the daily irrigation amount on oxygen content in the soil ambiance, in dripper adjacent soil profile, at a depth of 35 cm. Each filled bar represents the amount of irrigation on that specific day. Bars on the curves of each treatment indicate standard errors. Significant differences between the treatments ($p<0.05$) will be mentioned in the descriptive text only. Note: oxygen content averages are calculated for two periods during the day (am, pm), and shown through the period 14/06/2020 – 25/06/2020, and presented as days of year.

The VWC sensors located between trees, at a depth of 35 cm (Figure 28), showed the amount of moisture at this location. In Figure 28, the maximum NVWC values in all the treatments (TWW, FW, COM, and TUF) in soil profiles located adjacent to the dripper were significantly higher than the NVWC values in soil profiles located between trees. The curves of the NVWC in all the treatments excluding TWW, were constant between the trees at a depth of 35 cm (Figure 28). In TWW the NVWC curve changed in response to the given DIA, by increasing the NVWC following an irrigation event.

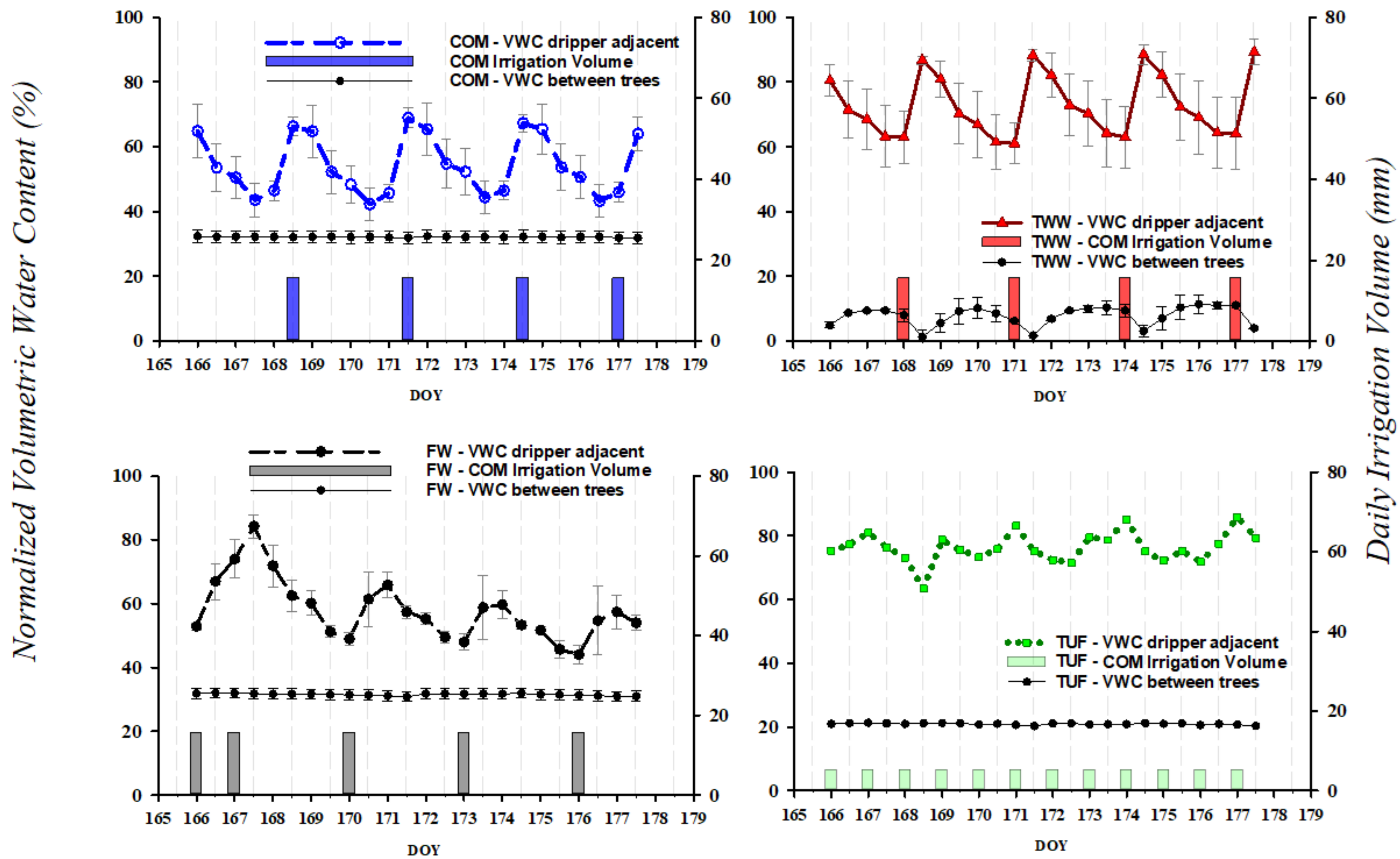

Figure 28. Effect of the treatments COM (A), TWW (B), FW (C) and TUF (D), the daily irrigation amount, and the location of the sensor, on the volumetric water content of the soil at a depth of 35 cm. Each filled bar represents the amount of irrigation on that specific day. Bars on the curves of each treatment indicate standard errors. Significant differences between the locations (p<0.05) will be mentioned in the descriptive text only. The period us between 14/06/2020 – 25/06/2020 and presented as days of year.

7. Discussion

7.1. <u>Chemical analysis:</u>

To achieve the first objective of the research, the effects of the irrigation water quality on the physico-chemical characteristics of the soil were investigated in each treatment (TWW, COM, FW, TUF) by analysing soil samples from soil profiles located either adjacent to the dripper (in the wetting zone) or between trees (mid-distance between trees – distant from the wetting zone). Four soil sampling campaigns were undertaken in the Fall and Spring of 2018 and 2019.

Three treatments (TWW, COM, and TUF) were irrigated with secondary treated wastewater (TWW), and one was irrigated with freshwater (FW). We point out that in the TUF treatment, soil samples at a depth of 0-30 cm, were not collected from the tuff trench, but in the wetting area adjacent to the tuff stones. Furthermore, the driplines in the COM treatment, were located at a depth of 20 cm from the soil surface (subsurface irrigation).

7.1.1. *Soil sampling location: between trees*

Soil profiles located between trees were not in contact with the dripper wetting zone (Figure 4), and were, therefore, mostly subjected to leaching by rainfalls in winter, and evaporation in summer, consequently in general, ions concentration in the soil solution of these soil profiles, were lower than those in dripper adjacent soil profiles. Based on that the resulted EC, SAR values, AS and VWC for soil profiles between the trees, were comparable for all the treatments. Conversely, DOM characteristics values (Figure 14, Figure 31, Figure 32), were significantly higher between the trees than in the irrigated soil profiles. These findings regarding the DOM concentrations are likely to result from detached leaves or roots decomposition and exudates.

7.1.2. *Soil profiles location: dripper adjacent*

Dripper adjacent soil profiles treated with FW, were naturally of low salinity and sodicity attributes (mainly Cl and Na), due to lower Cl and Na in the FW (Table 5) than in TWW, which leads to a sufficient leaching through the soil profile depth (0-90 cm). On the other hand, soil profiles irrigated with TWW, exhibited significantly high salinity and sodicity levels due to the high concentrations of ions in TWW composition (Table 5) up to a depth of 60 cm. Irrigation amounts and periods in TWW treatment were similar to those in FW treatment, yet they seem to be inadequate as they were not sufficient to wash the soil profile, where most of the salinity and sodicity indicators were significantly higher than in FW at least up to 60 cm depth.

Chemical analysis of the topsoil layer (0-30 cm) in dripper adjacent soil profiles, showed the TUF's advantage in general reduction of the salinity indicators (EC, Cl, Na, Ca+Mg, K) over the rest of the treatments that were irrigated with TWW (TWW and COM). The observed reduction in salinity at the vicinity of the tuff trench, agrees with the findings of Berezniak et al, (2018) where coarse sand surrounded with fine textured sand, improved the leaching of salts from the fine textured sand around the root zone. Those results can be explained by the higher hydraulic conductivity of a porous medium like tuff (Table 3) which improves the leaching of salts along the trench and in its vicinity. Salinity indicators (Figure 9) at 0-30 cm were similar for FW and TUF. However, the SAR at 0-30 cm, in TUF (Figure 13. B) was significantly higher than that of FW, that because of the much lower Ca+Mg concentration in TUF than in FW (Figure 12).

Due to improved leaching in FW and TUF treatments, unlike COM and TWW, the Na concentrations at the bottom soil layer (60-90 cm) was significantly higher than at the topsoil layer (0-30 cm). However, this did not result in a significant difference between the treatments' SAR at 60-90 cm, because the Ca+Mg concentrations also increased at this depth in TUF and FW.

At the upper soil layers (0-30 cm), the disadvantage of COM over the rest of the treatments (TUF, TWW, and FW) with respect to EC and Na, was noted. Recalling that the COM treatment is irrigated with subsurface driplines (at depth of 20 cm), it seems that this type of irrigation method does not enable the leaching of the salts from the soil surface downward the soil profile. The high salt concentrations in COM at the top layers, can also stem from the chemical characteristics of the compost, that despite its advanced maturity stage, it might continue to decompose and release salts, in addition to the capillary rise of salts due to evaporation.

Unlike the salinity indicators, the results showed that SAR values at a depth of 0-30 cm, were completely controlled by the irrigation water quality, and independent of the agro-technical methods. Due to the composition of the irrigation water which controlled the Na vs. Ca+Mg ratio.

SAR at 30-60 cm was comparable for all the treatments, based on HSD-Tukey Kramer analysis ($p<0.05$). It was noted that COM was the only treatment of SAR significantly higher than that of FW at a depth of 30-60 cm. That due to the substantially lower Ca+Mg concentration in COM compared with TWW. The reason for that is not fully understood. The comparable SAR among the treatments at a depth of 60-90 cm, is ascribed to the comparable Na levels at this depth.

Many studies showed the effect of DOC on increasing the SAR values, by binding Ca to organic molecules in addition to clay particles (Ali and Mindari, 2016; Robert et al., 2019; Tarchitzky et al., 1993). However, for COM at a depth of 60-90 cm, its DOC was significantly higher than that of FW, yet the SAR of all the treatments was comparable. Probably in our system the DOC concentrations (20-50 mg/l) were not sufficient to affect the SAR.

The ESP values were obtained based on a modified USSL staff 1954 equation (Eq. 13), that served for estimating ESP values based on soil CEC and SAR of the saturated soil paste as was already described in section 6.1.1. We expected some resemblance between our modified equation (Eq. [13]) and the USSL Staff 1954 empirical equation (Eq. [9]). However, the slope of our linear correlation deviated by 38.3% compared with that of the USSL 1954 correlation, leading to a smaller Gappon coefficient (0.0091). This result can be supported by Zaman et al., (2018), who suggested that the curves developed by the USSL Staff (1954) represent the soil in Western North America, which might not be valid to soils of other regions. Additional explanations for the difference between actual ESP values than those derived when the USSL Staff (1954) relatoinship was used, were provided by Levy et. al, (2014), and Kopittke et al., (2006). We suggest that the deviation of our Gapon coefficient, stems from inconsistency in the relationship between SAR and ESP which should be determined immediately, due to the impact of long storage time on the effect of ionic strength and additional factors on the actual SAR and ESP values, in addition to the absence of adequate equilibrium for the SAR and ESP in the soil solution in the field.

As expected, the distribution pattern of ESP (Figure 30 in appendix) through the soil profile, and the differences in ESP between the treatments at any given depth in the soil profile, were similar to those of SAR (Figure 13), as ESP was calculated by Eq. [13]. Hence, the explanations given for SAR are valid for ESP.

The calculated ESP values were obtained following 7 years of irrigation with TWW, yet these values fall under 15, the value determined by the USSL Staff (1954) for soils defined as sodic. However, according to Shainberg and Letey, (1984) and Levy (2014), the soil might show sodicity related behavior, depending on the ionic strength, that may fall undert the required total electrolyte concentration (TEC) value that keeps the soil floculated (Assouline et al., 2016; Kopittke et al., 2006; Tarchitzky et al., 1999). To find out whether our soil exhibits a sodic behavior, and in support of the chemical analysis and the calculated ESP, AS measurements were conducted (Figure 15). The AS measurements at a depth of 0-30 cm corresponded with the SAR and ESP values, whereby less stable aggregates were associated with a significantly high SAR and ESP values. Enhancing the water quality from TWW to FW, reversed not only the SAR and ESP values, but also improved the AS of the soil at this depth (Figure 19. A). The significant differences obtained in the AS between the water qualities at a depth of 30-60 cm (Figure 19. C), was not completely corresponding with the SAR and ESP values of the treatments at this depth. Use of good quality water (FW) resulted in significantly higher AS than that in the rest of the treatments that were irrigated with TWW. Yet treatments that were irrigated with TWW (TWW, and TUF), but for COM, led to ESP and SAR that were comparable with those of FW. It is suggested that AS is sensitive to small changes in SAR, that do not always appear significant.

Observing the low soil AS in treatments irrigated with TWW, together with their relatively low ESP values (<15), emphasizes the statements made by Shainberg and Letey, (1984), Levy (2014) and others, about sodic behaviour emerging already at ESP ~5 stimulated by the absence of sufficient TEC value in the soil solution.

Knowing that at the highest EC value given at depth of 30-60 cm (Figure 9, TWW, 1.59 dS/m in diluted soil water extract) did not help to prevent sodic behaviour (low AS), means that this EC value is lower than the TEC which is needed to keep the soil flocculated at the given SAR and ESP values. Given that the EC value was determined in a dilute soil water extract, the real EC value in the field is at least double that, which might not be tolerated by the crop. This leads us to conclude that the EC values needed for flocculation might be higher than our soil EC following irrigation with TWW, yet higher EC values, might not be practical or accepted in agricultural fields.

7.2. Soil oxygen and volumetric water content (VWC) monitoring:

The oxygen content and normalized VWC, were measured continuously at a depth of 35 cm, which falls in the depth range of 30-60 cm. The effect of the water quality (FW or TWW) on the plant water uptake was observed by Paudel et al, (2018) and Nemera et al, (2020) where they noted the decreased water uptake in TWW treatments, due to the high osmotic potential in the root zone.

Those findings agree with our findings where the normalized VWC results were the highest for TWW and TUF, due to high salinity levels. Additional explanation for the high VWC in TUF at a depth of 35 cm, might be the effect of the transition from a high HC of TUF to the low HC of the clayey soil (Berezniak et al., 2018; Russo et al., 2020) and the higher irrigation frequency (Russo et al., 2020). In COM on the other hand, the moisture content was as low as in FW, despite its equivalent irrigation amounts and intervals to those of TWW and FW. We suggest an enhanced plant water uptake in COM, by a well-developed root system, stimulated at early growth stages, due to porous compost trench, which provides improved aeration and better conditions for roots growth than those in clay soil similar to the results found in coconuts fiber substrate (Rubio-Asensio et al., 2018).

As water leaves the soil, oxygen diffuses into the soil pores, thus oxygen content in COM and FW were higher than in TWW. However, in TUF there was a different case, where despite its high VWC, the sensor at a depth of 35 cm determined high oxygen content like in FW (Figure 26 and Figure 27). This observation is supported by the fact that the coarse texture of the tuff in the trench enables sufficient aeration, where the atmospheric oxygen must cross a short distance in the fine textured soil before it reaches the sensors location. Likewise, in COM, where the location of the driplines (subsurface) keeps the upper soil layers (up to 20 cm) dry and aerated sufficiently, in addition to the porous property of the compost, this allows larger air capacity at a depth of 35 cm. Since the VWC was the highest in TWW, oxygen content was the lowest during irrigation, and for longer periods with low oxygen contents that might descend to near hypoxic conditions (Assouline and Narkis, 2013; Yalin et al., 2017).

Based on the AS results, we expected treatments of deteriorated AS at a depth of 30-60 cm, to have deteriorated physico-mechanical properties, in a way that decreases the HC of the soil, increase VWC, and decrease the oxygen content. But the AS was completely controlled by the water quality, while the VWC and oxygen content, were substantially affected by the type of the agro-technical methods (trenches). Thus, opposed to our expectations, when applying trenches (COM or TUF), the VWC and oxygen content, are independent of AS, unlike the TWW treatment.

7.3. Effect of the soil profile location and the season:

The water from the drippers did not reach the VWC sensors between the trees, where the normalized VWC was constant for all the treatment, except for TWW (Figure 28) where a minor water fraction seemed reach the sensor between the trees. This stimulated horizontal movement (matric potential), might be induced by the longer periods of high VWC in TWW.

7.4. Effect of the seasons:

Rain had a favorable effect on reducing soil salinity, as the major salts were leached to deeper soil layers, as observed in Spring seasons (Figure 17, Figure 19, and in appendix: Figure 33, Figure 34) and in agreement with (Erel et al., 2019; Lado et al., 2012b). Yet its effect on SAR was limited, as in a soil of a low calcite content (Table 2), the role of calcite born Ca is minor and does not contribute much to alleviating the soil SAR (Erel et al., 2019).

Comparing the pH at Fall to that at Spring (Figure 16), we notice a decrease in pH following the irrigation season (Fall). We attribute this pH reduction to the NH4 - based fertilizers that were injected into the trickle system to all the treatments, and to the intensive biological mineralization and nitrification (data are not shown) in the irrigated soil profiles (Tamir et al., 2013). Since the pH was comparable for all the treatments, the reduction in pH following irrigation is not attributed to the water quality neither to the agrotechnical methods.

7.5. Limitations:

The only physical parameter that was measured was soil aggregate stability, we think that measuring of the hydraulic conductivity, retention curve, and bulk density, could provide better understanding of the effect of the treatments on the soil water and oxygen dynamics, under the dripper and spatially. More frequent soil sampling campaigns for chemical analysis of the soil samples, and in-situ chemical analysis, could provide a clearer vision of the treatments' effects and the seasons' effects on the soil. Analysis of the current soil organic matter after 6-7 years of maturity, an observation of the carbonates and bicarbonates of the soil solution, additional oxygen and moisture sensors installed at more depths and widths, could provide a better understanding.

8. Conclusions

Enhancing the water quality from TWW to FW, reduced salinity, sodicity, increased AS, and provided optimal oxygen content due to enhances water leaching and plant water uptake.

TUF reduced salinity, similarly to FW, yet it did not mitigate sodicity at 0-30 cm. Additionally, it did not improve the soil AS.

The soil under the tuff trench was of high VWC, yet of optimal aeration.

COM was similar to TWW in salinity, sodicity indicators and AS. However, it provided enhanced plant water uptake and leaching (low VWC) and optimal oxygen content.

All the above conclusions are related to dripper adjacent soil profiles. While no significant effect was observed in soil profiles between trees.

DOM characteristics (DOC, UV and SUVA) were comparable for all the treatments, in dripper adjacent soil profiles and between trees, where in the latter, DOM was significantly higher than in dripper adjacent soil profiles.

The effect of the rain was prominent and decreased the effect of TWW, excluding SAR and ESP where it did not differ much following the irrigation seasons, in Fall.

The soil exhibited sodicity symptoms (low AS, and low aeration), at ESP~ 5.

Opposed to our hypotheses, the compost trenches did not improve the physico-chemical properties of the clayey soil profile. While the tuff trenches reduced only salinity, yet they did not improve sodicity indicators. However, both trenches treatments, similarly to the FW treatments, improved the oxygen content at a depth of 35 cm.

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10.Appendix

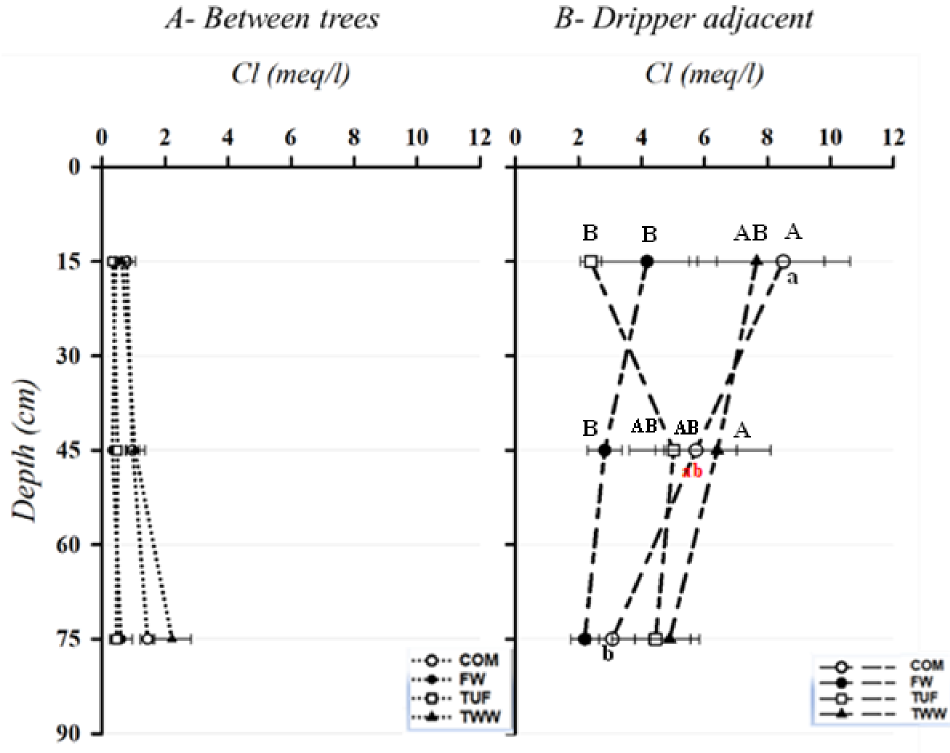

Figure 29. Effects of the soil profile location: A – between trees, B – dripper adjacent, treatments (COM, FW, TUF and TWW), and depth on average Cl concentration of the soil water extract. Bars indicate two standard errors. Different uppercase letters on the curve, indicate significant difference ($p < 0.05$) between treatments at a given soil depth. Different lowercase letters on the curve, indicate significant difference ($p < 0.05$) between depths for a given treatment.

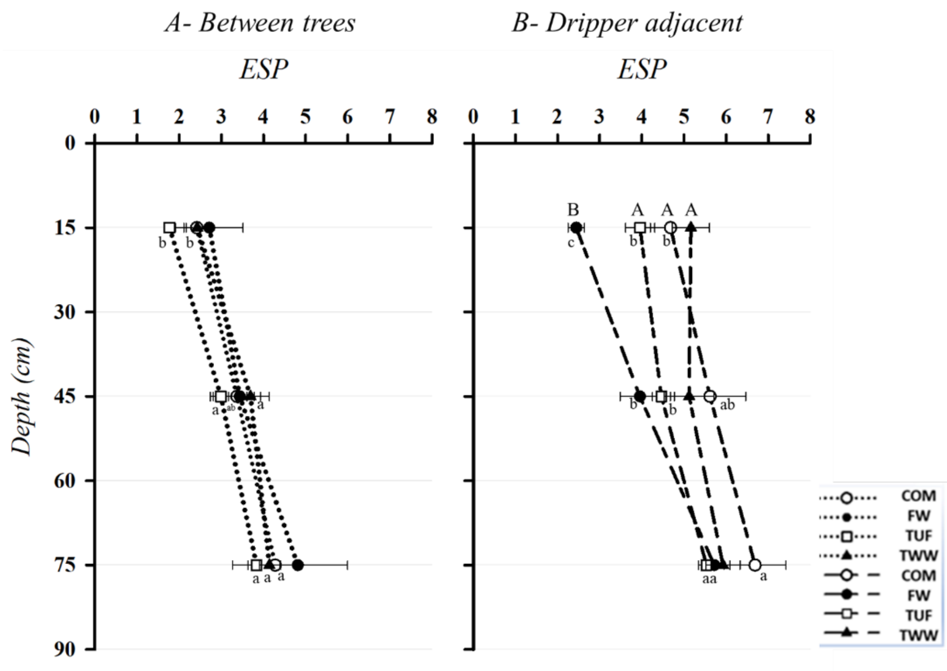

Figure 30. Effect of the soil profile location: A – between trees, and B – dripper adjacent, the treatments: COM, FW, TUF and TWW, and the depth in each treatment, on average ESP of the soil water extract. Bars indicate two standard errors. Each uppercase letter on the curve, indicates a significant difference (p < 0.05) between treatments at each soil profile location. Each lowercase letter on the curve, indicates significant difference (p < 0.05) between depths for each treatment.

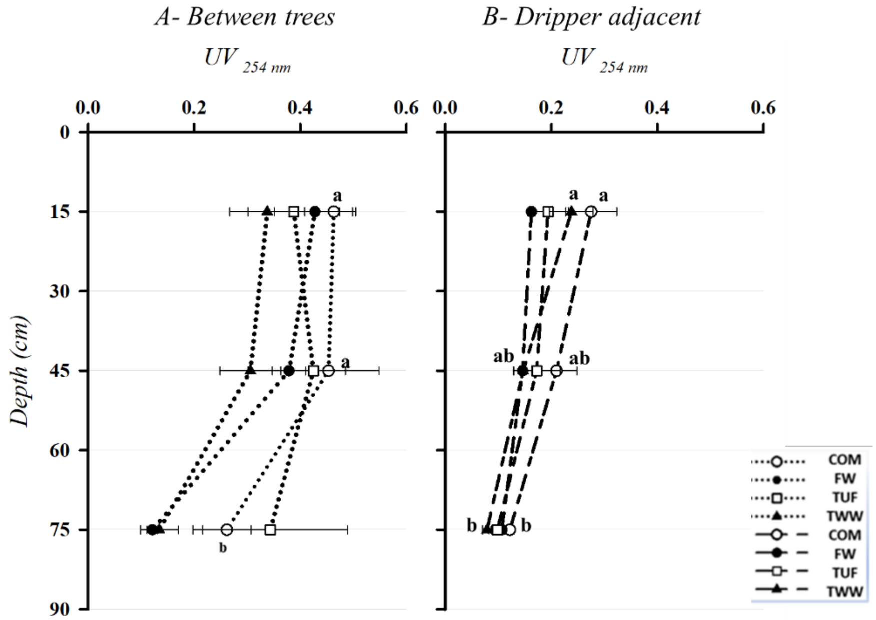

Figure 31. Effect of the soil profile location: A – between trees, and B – dripper adjacent, the treatments: COM, FW, TUF and TWW, and the depth in each treatment, on average UV_{254nm} absorbance of the soil water extract. Bars indicate two standard errors. Each uppercase letter on the curve, indicates a significant difference ($p < 0.05$) between treatments at each soil profile location. Each lowercase letter on the curve, indicates significant difference ($p < 0.05$) between depths for each treatment.

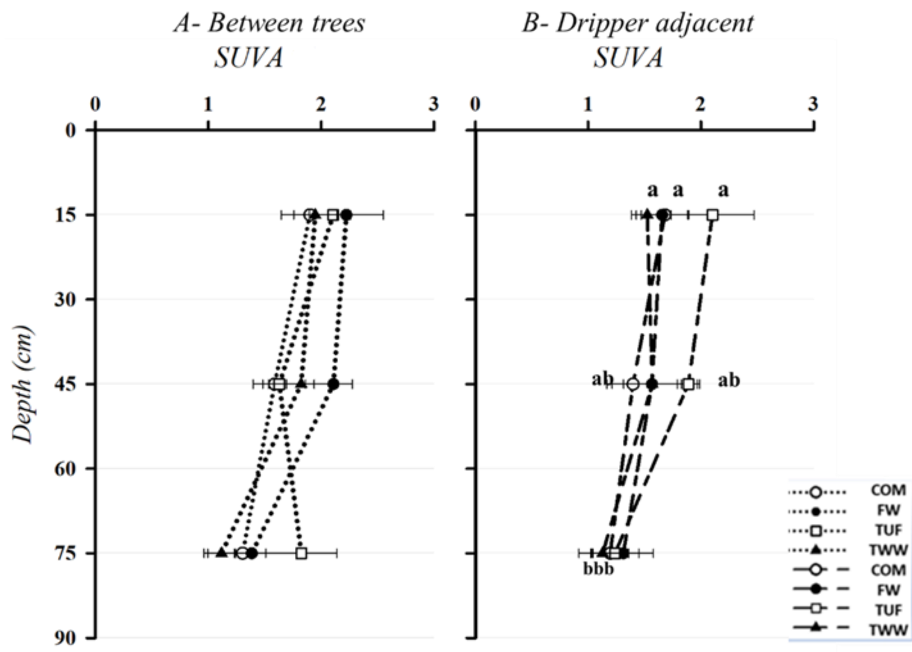

Figure 32. Effect of the soil profile location: A – between trees, and B – dripper adjacent, the treatments: COM, FW, TUF and TWW, and the depth in each treatment, on average specific ultraviolet absorbance (SUVA) of the soil water extract. Bars indicate two standard errors. Each uppercase letter on the curve, indicates a significant difference ($p < 0.05$) between treatments at each soil profile location. Each lowercase letter on the curve, indicates significant difference ($p < 0.05$) between depths for each treatment.

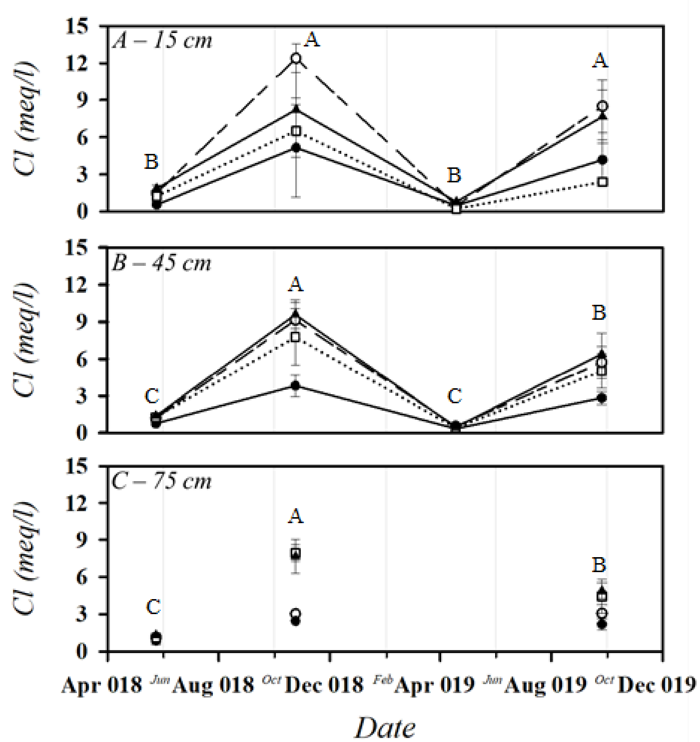

Figure 33. Effect of the season (soil sampling date) on the average Chloride concentration in the soil water extract, of soil samples collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant differences ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Significant differences between the treatments in each date and each depth, will be mentioned in the descriptive text only.

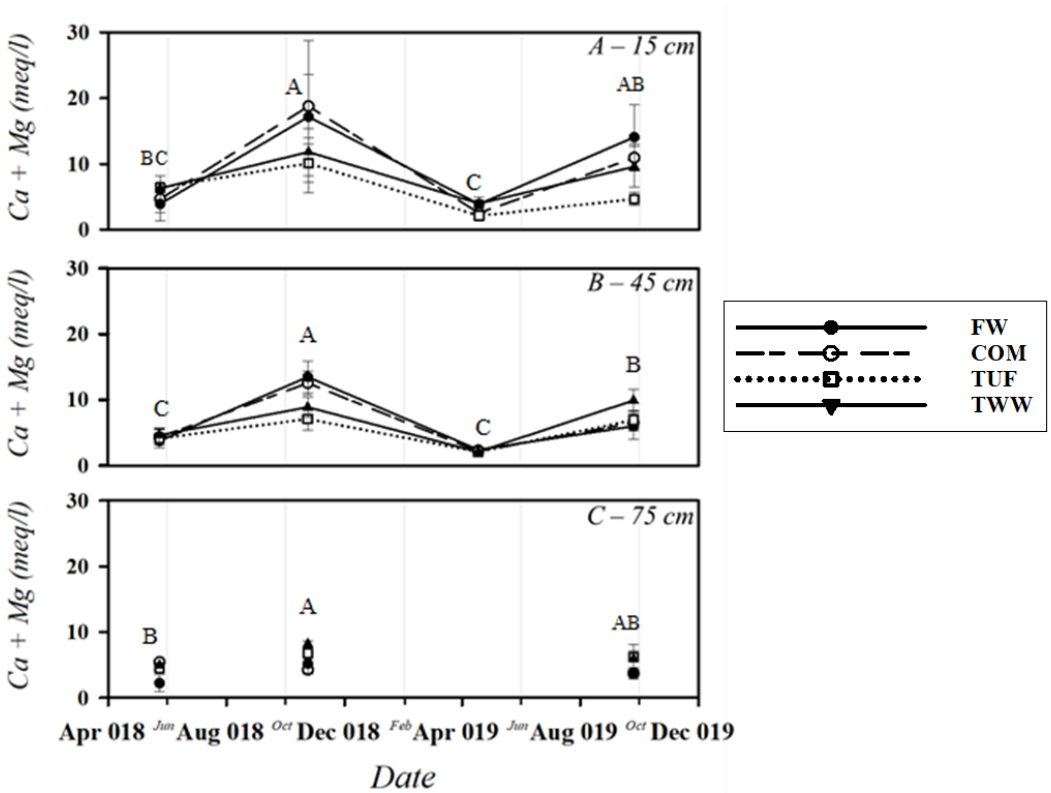

Figure 34. Effect of the season (soil sampling date) on the average Calcium and Magnesium concentrations (meq/l), in the soil water extract, of soil samples collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Significant differences between the treatments in each date and at each depth, will be mentioned in the descriptive text only.

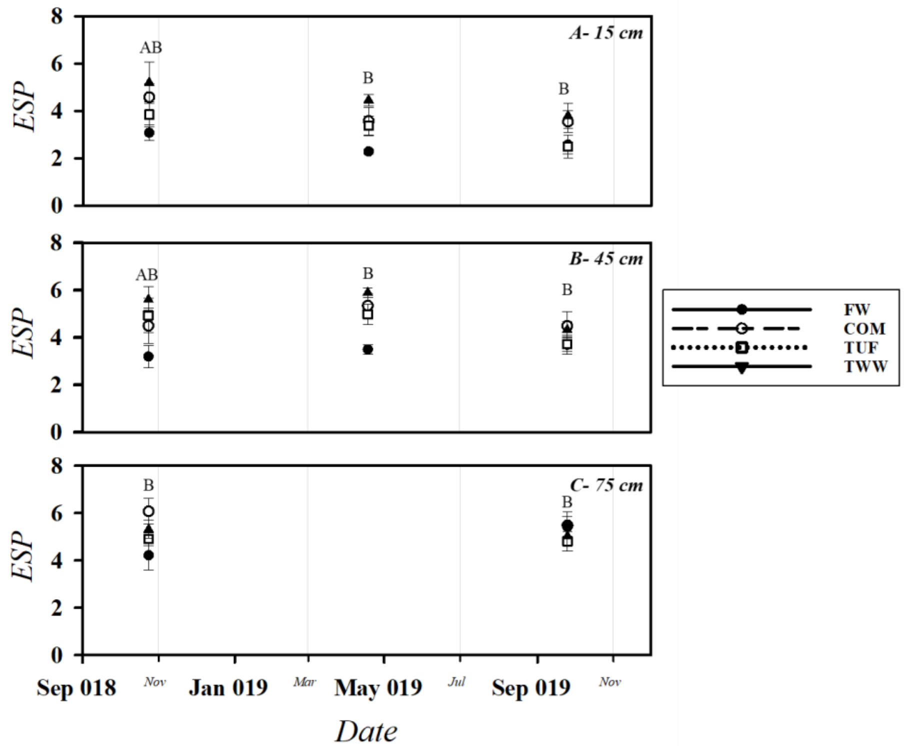

Figure 35. Effect of the season (soil sampling date) on the average exchangeable Sodium percentage, in the soil water extract, of soil samples collected from dripper-adjacent soil profile at three average depths: 15 (A), 45 (B) and 75 (C) cm. Bars indicate two standard errors. Each uppercase letter on the curve, indicates significant difference ($p < 0.05$) between soil sampling dates at each depth. Note: April 2019 is a missing soil sampling date at 75 cm depth (C). Significant differences between the treatments in each date and at each depth, will be mentioned in the descriptive text only.

תקציר

השקיה ארוכת טווח בקולחים שניוניים הינה גורם מרכזי לירידה ביבולים, במיוחד במטעים הנטועים על קרקעות חרסיתיות. הסיבות האפשריות להשפעות השליליות של השקיה בקולחים הינן ריכוז הנתרן הגבוה והמליחות של מים אלו שגורמים לשינויים דרסטיים בתכונות כימיות והפיזיקליות של הקרקע. שינויים אלה גורמים לפחיתה במוליכות ההידראולית של הקרקע ולעליה בפוטנציאל האוסמוטי של המים בקרקע שמגבילים את קצב חלחול המים ואת קליטת המים על ידי העצים, בהתאמה. כתוצאה משינויים אלה, תכולת החמצן באזור השורשים פוחתת, נגרם מחסור בחמצן לשורשים שפוגע בנשימת השורשים וכתוצאה מכך בפעילות ובצמיחה של השורשים והעצים.

מחקרים רבים חקרו את השפעות ההשקיה לטווח הקצר והארוך על קרקעות חרסיות, אולם רק מעט מחקרים בחנו את היישום של מצעים בחלק מנפח הקרקע כאמצעי אגרו-טכני, ולהתמודד עם בעיות מליחות, נתרון וחוסר חמצן במטעים.

השערת המחקר שלנו היא ששימוש בתעלות טוף וקומפוסט במטעים הגדלים בקרקעות חרסיתיות ומושקים בקולחים (i) יעזרו לשמור על תכונות הקרקע באופן דומה לזה של קרקע במטעים המושקים במים שפירים (ii) ישפרו את חדירות הקרקע לאוויר ומים על ידי שינוי צפיפות גושית בקרקע כתוצאה מהפחתת יחס ספיחת הנתרן (SAR) של תמיסת הקרקע ושל אחוז הנתרן בקומפלקס הסופח (ESP).

בהתבסס על כך, מטרת המחקר העיקרית הייתה לבחון כמה תכונות כימו-פיסיקליות של הקרקע בעקבות שימוש באיכויות מים שונות ושימוש בתעלות טוף וקומפוסט (כשיטות אגרו-טכניות), כאמצעים להפחתת רמות המליחות והנתרון בקרקעות חרסיתיות, המושקות לטווח ארוך עם קולחים שניוניים. מטרות המחקר הייחודיות היו לחקור את השפעות הטיפולים על: (i) מליחות, נתרון ומאפייני DOM בחתך הקרקע בסוף עונות ההשקיה והגשמים, (ii) התפלגות מרחבית של מליחות, נתרון וחומר אורגני מומס (מאפייני DOM סביב קו הטפטוף, (iii) יציבות תלכידים בחתך הקרקע והתפלגותה המרחבית בסוף עונת ההשקיה, ו (iv) דינמיקה של תכולת המים בקרקע וריכוז החמצן באוויר הקרקע בשדה.

כדי לענות על מטרות אלו הותקנו תעלות אוורור בשני צידי שורות העצים, בפרדס שקדים מסחרי, נטוע על אדמה חרסיתית (גרומוסול) ליד הכנרת, שהושקה בקולחים שניוניים מאז 2013. התעלות, בעומק 30 ס"מ ורוחב 25 ס"מ, מולאו בקומפוסט זבל בקר או טוף. לפיכך, הניסוי כלל ארבעה טיפולים: (i) השקיה עם מי קולחים שניוניים (TWW) (ii) השקיה עם מים שפירים (FW), ללא תעלות, (iii) ו- (iv) השקיה עם TWW בנוסף להתקנת תעלות טוף (TUF) או תעלות קומפוסט (COM), בהתאמה. בכל טיפול היו חמש חזרות מאורגנות בבלוקים באקראי. המטע הושקה במערכת טפטוף שכוללת שתי שלוחות טפטוף

משני צידי שורות העצים, המונחות על פני הקרקע חוץ מאשר בטיפול הקומפוסט שבו השלוחות הוטמנו בעומק 20 ס"מ כדי להבטיח הרטבה ואוורור אחידים של מצע הקומפוסט.

השפעת הטיפולים (איכות מים ושיטות אגרו-טכניות) על תכונות הקרקע נבדקו על ידי ביצוע אנליזות כימיות ופיזיקליות של דגימות קרקע במעבדה. דגימות קרקע נאספו בסוף עונת ההשקיה ובסוף עונת הגשם (סתיו ואביב, בהתאמה) במשך שנתיים רצופות (2018 ו- 2019), משני מיקומים יחסית לטפטפות (סמוך לטפטפת ובין עצים) ועד עומק של 90 ס"מ. הניתוח הכימי כלל את הרכב תמיסת הקרקע (EC, Cl, Na, Ca, Mg, K, DOC ו- UV_{254}), ואילו הניתוח הפיזי כלל מדידות של יציבות תלכידי הקרקע (AS). תכולת המים בקרקע וריכוז החמצן באווירת הקרקע נוטרו באופן רציף בשדה על ידי חיישנים מתאימים שהוטמנו בעומק של 35 ס"מ מתחת לקו הטפטוף. בנוסף, חיישני הרטיבות הוטמנו גם בתוך שורת העצים.

התוצאות הראו כי ברוב המקרים חתכיי הקרקע בתוך שורת עצים הורטבו רק באופן חלקי מחוץ לאזור ההרטבה של הטפטפת, ולכן, בכל שכבות הקרקע עד לעומק של 90 ס"מ, רמות המליחות, הנתרון וריכוזי רוב היונים היו נמוכים באופן משמעותי מאשר בחתך הקרקע ליד קו הטפטוף. בנוסף, חתכי קרקע אלה היו בעלי מאפייני AS ו- DOM גבוהים (DOC, UV254 ו- SUVA). לעומת זאת, חתכי קרקע סמוכים לקו הטפטוף היו בדרך כלל בעלי מליחות ונתרון גבוהים משמעותית, DOM ו- AS נמוכים, VWC תכולות רטיבות גבוהות וריכוזי חמצן נמוכים יותר בהתאם לטיפול ולעומק. בנוסף, ערכי ה- pH וה- DOM היו דומים לכל הטיפולים בכל עומק נתון (עד 90 ס"מ).

בדגימות קרקע שנאספו לאחר עונת הגשמים (אביב) מדדי המליחות היו נמוכים יותר, וערכי pH גבוהים מאשר בדגימות קרקע שנאספו בסתיו, עקב שטיפת הגשמים. לעומת זאת מדדי הנתרון לא השתנו באופן ניכר ביחס לדגימות הקרקע שנאספו בסתיו, בגלל מיהול של תמיסת הקרקע במי הגשמים, מה שמגביר את השפעת הנתרן הספוח, במיוחד כאשר הקרקע היא בעלת אחוז גיר נמוך.

לאחר עונת ההשקיה (בסתיו), חתכי הקרקע הסמוכים לטפטפות, בעומק 0-30 ס"מ, היו עם מדדי מליחות נמוכים משמעותית ב- טיפולי TUF ו- FW, בעוד שבטיפול ה- COM ו- TWW המליחות הייתה גבוהה. בעומק זה, SAR היה תלוי לחלוטין באיכות המים, ולכן כל הטיפולים שהושקו ב- TWW, היו בעלי SAR גבוה משמעותית מזה של FW. בעומק 30-60 ס"מ נצפתה מגמה לפיה טיפולי התעלות יכולים להקטין את המליחות, ולכן הם היו בינוניים בין FW ל- TWW, כאשר בטיפול ה- TWW היתה מליחות גבוהה משמעותית מאשר בטיפול FW. עם זאת, ה- SAR של ה- COM היה גבוה יותר באופן מובהק מזה של ה- FW, כאשר ערכי ה- SAR של TUF ו- TWW לא היו שונים במובהק מאשר טיפול ה- COM ו- FW. בשכבת הקרקע התחתונה (60-90 ס"מ), הטיפולים היו דומים ברוב הפרמטרים הכימיים שנמדדו כולל ה- SAR. ראוי לציין שבטיפול ה-COM ה- DOC היה גבוה יחסית וריכוזי Ca + Mg נמוכים מאשר בטיפולים האחרים, שילוב שצפוי היה להוביל לעלייה ב- SAR.

יציבות התלכידים (AS) הושפעה באופן מובהק מטיפולי איכות המים; לפיכך, עד לעומק של 60 ס"מ, יציבות התלכידים בטיפול המים השפירים הייתה גבוהה באופן מובהק מזה של כל הטיפולים שהושקו בקולחים שניוניים, בעוד שבעומק של 60-90 ס"מ, יציבות התלכידים הייתה דומה בכל הטיפולים.

בניסיון לקבל אינדיקציה נוספת על מצב הניתרון בקרקע, התאמנו משוואה לחישוב ה- ESP על בסיס המשוואה שפותחה על ידי מעבדת המליחות בריוורסייד (1954) של USSL 1954., מקדם גאפון Gapon במשוואה שלנו חרג ב -38% מזה של ה- USSL 1954 (0.009 לעומת 0.0145), מה שהוביל לערכי ESP מחושבים עד 5. מאחר שערכי ה- ESP בתוצאות מחושבים על בסיס ערכי ה- SAR, התלות של ה- ESP בטיפולים דומה לזו של ה- SAR.

הערכים המדודים של ה- AS בעומק 0-30 ס"מ היו בקורלציה הפוכה עם ערכי ה- ESP בעומק זה, ושניהם נשלטו על ידי איכות המים. לפיכך, ערכי ה- AS בטיפולים שהושקו בקולחים היו נמוכים במובהק מאשר בשפירים, וערכי ה- ESP היו גבוהים במובהק מאלו של השפירים. כמו כן, ב- 30-60 ס"מ, ה- AS, שוב, נשלט על ידי איכות המים, אך לא הייתה התאמה עם ערכי ה- ESP בעומק זה.

חיישני תכולת הלחות והחמצן הונחו בעומק של 35 ס"מ (5 ס"מ מתחת לתעלות), שהם בין 30-60 ס"מ. לפיכך, היה הגיוני להתייחס לקשר בין האנליזות הכימיות והפיזיקליות ב 30-60 ס"מ, למדידות החיישנים. חיישני הלחות הראו תכולת מים גבוהה יותר עבור TWW ו- TUF, מאשר עבור COM ו- FW. בעוד שחיישני החמצן הראו תכולת חמצן נמוכה יותר ל- TWW מאשר בשאר הטיפולים. אני משערת שהמליחות הגבוהה ב- TWW הגדילה את הפוטנציאל האוסמוטי באופן שהגביל את צריכת המים על ידי הצומח. לכן, צפוי היה שתכולת מים גדולה יותר תצטבר באזור השורש בטיפול ה- TWW. בנוסף גם הפגיעה ב- AS בהשקיה בקולחים מצביעה על פגיעה במוליכות ההידראולית וכתוצאה לרטיבות גבוהה בשכבה זו בקרקע. אני מציעה שתכולת המים הגבוהה בקרקע מתחת לשכבת ה- TUF יכולה להיות קשורה במעבר החד בין מוליכות הידראולית גבוהה של מצע הטוף, למוליכות הידראולית נמוכה של הקרקע. בנוסף לכך תדירות ההשקיה הגבוהה בטיפול הטוף שמרה על רטיבות גבוהה בקרקע זו. בדרך כלל קיים קשר הפוך בין תכולת המים לתכולת החמצן; לפיכך, תכולת מים גבוהה יותר מובילה לתכולת חמצן נמוכה יותר. עם זאת, ב- TUF זה לא היה המצב, כך שחיישני החמצן הראו תכולת חמצן גבוהה, למרות תכולת המים הגבוהה. ההסבר לכך הוא שבתוך תעלת הטוף ריכוז החמצן גבוה כמו מעל פני הקרקע, כך שהחיישן בקרקע נמצא במרחק קצר לדיפוזיה בקרקע מריכוז חמצן גבוה. יש לציין כי למרות ההשפעה השלילית של טיפול הקומפוסט על תכונות כימיות ופיזיקליות של הקרקע (SAR גבוה ו- AS נמוך עד לעומק של 60 ס"מ), בטיפול זה היו תכולות מים וחמצן אופטימלים. אני מייחסת את התוצאה האחרונה, לשורשים המפותחים של העץ בתעלת הקומפוסט ולהשפעה אפשרית של הטפטוף הטמון. לאחר ההשקיה הירידה ברמות

החמצן ב- TWW הייתה חדה, והחזרה לערכים תקינים ארכה זמן רב יותר מאשר בשאר הטיפולים, כנראה כתוצאה מקליטת מים מוגבלת של העצים ומהפגיעה במוליכות ההידראולית.

מהמחקר הסקתי ששיפור איכות המים מ- TWW ל- FW, הפחית את המליחות, הנתרון, ושפר את ה-AS, וסיפק תכולת חמצן אופטימלית עקב הגברת שטיפת המים וקליטת השורשים. TUF הפחית את המליחות, בדומה ל- FW, אך עם זאת הוא לא הפחית את הSAR ב-0-30 ס"מ. בנוסף, TUF לא שיפר את ה- AS. הקרקע מתחת לתעלת הטוף הייתה בעלת תכולת רטיבות גבוהה, אך עם זאת אוורור אופטימלי. טיפול ה- COM היה דומה ל- TWW במליחות, במדדי SAR וב- AS. עם זאת, הוא סיפק צריכת מים ושטיפת מים משופרת ותכולת חמצן אופטימלית. כל המסקנות הנ"ל קשורות לחתכי קרקע סמוכים לטפטפות, בעוד שבין העצים לא נצפתה השפעה משמעותית של הטיפולים. מאפייני DOM (SUVA -ו DOC, UV) היו דומים לכל הטיפולים, בחתכי קרקע סמוכים לטפטפות ובין העצים, כאשר בין העצים ה- DOM היה גבוה באופן מובהק מאשר בחתכי קרקע סמוכים לטפטפות. השפעת הגשם הייתה בולטת והפחיתה את ההשפעה של TWW, למעט SAR ו- ESP אשר לא היי שונים מאשר בסוף עונות ההשקיה, בסתיו. בניגוד להשערת המחקר, תעלות הקומפוסט לא שיפרו את התכונות הפיזיקו-כימיות של חתך הקרקע החרסיתית. בהתאם להשערת המחקר תעלות הטוף הפחיתו את המליחות, אך הן לא שיפרו את מדדי הנתרון. יתר על כן, טיפולי התעלות לא שיפרו את יציבות התלכידים. עם זאת, שני טיפולי התעלות, בדומה לטיפולי FW, שיפרו את תכולת החמצן בעומק של 35 ס"מ.

השפעת תעלות קומפוסט וטוף על תכונות כימו-פיזיקליות של קרקע חרסיתית עקב השקיה ארוכת טווח במי קולחים שניוניים, במטע שקדים

העבודה התבצעה בהדרכת ד"ר אשר בר-טל וד"ר גיא לוי, המכון למדעי הקרקע, המים והסביבה, מנהל המחקר החקלאי, מרכז וולקני, ראשון לציון.

עבודה זו מוגשת כחלק מהדרישות לקבלת תואר מוסמך למדעי הקרקע ומים בפקולטה לחקלאות, מזון וסביבה על שם רוברט ה. סמית, האוניברסיטה העברית בירושלים

על ידי

יוסרה זרעיני

דצמבר, 2020 רחובות