Calculating the water deficit of apple orchard by means of spatially resolved approach

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Abstract. *In semi-humid climate, spatially resolved analysis of water deficit was carried out in apple orchard (Malus* x *domestica 'Pinova'). The meteorological data were recorded daily by a weather station. The apparent soil electrical conductivity (ECa) was measured at field capacity, and twenty soil samples in 30 cm were gathered for texture, bulk density, and gravimetric soil water content analyses. Furthermore, ten trees were defoliated in different ECa regions in order to estimate the leaf area ratio (LAR).*

The crop evapotranspiration (ETc; mm/d) was computed by multiplying the actual evapotranspiration (ETa; mm/d) and considering the soil water stress coefficient (Ks), soil surface evaporation coefficient (Ke) and LAR. These values were implemented in the Geisenheimer irrigation model for calculating the water deficit using crop coefficient (Kcb) in the crucial developmental stages: full bloom, cell division stage, and harvest. A positive correlation was observed between the ECa and total available water content in the root zone (r = 0.78, p<0.05). Furthermore, the influence of LAR on the water balance was quantified, pointing to the reasonability of spatially resolved water balance.

Keywords. *Precision horticulture, ECa, LAR, water balance, evapotranspiration*

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Abbreviations

$D_{r,i}$	Water depletion in the root zone at the end of day i [mm]
D_e	Daily cumulative depth of water depleted from the surface [mm]
ECa	Apparent soil electrical conductivity [mS/m]
ET_a	Actual evapotranspiration [mm]
ET_c	Crop evapotranspiration [mm]
ET_o	Potential evapotranspiration [mm]
h	Mean tree height [m]
K_{cb}	Crop coefficient
$K_{cb,ini}$	Crop coefficient during bud break and full bloom
$K_{cb,mid}$	Crop coefficient during full bloom and harvest
$K_{cb,end}$	Crop coefficient after harvest
$K_{cb,min}$	Minimum crop coefficient for bare soil
$K_{cb,full,mid}$	Crop coefficient based on daily weather conditions and h during bud break and full bloom
$K_{cb,full,end}$	Crop coefficient based on daily weather conditions and h after harvest
$K_{cb,full,max}$	Maximum value of K_{cb} during the cultivation period
K_e	Soil surface evaporation coefficient
K_s	Soil water stress coefficient
K_r	Soil evaporation reduction coefficient
LAI	Leaf area index [m^2/m^2]
LAR	Leaf area ratio [m^2/tree]
TAW	Total available water in the root zone [mm]
TEW	Maximum cumulation of depletion from the soil surface [mm]
RAW	Readily available water content in the root zone [mm]
REW	Cumulative depth of evaporation [mm]
p	the average fraction of TAW that can be depleted from the root zone before the revealing of moisture stress
P	Precipitation [mm]
R_n	Solar radiation [W m^{-2}]
RH	Mean daily relative humidity [%]
T	Temperature [^{O}C]
u	Wind speed [m/s]
WB	Geisenheim water balance model [mm]
Z_e	Effective depth of soil evaporation layer [m]
z_R	Average root depth [m]
Θ_{FC}	Soil water content at field capacity [m^3/m^3]
Θ_{WP}	Soil water content at wilting point [m^3/m^3]

Introduction

The field of horticulture includes some of the most important cultivations worldwide. Apples are the most planted fruit trees in Europe with an increasing planted area to take place each year. Precision horticulture (PH) is the implementation of precision agriculture approaches adapted to the challenges in horticultural production (Zude-Sasse et al., 2016). PH application needs a detailed monitoring of tree spatial variability during the cultivation period (Aggelopooulou et al., 2013).

It has been observed that soil spatial variability results in significant differences in orchards (Fountas et al., 2011; Uribeetxebarria et al., 2018 among others). Soil attributes commonly measured in PH are soil texture, water and nutrients, and apparent electrical conductivity (ECa). An integrative illustration of soil properties could be achieved with the measurement of ECa (Humphreys et al., 2005; Shaner et al., 2008). It provides valuable information for soil texture due to the fact that is affected by many parameters: soil humidity, salinity, soil texture, roots, nutrients and organic matter (Corwin and Plant, 2005). Previous studies have reported significant correlations between ECa and fruit trees properties. High spatial variability was indicated between ECa, soil properties and yield in small scale apple and pear orchards (Aggelopoulou et al., 2011; Vatsanidou et al., 2017). Käthner (Käthner and Zude-Sasse, 2015) observed that ECa and soil properties are related to tree growth, yield and quality related fruit size in plum trees.

Another significant factor that should be considered is the water needs of the trees in the orchard. This dynamic parameter is, again, depended from soil properties, but also microclimate and tree physiology. Thus, it is necessary to understand the spatial variability of soil texture as this remains the most stable property and could be interpreted as a key parameter for the computation of water needs (Hedley et al., 2009). The knowledge of temporal and spatial variability of readily available water content (RAW) is a factor of major significance as it indicates the threshold before the beginning of water stress (Jensen et al., 1990; Allen et al., 1998). The calculation of water needs during the cultivation period could improve the management in orchards (Alexandridis et al., 2014).The spatial variability of total available water content in the root zone (TAW) was calculated based on the ECa and soil texture in cereals (Haghverdi et al., 2015) and vineyards, where Hedley and Bradbury (Hedley and Bradbury, 2010) developed a variable rate model which was based on ECa and TAW maps in order to optimize irrigation in the field.

However, tree water needs are affected also by morphological and physiological parameters, such as the fruit development stage, tree height and leaf area. The effect of canopy size and more specifically of leaf area index (LAI) on evapotranspiration has been well documented. It should be noted that the canopy volume in fruit trees, is influenced by the tree water supply through the cultivation period (Naor et al., 2006; Bustan et al., 2016). Furthermore, a positive relationship of leaf area and evapotranspiration rate was found in citrus and olive trees (Ayyoub et al., 2017). Thus, these and the weather variables need to be considered during the calculation of crop evapotranspiration (ET_c) and, subsequently, in the water balance model. Additionally to the yield, fruit quality can potentially be influenced by the spatial variability of TAW (Hunsaker et al., 2015). The interaction of soil water status and tree growth parameters has been specified in arid and semi-arid conditions (Blum, 2017; Käthner et al., 2017). However, no spatially resolved water balance has been calculated in orchards so far.

The objectives of the present study were (i) to investigate the impact of soil patterns on the actual LAR in an apple orchard; (ii) to implement measured soil and simulated plant data from low, mid and high ECa regions in Geisenheim irrigation model in order to analyze the water deficit spatially in the orchard.

Material and methods

Site description

The experiment was conducted in a commercial apple orchard (5 ha) located in Brandenburg, Germany, during 2017. The orchard was planted with *Malus* x *domestica* 'Pinova'. Apple trees were trained as slender spindle at horizontally parallel wires and were spaced 6 x 1 m. The apple orchard was located on a plateau. The northern part had visually richer soil properties compared to the southern part.

ECa measurement and guided soil sampling

A Wenner electrode configuration, with four equidistantly spaced electrodes in a straight line at the soil surface was used for the calculation of soil resistivity (eq. 1). The depth of the measurement was fixed at 25 cm depth, which corresponds to the main root system. Measurements were done at field capacity. The calculation of ECa utilized the inversion of resistivity (eq. 2)

$$\rho = 2\pi a(\Delta V/I) \quad (1)$$

$$ECa = 1/\rho \quad (2)$$

Where ρ = the apparent soil resistivity [Ω*m], a = the electrode spacing [m], ΔV = the voltage [V], I = the current [A] from which the ECa [mS/m] was calculated. Values were saved from the data logger (4-Point Light, LGM, Germany) and analyzed in ArcGIS (10.2.2 ESRI, USA). The measurement took place for every forth tree and every second row (n = 460). Hence, a spatial grid of 4 x 4 m was applied for the ECa data, using Kriging interpolation. The interpretation of spatial variability enabled guided soil sampling. Thus, an Edelman combined soil sampler, utilized in 20 locations, covered the whole range of ECa. The samples were analyzed with Bouyoukos method. 60 soil cores were used for bulk density measurement at 30 cm, three for each soil sample.

Finally, the LAR from low, mid and high ECa regions was acquired after the defoliation of 10 trees (figure 1). The LAR has been measured with a portable area meter (CI-203, CID Bio-Science, Inc., USA).

Water balancing

A weather station (IMT 280, Pessl, Austria) located inside the orchard, could record the air temperature (T), relative humidity (RH), wind speed (u), solar radiation (R_n) and store the datasets in 15 minutes interval in the following website: http://technologygarden.atb-potsdam.de.

The calculation of ETc [mm] (eq. 3), requires also the estimation of crop coefficient (K_{cb}), soil surface evaporation coefficient (K_e), soil water stress coefficient K_s and the potential evapotranspiration (ET_0). ET_0 was calculated using the Penman–Monteith equation (Allen et al., 1998), and the coefficients were estimated according to the methods proposed earlier (Allen et al., 1998; Jensen et al., 1990).

$$ET_c = (K_s\ K_{cb} + K_e)\ ET_o \tag{3}$$

The K_{cb} tabulated in FAO-56 from bud break to full bloom ($K_{cb,ini}$), has been set at 0.8 (Allen et al., 1998; table 12). Whereas the coefficients between full bloom till harvest ($K_{cb,mid}$) and end-season ($K_{cb,end}$) were adjusted to the local soil, crop parameters and daily climatic conditions.

$$K_{cb,mid} = K_{cb,min} + (K_{cb,full,mid} - K_{c,\ min})(1- \exp[-0.7\ LAR]) \tag{4}$$

$$K_{cb,end} = K_{cb,min} + (K_{cb,full,end} - K_{c,\ min})(1- \exp[-0.7\ LAR]) \tag{5}$$

$$K_{cb,full,mid} = K_{cb,mid(tab)} + [0.04\ (u-2)-0.4(RH-45)]\ \left(\frac{h}{3}\right)^{0.3} \tag{6}$$

$$K_{cb,full,end} = K_{cb,end(tab)} + ([0.04\ (u-2)-0.4(RH-45)]\ \left(\frac{h}{3}\right)^{0.3} \tag{7}$$

The $K_{cb,min}$ was set at 0.15 assuming a bare soil surface. The measured range of LAR for the ECa regions have been implemented (eq. 4, 5) for simulation of relevant range of LAR. The values of $K_{cb,mid(tab)}$ (1.20) and $K_{cb,end(tab)}$ (0.85) were proposed earlier (Allen et al., 1998; table 12). The $K_{cb,full,mid}$ and $K_{cb,full,end}$ were estimated based on daily weather conditions and a mean tree height h = 3 m (eq. 6, 7). The RH_{min} addresses the entire cultivation period.

The K_s was estimated (eq. 8, 9, 10), only when the D_r exceeded the RAW.

$$K_s = \frac{TAW-Dri}{TAW-RAW} \tag{8}$$

$$TAW = 1000(\Theta_{FC}-\Theta_{WP})\ Z_R \tag{9}$$

$$RAW = TAW\ p \tag{10}$$

As noted before, TAW is the total available soil water in the root zone; $D_{r,\ i}$ is the water depletion in the root zone at the end of day i [mm]; RAW, the readily available soil water content [mm]; p, the average fraction of TAW that can be used by the plant in the root zone. Θ_{FC} is the volumetric water content of the soil sample at field capacity [cm^3/cm^3]; Θ_{WP} is the volumetric water content at wilting point of the soil samples [cm^3/cm^3] and Z is the average root depth for the apple trees as indicated by FAO-56 with 0.25 m.

For considering soil evaporation in the water balance model, the Ke for the mid or the last growth stage was calculated according to previous experiments (Allen et al., 2005; Paço et al., 2012) (eq. 11). Where the $K_{cb,full,max}$, is the maximum value of K_{cb} during the cultivation period. The estimation of K_e takes place when the soil starts to dry. In other words, when the daily cumulative depth of water depleted from the surface ($D_{e,i}$) exceeds readily evaporable water (REW). This can be defined by the soil evaporation reduction coefficient (K_r) (eq. 12). The REW was at 8 mm (Allen et., al., 1998; table 12). TEW (eq. 13) is the maximum evaporable water, which was defined according to the soil texture analyses. Furthermore, Z_e is the depth of soil that can be dried from evaporation, which was at 16 mm (Allen et., al., 1998; table 12).

$$K_e = K_r\ (K_{cb,full,max} - K_{cb,mid,end}) \tag{11}$$

$$K_r = \frac{TEW-De,i}{TEW-REW} \tag{12}$$

$$TEW = 1000(\Theta_{FC}-\Theta_{WP})\ Z_e \tag{13}$$

Consequently, the three different ET_c cases considering the low, mid, and high ECa regions and simulated LAR values were implemented in Geisenheim model for calculating the daily water balance [mm] in the orchard (eq. 14). P is the daily precipitation [mm].

$$WB = ET_c - P \tag{14}$$

Data analysis

Initially, outliers were removed and spherical semivariogram based on the least square regression was produced for the ECa map. Subsequently, ordinary Kriging interpolation following the semivariogram pattern and quantile classification was utilized for the ECa spatial variability interpretation into thematic map. The analysis was carried out in ArcGIS (Version 10.2.2, ESRI). Furthermore, the analysis of variance (ANOVA) was utilized in order to see the interaction of soil properties with the ECa. Finally, Kruskal and Wallis test, a non-parametrical analysis, took place in order to investigate the potential significance between the water balance and the different soil types. The last two analyses were carried out in Matlab (Version R2017a, Mathworks).

Results and discussion

Soil properties

The results from soil analysis after the guided soil sampling revealed that the soil texture was characterized as silty sand and loamy sand. In the ANOVA analysis, with the ECa to be considered as a depended variable, the results showed that the ECa is affected by coarse silt, with F ratio = 6.3 and p = 0.09. Furthermore, the ordinary Kriging interpolation revealed that the highest values of the ECa was located mainly in the north and south part of the field, while the lowest values have been depicted in the center of the orchard (Figure 1). Nevertheless, the soil texture analysis at 30 cm showed low to middle variation (Table 1). The soil was mainly composed by sand and more specifically by middle sand, which also had a low coefficient of variance (CV=12%). The values of ECa varied between 10 to 27.26 mS m^{-1} characterized as low, between 27.27 to 39.22 mS m^{-1} as mid, and between 39.23 to 60 mS m^{-1}as high ECa zone.

Table 1. Descriptive statistic of soil texture (N = 20) providing standard deviation (SD), and coefficient of variance (CV).

	Mean	SD	Range	Minimum	Maximum	CV%
Fine silt [mg kg^{-1}]	26.00	8.12	27.00	11.00	38.00	31
Middle silt [mg kg^{-1}]	40.25	11.92	39.00	22,00	61,00	30
Coarse silt [mg kg^{-1}]	77.75	19.33	73,00	42.00	115.00	25
Fine sand [mg kg^{-1}]	302.85	60.76	228.00	153.00	381.00	20
Middle sand [mg kg^{-1}]	395.20	47.17	146.00	323.00	469.00	12
Coarse sand [mg kg^{-1}]	117.75	63.64	245.00	40.00	285.00	54

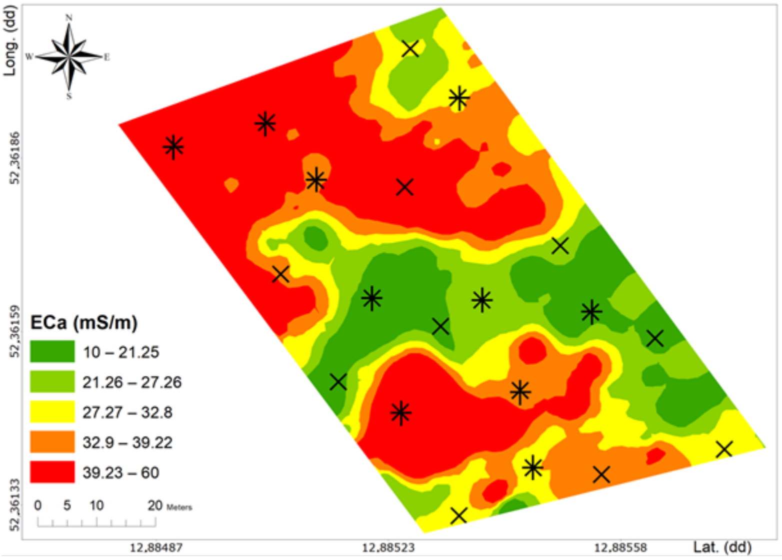

Figure 1. Thematic map of apparent soil electrical conductivity at 25 cm [mS m^{-1}]. The locations of guided soil samples at 30 cm are illustrated with crosses throughout the orchard. The locations of guided soil samples at 30 cm and LAR measurement are illustrated with stars.

The mean value of bulk density was 1.08 g cm^{-3}, with mean porosity of the soil sample of 26.5%. It should be noted that the values of TAW varied between 7.11 and 59.47 mm between sand and silt soils according soil texture analyses. At significance level of 5% using Pearson correlation, the soil texture partially correlated with the ECa: silt related positively (r = 0.52), while the sand was correlated negatively (r = -0.51 Furthermore, a significant correlation was observed between the ECa and the TAW (r = 0.78) simply indicating that enhanced ECa areas can hold increased amount of water in the root zone. Recently, Lo investigated and correlated the spatial patterns of the available water in the root zone and the ECa (McCutcheon et al., 2006, Lo et al., 2017) confirming our results. Considering the plant response, the mean value of LAR was 5.42 m^2 (Table 1). in low ECa region the LAR was 1.5 m^2, in mid ECa regions varied between 3 m^2 and 5.5 m^2, and in high ECa zone between 8 m^2 and 12 m$^{2.}$, Consequently, the ECa was correlated with the LAR in the present study (r = 0.80).

Table 2. Descriptive statistics for apparent soil electrical conductivity (ECa), total available water in the root zone (TAW) in 25 cm, porosity, bulk density (BD), and leaf area index (LAR). The number of samples (N), standard deviation (SD), and coefficient of variance (CV) are presented.

	N	Mean	SD	Range	Minimum	Maximum	CV%
ECa [mS/m]	461	35.83	16.13	98.18	8.15	60	45
TAW [mm]	20	38.36	12.68	52.36	7.11	59.47	33
Porosity [%]	20	26.4	17.17	56.08	11.23	67.13	65
BD [g cm^{-3}]	20	1.08	0.19	0.60	0.87	1.47	18
LAR [m^2]	10	5.42	3.50	9.69	1.50	11.19	65

Water balance

The precipitation rate remained low during the bud break. During full bloom, frosts occurred, while the air relative humidity fluctuated between 65% and 80%, whilst in the rest of the season a decrease in fluctuation was noted with values around 90% at harvest (Figure 2).

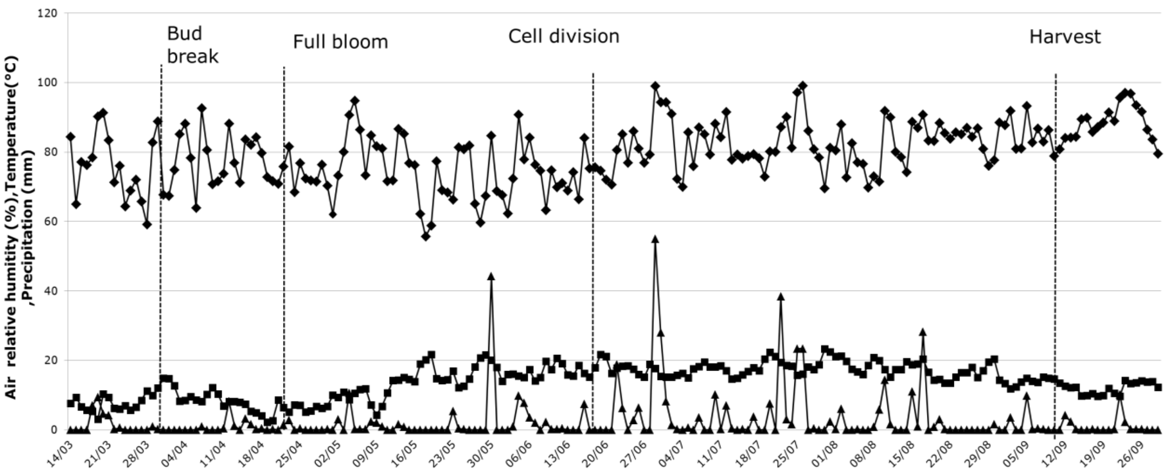

Figure 2. Daily weather conditions during the cultivation period considering air humidity (closed circle), temperature (closed square) and precipitation rate (closed triangle).

The Geisenheim model was employed in order to estimate the water needs in each month. The determination of the threshold according to the soil water properties and the influence of canopy size in the different ECa regions on the ETc enabled the understanding of variance of spatially resolved daily water balance.

Low irrigation threshold was found for low ECa region and high irrigation threshold for high ECa area, since high ECa corresponds to enhanced volumetric water content and vice versa expressed as RAW. These two thresholds were kept for all three ECa cases found in the orchard (Figures 3-5). Furthermore, five values of LAR, according to the range from the measured values, have been applied in the calculation of K_{cb} values in order to evaluate the effect of LAR on the water needs in low, mid and high ECa soils.

In regions with low ECa values, the LAR of 12 m^2 and 8 m^2 depict steep fluctuations always above the thresholds, indicating water stress, with the highest water deficit of 180 mm after harvest period (Figure 3). The water deficit for LAR below 5.5 m^2 remained lower with the highest value reaching 80 mm during July. Furthermore, the reduced LAR of 1.5 m^2 and 3 m^2 exceed the high threshold corresponding to enhanced RAW, mainly during June and July.

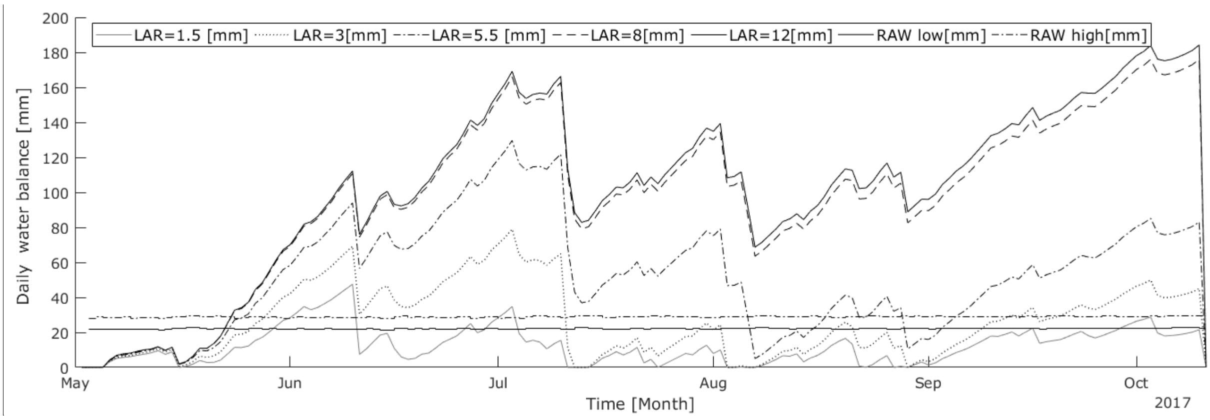

Figure 3. Simulation of LAR values (1.5, 3, 5.5, 8 and 12) in Geisenheim model in low ECa regions [mm]. Readily available water content (RAW) in 80% field capacity from low ECa regions considered as two orchard-uniform thresholds values.

The trees from mid ECa showed reduced water deficit with the maximum value to be observed at 52.5 mm (Figure 4). More specifically, as a consequence of enhanced precipitation rate, two steep decreases have been noted during June and July in all models. The water needs of 5.5 m^2 LAR and above reveal drought stress during June, July and late September. However, the trees with diminished LAR of 1.5 m² had reduced water needs and only 3 m^2 exceeded the high and the low threshold during June, July. It should be noted that during May none of the LAR values exceeded the thresholds, a fact which signifies that the trees did not face water stress in full bloom considering this mid ECa region of the orchard.

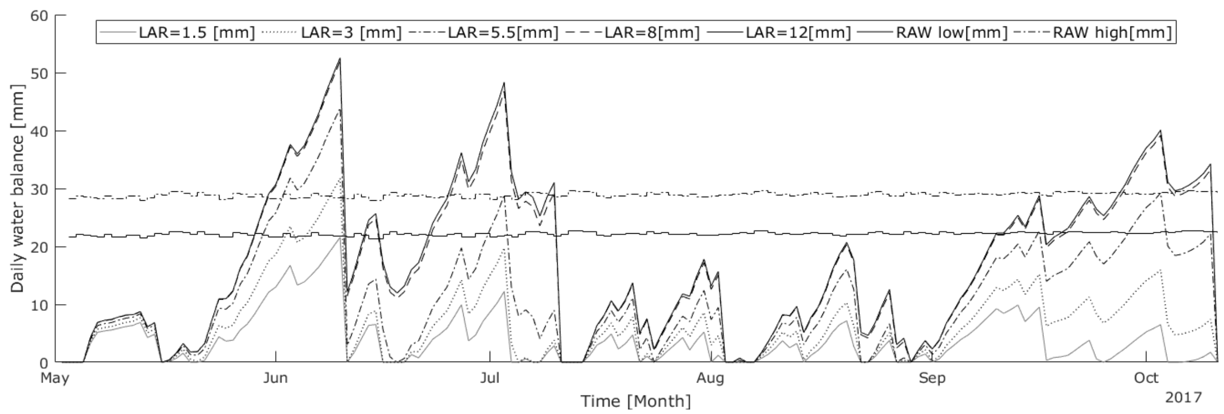

Figure 4. Simulation of LAR values (1.5, 3, 5.5, 8 and 12) in Geisenheim model in mid ECa regions [mm]. Readily available water content (RAW) in 80% field capacity from low ECa regions considered as two orchard-uniform thresholds values

Trees from high ECa areas show slightly enhanced water deficit compared to the mid ECa regions with maximum value around 63 mm. Similarly as in the previews graph, the patterns of water deficit for the LAR remained the same. However, a slight increase in water needs of LAR 5.5 m^2 and above was observed. Consequently, the water balance for these values point to drought stress between June and July and during August, which escalated during harvest period.

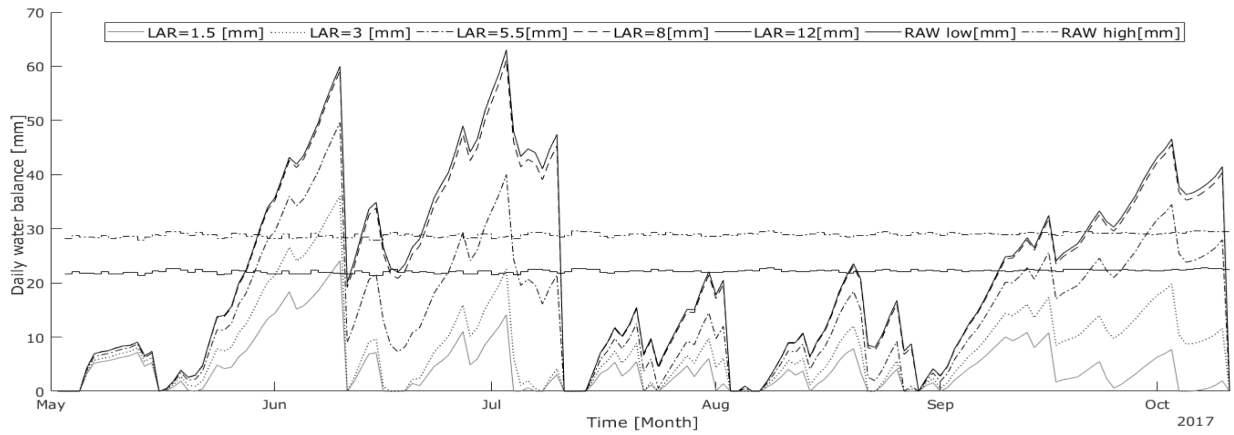

Figure 5. Simulation of LAR values (1.5, 3, 5.5, 8 and 12) in Geisenheim model in high ECa regions [mm]. Readily available water content (RAW) in 80% field capacity from low ECa regions considered as two orchard-uniform thresholds values.

The average monthly values from each ECa region were compared for each model. This was performed utilizing Kruskal and Wallis test, a non-parametric model used to test the differences among the models (Table 2). The model of 1.5 m^2 and 3 m^2 LAR were statistical different between low–mid ECa and low-high ECa regions ($p<0.05$), whereas no statistical significance have been observed in mid–high regions (p=.429, p=.148). However, the water balance of 5.5 m^2, 8 m^2 and 12 m^2 LAR were different in all ECa regions.

Table 3. Kruskal-Wallis non parametric analysis among the water balance models for low, mid and high ECa region.

Region	WB LAR=1.5	WB LAR=3	WB LAR=5.5	WB LAR=8	WB LAR=12
Low ECa [mS/m]- Mid ECa [mS/m]	.000	.000	.000	.000	.000
Low ECa [mS/m]- High ECa [mS/m]	.000	.000	.000	.000	.000
Mid ECa [mS/m]- High ECa [mS/m]	.429	.148	.008	.024	.024

The water deficit rapidly increased from bud break till the canopy is fully developed by the end of April. In parallel, the temperature rise and enhanced LAR resulted in increased evapotranspiration demands. During June and July, the maximum water use takes place by the tree. A water balance experiment was utilized in citrus orchard, the researchers examined the differences on water balance of a non-irrigated area and an irrigated area at the same field (Petillo and Castel, 2007). They suggested that the variation in daily ET_c values, even in short intervals, in the same month could be due to lack of water availability to the trees or the influence of climatic conditions. Odi-Lara and co-workers (Odi-Lara et al., 2016), in a remote sensing water balance model in apple trees, suggested that possible peaks in the water balance can be minimized by the daily monitoring of K_{cb} value. Furthermore, Ferreira, (2017), stressed that due to the fact that woody plants are adapted to soil conditions, the modeling of water balance taking into account the RAW and K_s need to be considered for an irrigation scheduling. The present findings on the influence of varying LAR confirm these assumptions.

Conclusion

The outcomes of this study reveal differences in the water balance when considering the spatial variability of the soil and the leaf area. In the center of the orchard, the ECa values mainly were lower than in the south or in the north, while lower LAR values also detected in the center of the field. According to the soil texture analysis regions of high ECa hold enhanced amounts of water content resulting in varying, here two, thresholds.

Considering the trees with high LAR, enhanced water deficits were found particularly in low ECa regions. However, the orchard had a light soil profile with high amounts of sand and silt, a fact which assist high soil evapotranspiration within the orchard, an effect which might be reduced in heavier soils.

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