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Survey of Soil Water Distribution in a Vineyard and Implications for Subsurface Drip Irrigation Control

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Abstract

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Controlling a subsurface drip irrigation system based on soil water monitoring is a very efficient way to supply grapevines with water for optimal thriving and high vintage quality. However, finding an adequate location for sensor installation is a great challenge due to the well-known spatio-temporal variability of soil moisture and possible measurement uncertainties. The variations depend on soil structure, soil hydraulic properties, or plant water uptake, for instance. Subsequently, these factors are influenced by management practices such as soil cultivation or cover cropping. The main objective of this study was to gain experience in order to give recommendations for soil water monitoring in a vineyard in accordance to local management practices. Soil moisture was surveyed across a study plot in a vineyard. A gouge auger was used to obtain soil samples from both sides of two vine rows for determining gravimetric water content. Volumetric soil water content was measured near the vine rows by inserting a portable soil water probe into pre-installed access tubes. Soil water variability was investigated under rain-fed conditions, and before and after a subsurface drip irrigation event. Differences were considered between inter-rows that were frequently tilled and those with permanent crop cover. In the first of two study years the variability of soil water content was small as the soil characteristics were relatively homogeneous across the plot and the atmospheric conditions were rather wet. In the second year the deviations were greater due to the more dynamic outer conditions. The alternating cultivation of every second inter-row had a substantial effect on soil water distribution in both years. Representative monitoring across the entire plot should thus consider all inter-rows with distinct cultivation. However, a more efficient procedure is recommended as a basis for irrigation control, considering the uncertainties caused by spatial variability.

Keywords: gravimetric water content; Sentek Diviner; spatio-temporal variability; volumetric water content

Availability of water is vital for plant growth and development. For agricultural production optimal conditions are aspired to achieve yield stability and a good product quality (Allen *et al.* 1998). Grapevines – like other crops – have specific water requirements. While excessive rainfall (and irrigation) as well as severe water deficit stress are expected to reduce grape quality, moderate stress commonly supports an improved vintage quality (Van Leeuwen *et al.* 2009; Ruiz-Sanchez *et al.* 2010). An excellent quality is of particular importance when grapes are cultivated for high-quality wine production. In this regard, an adequate irrigation management – combining an efficient irrigation system with demand-oriented scheduling – is required to optimally provide plants with water.

Subsurface drip irrigation (SDI) is widely accepted as a very efficient irrigation system (Camp 1998; Ayars *et al.* 1999). This is the case as the drip laterals are buried in the ground and water is applied directly to the rooting zone where it is immediately available for plant uptake. However, SDI works ef-

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ficiently only if soil surface is maintained dry (thus avoiding unproductive water losses arising from bare soil evaporation), and the applied amount of water does not exceed the water holding capacity of the soil within the rooting zone. Otherwise, water will percolate towards deeper zones that are out of reach for roots (Ayars *et al.* 1999). Therefore, it is beneficial to monitor soil water content and keep it within a range that is optimal for winegrowing according to conventional approaches or special deficit irrigation strategies that have the potential to increase both yield quality and water use efficiency (De la Hera *et al.* 2007; Intrigliolo & Castel 2008, 2009; Ruiz-Sanchez *et al.* 2010). More and more Austrian farmers and winegrowers consider controlling irrigation based on sensor readings. Due to the lack of experience no clear recommendations can be given in accordance to local management practices (e.g. inter-row cropping) under varying weather conditions. This problem was the main motivation for this study.

A central challenge when installing soil water sensors is to find a suitable place. From a practical point of view this means that fieldwork, tillage operations, and maintenance of the irrigation system should remain unconcerned. Of equal importance is that sensor readings adequately represent soil water dynamics of the considered area. In this regard, the well-known spatial and temporal variability of soil moisture regularly causes inconveniences. The variations follow physical principles that depend on soil characteristics, soil hydraulic properties, topography, and boundary conditions such as atmospheric processes and plant water uptake (Starr 2005; Vereecken *et al.* 2008). In a natural environment the influencing parameters are interrelated with considerable complexity and they change with time. Water transport and storage mainly depend on soil hydraulic properties, which are closely related to structure (pore size distribution) and to a minor extent to texture (particle size distribution). Soil texture is generally time-invariant unless layers with different soil types are mixed artificially. In contrast, soil structure is highly dynamic due to root activity, tillage operations, swelling and shrinking processes, and frost action (e.g. Jury *et al.* 1991; Evett *et al.* 2009). Apart from their temporal dynamics these processes produce heterogeneous soil conditions. Further variability of soil moisture is induced by uneven distribution of irrigation water, which is particularly critical when operating an SDI system (Camp 1998; Dabach *et al.* 2015). In vineyards also the cultivation of the inter-rows – e.g. traditional tillage, cover cropping, mulching – is supposed to have an impact on soil water distribution (Celette *et al.* 2008; Medrano *et al.* 2015).

In the presented study, soil water variability was investigated in a vineyard managed according to local practices aiming at soil and water conservation. Soil-water related actions included on the one hand occasional tillage of the uppermost soil layer of every second inter-row, and on the other hand irrigation by means of subsurface drip lines. The investigations were concentrated on periods with different hydrological conditions in the years 2010 (annual precipitation: 775 mm) and 2011(450 mm). The first study year was characterized by frequent rainfall, so soil was sufficiently moist and no irrigation was required. Under such conditions, soil water distribution was assumed to arise mainly from water uptake by the grapevines and from soil attributes that were relatively homogeneous within the study plot. Another focus was set on soil moisture variability before and after an irrigation event, which could be investigated in the subsequent dry year. Furthermore, it turned out that the different conditions in the inter-rows considerably affected soil water distribution. From the findings recommendations can be concluded with respect to installation and operation of soil water sensors for controlling a SDI system.

MATERIAL AND METHODS

Site description. The study plot was located within a vineyard in the eastern part of Austria (47°48'16''N, 17°01'57''E). Its elevation of 118 m is almost the lowest in Austria, the absolutely lowest (114 m) lies in the same flat region.

The site is hydrologically characterized by an average annual temperature of 10.6°C and an annual precipitation of 570 mm (referring to the period 1996–2011). Rainfall and air temperature were measured at a weather monitoring station at a 3 km distance (operated by the Central Institute for Meteorology and Geodynamics, Austria, ZAMG) and also directly on the study plot using a Vaisala WXT 520 sensor (Vaisala Oyj, Helsinki, Finland) that was integrated into a wireless network (Nolz & Cepuder 2011).

The vines (*Vitis vinifera* L. cv. Chardonnay crafted onto Kober 5BB rootstocks) were planted early in 2010. Subsurface drip lines were installed on both sides of each row at a 0.5 m distance and 0.3 m deep.

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The tubes were 16 mm in diameter and comprised one pressure-compensating emitter per running meter with an outflow rate of 2.2 l/h. The study area surrounded six vine rows with 2.8 m spacing and five inter-rows, of which every second was occasionally cultivated (Figure 1). The rows were N–S oriented. Two vine rows were selected for the study and equipped with access tubes for soil water measurements.

Soil sampling in the field. Disturbed soil samples were taken for the determination of particle size distribution and gravimetric water content. Insertion spots for a gouge auger were arranged along four transects (T1, T2, T3, and T4) in parallel to the vine rows at a distance of 1 m to the latter and 0.5 m to the respective drip line (Figure 1). Eight profiles per transect were sampled. The sampling points for the replications were positioned in relation to the drip line with an estimated accuracy of 0.1 m. Each soil profile was separated into six increments, whereof the first was from 5 to 15 cm and referred to a 10 cm depth; the sixth and last was from 55 to 65 cm and referred to a 60 cm depth.

In 2010 the vineyard was not irrigated and three sampling dates were set forming similar time intervals: June 29, August 11, and October 1. In 2011 soil samples were taken on July 12, 14, and 16. On July 13 the vineyard was subsurface drip irrigated. The first sampling day was immediately before the irrigation event, the others shortly after it.

Soil analyses in the laboratory. Particle size distribution was determined using the soil material from the first year. Samples of each depth from around the access tubes were mixed, resulting in 36 pooled samples (six layers of six mixed profiles). The soil samples were fractionated using a wet sieving and a pipette method. The soil was classified as sandy loam according to the Austrian texture nomenclature with a fine fraction of 41% sand (2 mm > d ≥ 0.063 mm), 38% silt, and 21% clay. Particle size distribution was relatively homogeneous within the study plot and over depth (Figure 2): The maximum coefficient of variation was 6.4%, which is rather small compared to the potential range of 3 to 55% according to Jury *et al.* (1991).

Further soil analyses discovered 2% humus content in topsoil, an average dry bulk density of 1.46 g/cm^3, a particle density of 2.67 g/cm^3, and a total porosity estimated from the former of 0.45 cm^3/cm^3.

For analyzing soil moisture the disturbed samples were weighed, dried at 105°C until mass remained constant, and weighed again. Gravimetric water content w was calculated as (vaporized) mass of water (in g) divided by dry soil mass (in g), it is expressed in percent (%), being the same as g/g ×100.

Soil water sensing. A Diviner 2000 soil moisture probe (Sentek Pty Ltd, Stepney, Australia) was used to measure volumetric water content θ over multiple depths. The Diviner is a portable device with a hand-held logger and a capacitance sensor that is inserted into a plastic access tube (Sentek 2009). Its performance is well documented in literature (e.g. Evett *et al.* 2006, 2009). The sensor consists of two encapsulated metal rings. They are parts of a highly oscillating circuit and span an electromagnetic field in the surrounding soil. The oscillation frequency is influenced by the amount of water in the adjacent volume of soil. Therefore sensor readings can be related to θ via a soil-specific calibration function (Sentek 2001, 2009). Sensor readings were normal-

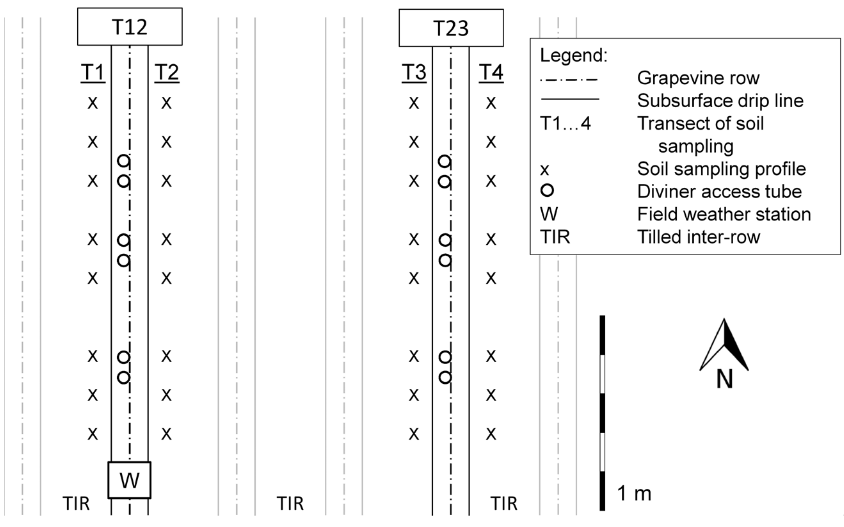

Figure 1. Sketch of the study plot within the vineyard

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ized to a so-called Scaled Frequency $SF = (F_a - F_s)/(F_a - F_w)$. Sensor-specific readings in air (F_a) and water (F_w) were determined for each sensor in the laboratory, F_s is the frequency reading in moist soil. θ was calculated from *SF* using the default calibration $SF(\theta) = 0.2746 \cdot \theta^{0.3314}$ as recommended by the manufacturer (Sentek 2001). It has to be noted that without site-specific calibration water content data might differ from values determined with core samples. However, in this study only comparative analyses are presented. θ is defined as volume of water per bulk volume of soil (cm^3/cm^3). In this paper sensor data are expressed in percent (%), which can also be interpreted as $cm^3/cm^3 \times 100$.

In total twelve plastic access tubes were installed at the study site (Figure 1). The rows were named T12 and T34, illustrating their positioning in relation to the transects of auger sampling. The access tubes were vertically drilled into the ground between the vine row and the adjacent drip line at a lateral distance of 0.2 m to the first and 0.3 m to the latter. In accordance with the auger sampling, θ was measured at 10, 20, 30, 40, 50, and 60 cm depths, of which each value represented a soil increment of 10 cm height (5–15 cm and so on).

Data evaluation. The basics for this study are the datasets of *w* from auger sampling and θ from sensor measurements. In the following sections different ways of averaging *w* and θ are distinguished in order to illustrate differences referring to depth increments, profiles, or transects. Furthermore, standard deviations (SD) were calculated to point out uncertainties between depth increments and transects due to spatial variability and (to a lesser extent) due to measurement errors. SD is also the basis for estimating errors on a certain confidence interval (e.g., 2-σ-error on a 95% confidence interval). As a precondition for the determination of SD, data were verified to be normally distributed by applying the Shapiro-Wilk test utilizing the open source statistical software R (R Development Core Team 2008). Shapiro-Wilk has proven to be a powerful normality test for sample sizes $n > 3$ (e.g., Razali & Wah 2011). The processed datasets contained 8–48 values.

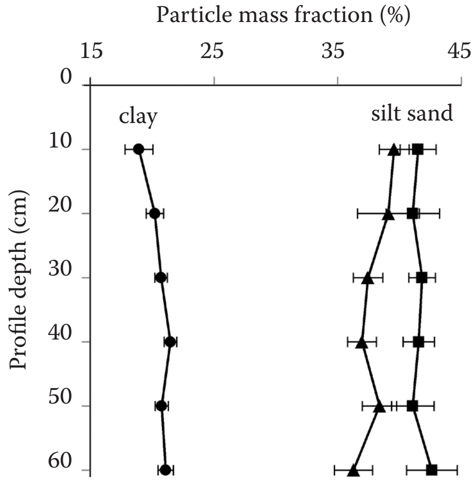

Figure 2. Particle size distribution over depth; bars represent standard deviation

For the 2010 dataset, the average gravimetric water content for a certain depth and transect w_{at} was calculated as the arithmetic mean of the values representing the corresponding depth increment of the eight sampling profiles. Analogously, $SD_{w_{at}}$ was calculated from the eight respective values. The gravimetric profile water content w_{ap} is the arithmetic mean of the six increment values of a certain profile. The gravimetric transect water content w_{pt} is the arithmetic mean of eight profile water contents w_{ap} of a certain transect. Deviations between the eight profile water contents of a transect are expressed by $SD_{w_{pt}}$. For the 2011 data only w_{pt} and the respective $SD_{w_{pt}}$ was determined.

The average volumetric water content for a certain depth and transect (row) θ_{at} was calculated

Table 1. Overview of water content data from 2010

	w (soil sampling) 4 transects	θ (sensor readings) 2 transects (rows)
Average water content (index at)	6 w_{at} values per transect: mean of 8 (horizontal) depth increments	6 θ_{at} values per transect: mean of 6 (horizontal) sensor readings
Profile water content (index ap)	8 w_{ap} values per transect: mean of 6 (vertical) depth increments	6 θ_{ap} values per transect: mean of 6 (vertical) sensor readings
Transect water content (index pt)	1 w_{pt} value per transect: mean of 8 profiles and 6 depth increments	1 θ_{pt} value per transect: mean of 6 profiles and 6 sensor readings

w – gravimetric water content; θ – volumetric water content

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as the arithmetic mean of the sensor readings at the corresponding depth of the six access tubes. The corresponding $SD_{\theta_{at}}$ was calculated from the six respective values. The volumetric profile water content θ_{ap} is the arithmetic mean of the six sensor readings of a certain profile. The volumetric transect water content θ_{pt} is the arithmetic mean of six volumetric profile water contents of a certain transect. The measurement dates were the same as for the soil sampling. Due to a failure, data of only ten measurement profiles could be used from 2011. The deviations between the six θ_{ap} values of a transect are expressed by $SD_{\theta_{pt}}$.

A paired, two-sided *t*-test was used to check if differences of w_{pt} and θ_{pt} were significant based on a 95% confidence interval ($P > 0.05$). The test was executed using R software (R Development Core Team 2008).

RESULTS AND DISCUSSION

The year 2010 was wetter than average: frequent rainfall produced moist soil conditions throughout the vegetative period, no irrigation was applied. Figure 3 illustrates w_{at} and $SD_{w_{at}}$ for all depths and transects at the three measurement dates. Vertical soil water distribution was relatively uniform, except for T1 and T3 on June 29. The non-uniform distributions were induced by unintended compaction of the uppermost soil layer that obviously had an impact

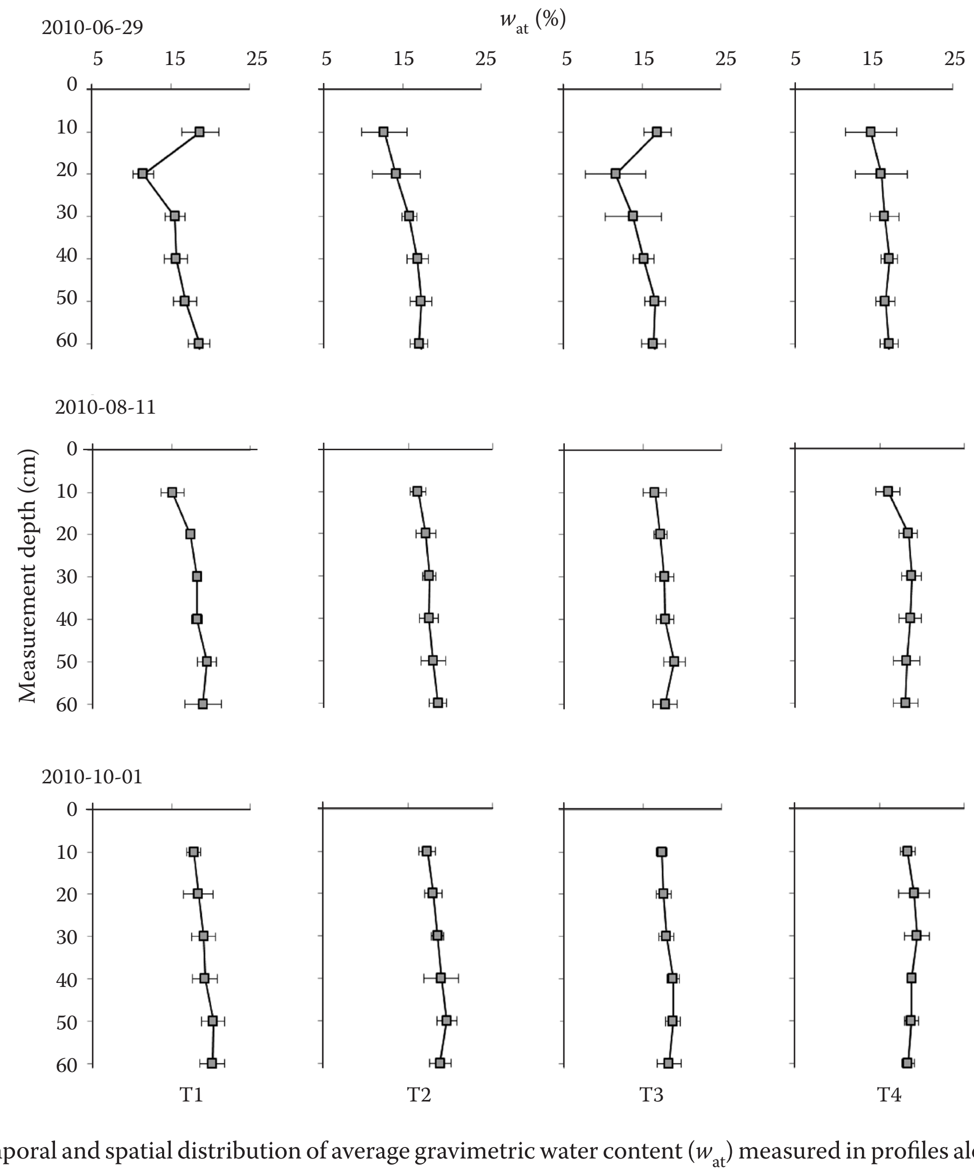

Figure 3. Temporal and spatial distribution of average gravimetric water content (w_{at}) measured in profiles along transects T1, T2, T3, and T4 at three dates in 2010

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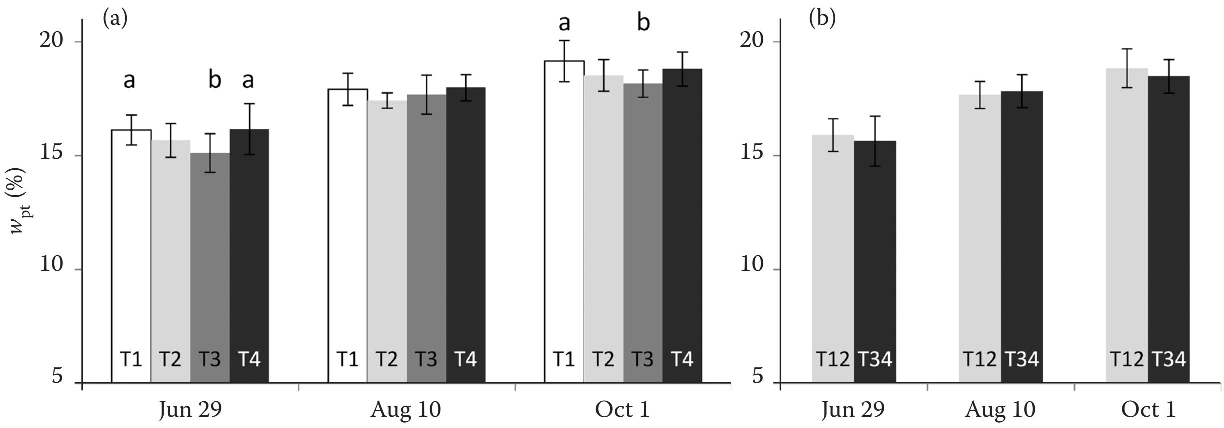

Figure 4. Gravimetric transect water content (w_{pt}) and standard deviation measured at three dates in 2010 (a) and combination of transect data (b); small letters indicate the same significance level ($P > 0.05$)

on pore size distribution and surface roughness. However, the relation between w_{ap} values of the four transects was similar at all dates (data not shown), so all profiles were considered for calculating w_{pt} without restriction for further interpretation. After the first sampling date, the topsoil was tilled and the mentioned influence was eliminated. The mean over six depths, four transects, and three dates of 6 × 4 × 3 $SD_{w_{at}}$ values was ± 1.5%, considering only the second and third sampling date it was ± 1.2%.

The w_{pt} showed a considerable spatial variability, at which T1 and T4 were (partly significantly) larger than T2 and T3 (Figure 4a). The most likely explanation for the wetter soil in T1 and T4 is that tilling the topsoil in the respective inter-row reduced weed growth and thus water uptake. For a better comparison with sensor measurements of T12 and T34, w_{pt} values from both sides of a vine row (T1 and T2; T3 and T4) were averaged. The result is given in Figure 4b. The average of T12 was not significantly different from T34, suggesting similar water uptake near both investigated rows of grapevines. Mean w_{pt} values of four transects at the three dates were 15.8, 17.7, and 18.7%. The respective $SD_{w_{pt}}$ values were ± 0.9, ± 0.7, and ± 0.8% (± 0.8% on average). The absolute increase from one measurement date to the other was 1.9 and 1.0%.

Volumetric water content θ showed a more distinct distribution over depth (Figure 5) than w values (Figure 3). θ was smaller in the upper soil layers and increased to a maximum at a depth of 40–50 cm. The mean over six depths, two transects, and three dates of 6 × 2 × 3 $SD_{\theta_{at}}$ values was ± 3.1%, expressing a considerably greater variability of sensor measurements compared to gravimetric samples. Such a large variance can complicate the analysis and interpretation of θ data.

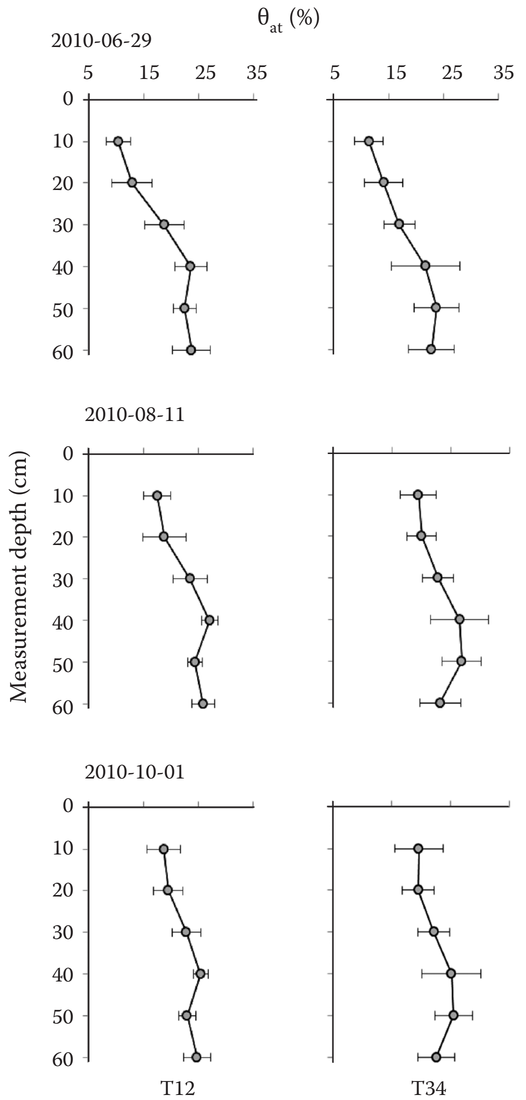

Figure 5. Temporal and spatial distribution of average volumetric water content (θ_{at}) measured down the profiles along the vine rows (T12 and T34) at three dates in 2010

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Reducing the uncertainty would require a considerable greater number of measurements (Evett *et al.* 2012). However, this would lead to a disproportional effort, especially for field calibration. Nevertheless, the latter is often recommended by manufacturers and researchers. For irrigation control the practicability of an according field calibration is questionable as the experimental procedure is destructive (soil samples have to be taken very close to the access tubes) and requires adjustment of distinct soil moisture conditions (Sentek 2001), which is the opposite to prerequisites for monitoring.

Similar to w_{pt} data, θ_{pt} data were not significantly different between transects (Figure 6). But the absolute difference of mean θ_{pt} data of transects T12 and T34 from one date to the next was 4% and –0.5%, which does not reflect the continuous soil moisture increase of w_{pt}. Potential reasons are, for example, measurement inaccuracies, soil heterogeneity, and non-uniform soil water distribution. Nevertheless, the data of both vine rows reflect the same status, so the most likely causes in this case are temperature effects on the sensors readings. The latter are assumed to deliver smaller θ values at a low temperature and *vice versa* (Kammerer *et al.* 2014). To determine specific impacts in detail is beyond the scope of this study, but it has to be noted that uncertainties are supposed to remain due to shortcomings of sensor performance (Evett *et al.* 2012). The mean SD of all θ values (six depths × six access tubes × two transects × three dates) was ± 1.6%. This value indicates the mean measurement uncertainty providing helpful information for interpreting soil water data.

The year 2011 was generally drier than 2010. Differences between adjacent transects were significant (Figure 7a). It is obvious that tilling of the topsoil of every second inter-row (T1 and T4) retained soil water, whereas the areas where weed could develop (T2 and T3) were drier. Similarly, Celette *et al.* (2008) and Monteiro and Lopes (2007), for instance, investigated smaller water contents under grass and similar permanent vegetation. The rank from largest to lowest (T4 > T1 > T3 > T2) was the same at all three dates, indicating a certain temporal stability of water content as described by several authors (e.g. Pachepsky *et al.* 2005). Although irrigation was applied on July 13, w_{pt} did not increase within the measuring period, revealing that the horizontal propagation of the wetting front did not reach the sampling zone at a 0.5 m horizontal distance. As a consequence, installation of soil water content sensors is recommended close to the drip laterals and also close to an emitter. Based on simulations, Dabach *et al.* (2015) recommend an optimal placement of tensiometers for irrigation

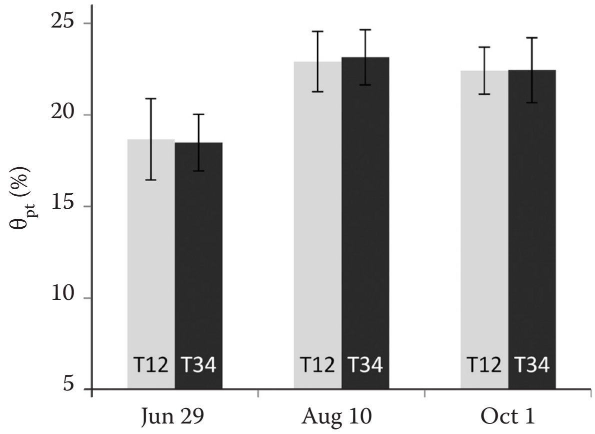

Figure 6. Volumetric transect water content (θ_{pt}) in the vine rows (T12 and T34), 2010

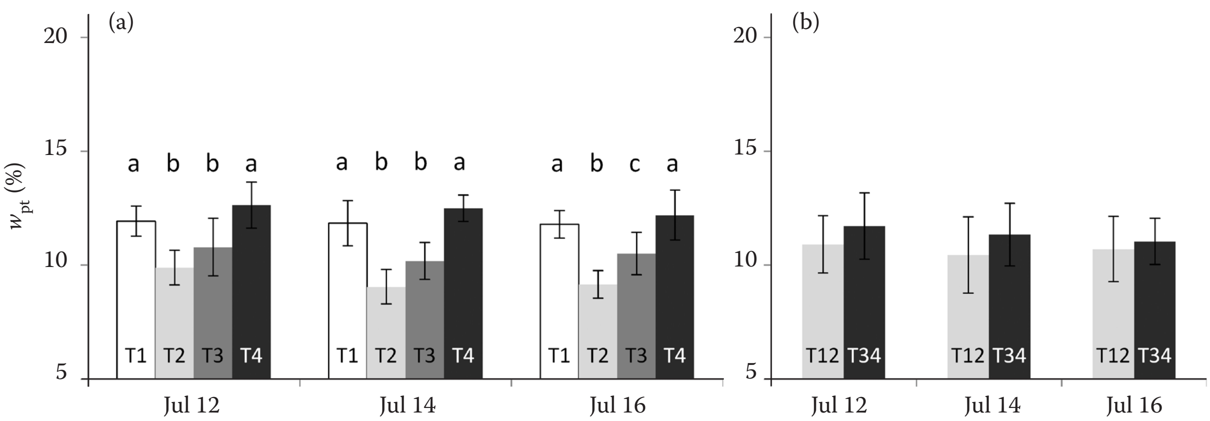

Figure 7. Mean gravimetric water content (w_{pt}) and standard deviation of transects (T1–T4) measured at three dates in 2011 (irrigation was applied on July 13) (a), combination of transect data (b); small letters indicate the same significance level ($P > 0.05$)

control at a distance of 30 cm from dripper. That means that the exact position of a subsurface dripper has to be known before installing soil water sensors. w_{pt} did not change significantly from one sampling date to the next (Figure 7b), but T12 was drier than T34, even though not significantly. Considering the data from 2010, where the relation between the T12 and T34 was changing (Figure 4b), it has to be concluded that the differences express a considerable spatio-temporal variability caused by the plant water uptake. In the given case, $w_{pt} \pm SD_{w_{pt}}$ was 11.0 ± 1.5%.

In contrast to w_{at} data, sensor readings reproduced clearly the irrigation event between July 12 and July 14, 2010 with an increase of mean θ_{pt} of two transects (T12 and T34) by 3% (Figure 8). After irrigation θ_{pt} was considerably (but not significantly) larger in T34. Alike the relation in Figure 7b, but in contrast to the status illustrated in Figure 4b, the soil was wetter near T34 in the investigated period. The mean difference of θ_{pt} was 1.8% between T12 and T34. $SD_{\theta\ pt}$ was the largest on July 14 (± 3.3%) – soon after irrigation – indicating the greatest variability of all measurement dates (Figure 6 and Figure 8). The deviations reveal once more a certain spatio-temporal variability of soil moisture, and consequently also potential inaccuracies of sensor readings (Evett *et al.* 2012). Such considerable uncertainties should be considered when controlling irrigation based on soil water monitoring.

Irrigation can be controlled in such a way that soil moisture is kept within a range that represents the readily plant available water stored in a certain soil profile (Allen *et al.* 1998). The limits are usually defined based on unsaturated hydraulic parameters (field capacity, permanent wilting point). By narrowing the range – reducing the upper limit and increasing the lower limit considering the determined SD

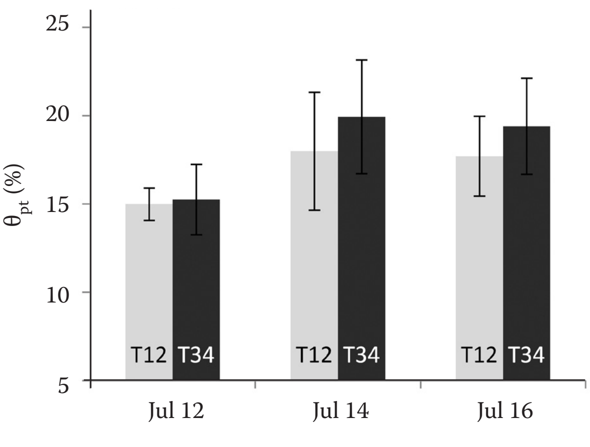

Figure 8. Mean volumetric water content (θ_{pt}) in the vine rows (T12 and T34), 2011 (irrigation was applied on July 13)

of water content – it can be avoided that soil water status runs out of the optimal range due to inaccurate measurements. That means that irrigation should be started and stopped before the "original" thresholds are reached, hence irrigation events and intervals are supposed to become shorter in average. In order to improve this basic adaption, further studies on the relationship between the competing water uptake of grapes and cover crops are necessary.

CONCLUSIONS

Variability of soil moisture was investigated in a vineyard by means of soil sampling (along transects on either side of a vine row) and soil water sensing (probes installed near the vine rows). In the first year the variability of water content was small due to relatively homogeneous soil characteristics and little fluctuating hydrological boundary conditions. Mean standard deviation of all gravimetric and volumetric water content values was ± 0.8% and ± 1.6%, respectively. In the second year the respective standard deviations were ± 1.5% and ± 3.3%. The greater values compared to the first study year arose from the more dynamic outer conditions. The alternating cultivation of every second inter-row had a substantial effect on soil water distribution in both years. The impact was more pronounced in the drier year 2011, when soil moisture was significantly different on both sides of a vine row. Transect water content was generally larger in the tilled inter-rows, indicating smaller unproductive water losses. Representative monitoring across the entire plot should thus consider all inter-rows with distinct cultivation. However, a more efficient procedure is recommended as a basis for irrigation control. Firstly, the focus should lie on plant water uptake; hence, soil water status should be monitored within the rooting zone of the vines very next to a subsurface emitter. Secondly, the uncertainties caused by spatial variability should be considered in such a way that the range of optimal water content for irrigation control is reduced in order to avoid unintended over-irrigation as well as water deficit stress. As a consequence, irrigation will be applied on average more often and with a shorter duration.

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