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Soil spatio-temporal distribution of water, salts and nutrients in greenhouse, drip-irrigated tomato crops using lysimetry and dielectric methods

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ABSTRACT

This work was mainly aimed at studying the spatio-temporal distribution of water content (θ_w), bulk (EC_a) and soil solution (EC_{SS}) electrical conductivity measured with a dielectric sensor (GS3) and a tension lysimeter (suction cup) throughout three drip-irrigated tomato crops in Mediterranean greenhouses. The mean θ_w (GS3) for the wet bulb was well estimated by measuring at representative positions, especially at the centre of the wet bulb. The EC_{SS} substantially increased in the wet bulb, irrespective of the soil position, reaching relatively high values (6–7 $dS\,m^{-1}$) in the second half of the cycles, mostly due to sodium and chloride accumulation. The mean EC_{SS} for the wet bulb was narrowly and linearly related to that measured at any of four representative positions in the wet bulb, which presented similar seasonal dynamics and absolute values throughout most of the crops. The mean EC_{SS} for the wet bulb can be well estimated by measuring at one of these positions, since the errors of using measurements from these positions were relatively low. The relationship between the EC_{SS} estimated from GS3 and that measured with suction cup varied depending mostly on soil position and cropping year, but the GS3 did not generally provide accurate EC_{SS} estimates, especially in the second half of the cycles, when salts accumulated in the soil. Despite this, measurements of EC_a and EC_{SS} from GS3 at the centre of the wet bulb might be useful for identifying tendencies or relevant salinity changes for automated irrigation systems. The solution concentration for main salts and nutrients can be fairly well monitored by sampling at any of the four representative positions of the wet bulb. However, it appears advisable to measure at the centre of the wet bulb, as samples from this position might respond faster to changes in the nutrient solution supply or the root activity, especially for very mobile elements, such as nitrate.

1. Introduction

In heavily fertigated, intensive agricultural systems such as Mediterranean greenhouses, feasible soil monitoring protocols are needed for optimising crop irrigation and fertilization, and especially for minimising soil and water pollution. This is particularly relevant in irrigation areas with scarce water resources of low or medium quality, such as the SE Spanish Mediterranean coast. In this area, the groundwater, the main irrigation source, has been vastly overexploited and presents increasing problems of nitrate contamination and salinization (Casas et al., 2015), but most greenhouse farmers still continue using irrigation and fertigation practices based on their experiences (Thompson et al., 2007b), without monitoring or controlling the soil water, nutrient and salt status.

A representative monitoring of the soil solute content in agricultural soils requires a thorough knowledge of the soil spatial distribution of water, nutrients and salts throughout the crop cycles, especially in intensive, drip-irrigated crops. Several lysimetry methods have been introduced for nutrient and salt soil monitoring, and the suction cup sampler is the most common one in Spanish Mediterranean greenhouse crops (Cabrera-Corral et al., 2016; De Pascale et al., 2017). In this area, there has been appreciable experimental work in recent years with the use of suction cup samplers, and extension materials with protocols for their use have been developed (De Pascale et al., 2017). This method, which extracts the soil solution with a low-cost tension lysimeter, is effective in greenhouse soils, usually maintained moist (at soil matric potentials close to field capacity), and appears to represent well the soil concentration of the available elements, especially under unsaturated

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flow conditions (Cabrera-Corral et al., 2016). Additionally, an increasing number of dielectric sensors are being developed for continuous measurement of the water content (θ_w) and the apparent or bulk electrical conductivity (EC_a) of soils for agricultural and environmental purposes. Some of these sensors can also estimate the electrical conductivity of the pore, a variable closely related to the soil salinity in contact with plant roots or the electrical conductivity of soil solution (EC_{SS}). The EC_a (i.e. the EC of the soil, water and air complex) is influenced by several physical and chemical soil properties, such as salinity, saturation percentage, water content, bulk density and temperature. It usually increases with water content, and the slope of this relationship depends on the level of salinity: the higher the salinity, the steeper the slope (Amente et al., 2000, Moret-Fernández et al., 2012). These authors also observed that the EC_a at a constant θ_w was linearly related to the EC_{SS}, showing steeper slopes at higher θ_w values. Incrocci et al. (2009) also found that the EC_a of horticultural substrates was best related to the EC_{SS} at high θ_w values. Moreover, Valdés et al. (2014) found that although the EC_a is not a true reading of the soil solution salinity, it is a closely related parameter, which can be regarded as a useful tool for mitigating the negative effects of saline conditions in the production of potted ornamental plants. Thus, when the EC_{SS} cannot be measured directly or estimated accurately, the EC_a appears to be a reliable variable for evaluating soil salinity in crop media usually maintained at high water contents.

The EC_{SS} can be measured periodically in soil solution samples extracted with suction cup or estimated continually with empirical calibration equations or physical based models using EC_a and θ_w measurements (Hendrickx et al., 2002). Several models of varying complexity have been developed to determine the EC_{SS} from dielectric sensor measurements (Amente et al., 2000; Hilhorst, 2000; Incrocci et al., 2009; Moret-Fernández et al., 2012): e.g. GS3 and WET sensors estimate the EC_{SS} with the expression developed by Hilhorst (2000). However, there are a variety of factors, such as soil solution salinity or soil type, which can influence the output of these sensors and their estimation methods (Malicki and Walczak, 1999; Visconti et al., 2014). Though the use of dielectric sensors for continuous monitoring of θ_w, EC_a and EC_{SS} in agricultural soils appears to be promising, further work and testing is required to improve their accuracy and applicability in the field, especially in intensive systems under saline soil conditions.

This work was mainly aimed at: i) studying the spatio-temporal distribution of water content, bulk and soil solution electrical conductivity measurements with a dielectric sensor (GS3) and a tension lysimeter (suction cup) throughout drip-irrigated greenhouse tomato crops; ii) assessing the reliability of bulk electrical and soil solution conductivity measurements using GS3 to monitor soil salinity status.

2. Material and methods

2.1. Site and experiment

Experiments were carried out in Parral-types greenhouses (24 m × 18 m) located at 'Las Palmerillas-Cajamar' Foundation (2°43′_W; 36°4′_N; 155 m.a.s.l.) on the Almería coast, SE Spain. The greenhouses were low-cost structures covered with plastic film and with layered soils, known as *enarenado* and of widespread use in the region (Wittwer and Castilla, 1995). A first tomato crop (*Solanum lycopersicum* L., cv. Genio) was grown from 3 February to 6 July 2015. The soil consisted of the naturally occurring, gravelly-sandy loam soil covered with a 0.4-m layer of imported silty-clay loam soil, a 0.02-m layer of dried manure, and an upper 0.1-m mulch layer of coarse sand and fine gravel particles. With time and use the manure layer was practically mineralised and disappeared, and the 0.1-m upper part of the imported soil layer was mixed with sand and gravel particles from the top layer. The upper limit of drained water content (field capacity) for the imported silty-clay loam layer was $0.37\,m^3\,m^{-3}$ and the lower limit (wilting point) was $0.14\,m^3\,m^{-3}$. The total amount of irrigation water supplied was 348 mm (+12 mm applied before planting), and irrigation was applied daily, except at the beginning of the cycle (February): The estimated seasonal crop evapotranspiration was 307 mm. This tomato crop was subjected to five irrigation strategies in order to obtain a wide and representative range of water and salt soil conditions.

- Strategy 1 (S1, 25/02–29/03/2015): Irrigation rates slightly lower than the crop water requirements (short irrigations of about 0.67 mm with water of about $1.7\,dS\,m^{-1}$ EC or with nutrient solution of $2.5\,dS\,m^{-1}$ EC) to enhance crop rooting.
- Strategy 2 (S2, 30/03–23/04): Irrigation rates about 30% higher than the crop water requirements (long irrigation events with a nutrient solution of about $2.5\,dS\,m^{-1}$ EC) to increase soil water availability.
- Strategy 3 (S3, 24/04–21/05): Short irrigation events of 0.67 mm with a nutrient solution of about $2\,dS\,m^{-1}$ EC, supplied automatically when the soil matric potential was lower than −20 kPa (at two of the three digital tensiometers) or than −30 kPa (at one tensiometer).
- Strategy 4 (S4, 22/05–14/06): Irrigation rates about 30% higher than the crop water requirements (long irrigation events with a nutrient solution of about $2.0\,dS\,m^{-1}$ EC) for salt leaching.
- Strategy 5 (S5, 15/06–06/07). Short irrigation events of about 0.67 mm with a nutrient solution of about $2.5\,dS\,m^{-1}$ EC supplied when the θ_w at 0.35 m depth below the emitter and plant was below $0.35\,m^3\,m^{-3}$ (at two of the three GS3 sensors) or below $0.33\,m^3\,m^{-3}$ (at one GS3). At the end of this strategy, the threshold θ_w values increased to $0.38\,m^3\,m^{-3}$ (at two of the sensors) and to $0.36\,m^3\,m^{-3}$ (at one).

A second (cv. Valkiria) and third (cv. Ateneo) tomato crop were also grown from 3 February to 29 June 2016, and from 13 September 2016 to 24 May 2017, respectively, in a similar Parral-type greenhouse (24 m × 18 m). The *enarenado* soil was of similar textural characteristics to that used in the previous season, but only about 0.05 m upper part of the imported soil layer was mixed with sand and gravel particles from the top layer.

Table 1
Mean values of the electrical conductivity (EC, $dS\,m^{-1}$) and the nutrient concentration ($mmol\,L^{-1}$) in the irrigation water (IW) and the supplied nutrient solution (NS) throughout the 2015, 2016 and 2016/17 tomato cycles.

	EC	NO_3^+	$H_2PO_4^-$	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	HCO_3^-	Na^+	Cl^-
2015										
IW	1.7	0.3	–	0.1	1.8	2.7	0.3	3.5	7.0	12.0
NS	2.5	5.2	1.3	5.2	3.5	2.7	0.9	2.9	7.3	12.7
2016										
IW	1.6	0.1	–	0.1	2.2	2.4	0.5	2.9	5.3	10.7
NS	2.7	7.6	2.0	5.2	5.4	2.8	1.4	0.8	6.8	11.8
2017										
IW	1.5	–	–	0.2	1.9	2.2	0.4	2.9	4.7	9.0
NS	2.6	8.0	2.1	6.2	5.6	2.4	2.0	0.8	6.2	9.3