FACTORS INFLUENCING THE OCCURRENCE OF WATER STRESS AT FIELD SCALE

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Abstract

The soil water content (SWC) of limited plant availability *(*θ_{la}*)* is not a stable property of soil but also depends on potential evapotranspiration; E_p. Below this critical SWC value, the relative evapotranspiration is less than 1. To avoid water stress water should be supplied to vegetation in order to maintain the optimal range of SWC above θ_{la} during important ontogenetic phases. The influence of soil texture and 8-m high hedgerow on field-scale fluctuations of θ_{la} were studied in western Slovakia near Moravský Sv. Ján (MSJ) village and in north-eastern Austria near the village Rutzendorf, respectively.

The results illustrate that both, hedgerow and soil texture influence the occurrence of soil water stress at field scale significantly. The spatial variability of θ_{la} can exceed its seasonal variability.

Key words: soil water stress, field scale, soil water availability, textural heterogeneity, hedgerow, microclimate variability

Anotácia

Obsah vody v pôde zodpovedajúci stavu zníženej dostupnosti vody pre rastliny *(*θ_{la}) nie je stabilnou charakteristikou konkrétnej pôdy, ale záleží tiež na hodnote potenciálnej evapotranspirácie, E_p v danom čase na danom mieste. Pod touto hodnotou obsahu vody v pôde klesá hodnota relatívnej evapotranspirácie pod hodnotu 1. Počas kritických ontogenetických fáz rastlín je potrebné zabezpečiť obsah vody v pôde v optimálnom rozsahu nad hodnotou θ_{la}, aby rastliny netrpeli vodným stresom. Vplyv pôdnej textúry a 8-m vysokého vetrolamu (pás drevín) na výskyt vodného stresu v mierke poľa bol osobitne študovaný na západnom Slovensku (Moravský Sv. Ján) a v severovýchodnom Rakúsku (Rutzendorf). Výsledky demonštrujú, že ako pôdna textúra tak aj vetrolam významne ovplyvňujú výskyt vodného stresu v mierke poľa, spôsobujúc priestorovú variabilitu θ_{la}, ktorá dokonca presahuje jeho variabilitu sezónnu.

Kľúčové slová: vodný stres, mierka poľa, dostupnosť vody pre rastliny, textúrna heterogenita, vetrolam, variabilita mikroklímy

Introduction

Water stress occurs when the water supply to the plant fails to meet the transpiration demand. Extended periods of soil water deficit and high air and soil temperatures can affect a wide range of physiological functions, leading to increases in root/shoot ratios, leaf abscission and a reduction in cell division (Hunt *et al.*, 2002).

In maize or cereal crops that are the major carbohydrate staples for humans, even intermittent water stress at critical stages may result in considerable yield reduction and crop failure

(Ludlow and Muchow 1990, Katerji *et al*., 2008). The knowledge about water stress occurrence in time and space is therefore advantageous.

The soil water storage that can be utilized by vegetation for photosynthesis (plant available water), is often estimated as the volume of water in the vadose zone or a defined soil layer, which relates to energetic binding between water and solid matter in the interval between the wilting point (θ_{fc}) and the field capacity (θ_{fc}). More recently, other water stress indices have been examined, including the photochemical reflectance index (Sarlikioti *et al*., 2010) and infrared thermography (Wang *et al*., 2010). However, these indices do not consider soil physical characteristics and therefore cannot be readily used to estimate plant water requirements in irrigated systems.

The estimation of θ_{fc} is often controversal because it lacks physical meaning. Standard laboratory methods of estimating θ_{fc} are well described in the literature by Bear *et al*. (1968) and Hillel (1980). Laboratory methods set θ_{fc} as a point on the SWC corresponding to a particular value of pressure head, mostly inside the range -10 kPa (e.g. Romano and Santini, 2002) and -33 kPa (Richards and Weaver, 1944), depending on soil texture. Neither the field nor laboratory methods however, could be applied universally (Hillel, 1980). Some researchers have also attempted to develop techniques for estimating field capacity using dynamic approaches, as reviewed by Twarakawi *et al*. (2009).

However it is estimated that the concept, θ_{fc} is a suitable measure to quantify the water-holding capacity of soils in catchment- or regional-scale hydrology (Orfanus, 2005) but represents no limiting constraint to plant physiology.

On the other hand, the wilting point is a more definite low-threshold SWC value, since by definition, most plant species wilt irreversibly if θ_{wp} is reached. Under conditions of permanent wilting, ecosystem resilience can be exceeded and changes towards aridisation activated. In agricultural systems, crop failure can occur if θ_{wp} is exceeded. Using any single threshold value to differentiate when soil water is relatively available is an oversimplification for a relationship that is actually continuous (Breshears *et al*., 2009). Therefore more progressive approaches relate the occurrence of water stress with actual evapotranspiration rate and the average SWC of the root zone. In other words; if there is only small potential evapotranspiration demand (e.g. 2 or 3 mm day^{-1}), a smaller SWC is needed to supply enough water to plant roots than is the case for high evapotranspiration demand (e.g. 5 or 6 mm day^{-1}). This logical assumption has been supported by several empirical observations (e.g. Denmead and Shaw, 1962; Novák, 1989). It means that the average value of the critical SWC is a function of time and cannot be simply ascribed to a particular pressure head value.

Novak and Havrila (2006) have defined the 'critical SWC of limited water availability (θ_{la}) as the average SWC of the soil layer at which the transpiration rate starts to decrease from its potential value, which is also followed by a decrease in biomass production. Although the latter part of the statement has been disputed, experiments showed that moisture contents under θ_{la} are really accompanied by symptoms of wilting (floppy convolute leaves) (Novák, 1986, 1989; Budyko and Zubenok, 1961; Denmead & Shaw, 1962; Budagovskij, 1964, 1986). In the last concept, the θ_{la} is considered to be a function of both the soil physical properties and evapotranspiration demand of actual weather conditions.

Soil physical properties can change dramatically over small distances (Orfanus *et al*., 2008) but the effect of soil texture as a factor that can modify water use efficiency has not yet been deeply studied (Katerji *et al*., 2008). On the other hand, the presence of landscape structures, like hedgerows can influence local microclimate conditions (Eitzinger *et al*., 2009) and consequently the hydrological balance of field-scale areas.

The objective of this study was to examine the effect of local textural variations of soil and the effect of microclimate variability caused by the presence of a landscape structure (hedgerow) on the field-scale distribution of potential water stress. As a measure of potential water stress occurrence at a certain location, the critical value of SWC, θ_{la} was applied and its spatial and temporal variability was analysed. The study was conducted on two research plots in south-western Slovakia and north-eastern Austria, respectively.

Materials and methods

Study area and data collection

Two agricultural fields located in the north-western part of the Pannonian Basin were selected for the research. The basin is one of the warmest and driest areas in Central Europe. In the NW part, the Vienna basin is also one of the windiest areas of Central Europe. The climate of this area is semi-arid with frequent occurrence of drought connected with significant losses on agricultural production.

MSJ-Field experimental site

At this experimental site research was conducted on a 4.5 ha (150 x 300 m) plot situated near the Moravský Svätý Ján (MSJ)village on Záhorská Lowland in south-western Slovakia. Soils of the area have formed from alluvium of the river Moravia and on the experimental plot are classified as Arenic Regosol (covering about 60% of the plot area) and Mollic Gleysol covering the remaining 40% of the plot area (ISSS-ISRIC-FAO, 1998). These soil taxons are divided by sharp and easily identifiable borderline. The Arenic Regosol has a loamy-sand texture and Mollic Gleysol is a clay loam. There is a thin area of several meters around the borderline that is texturally variable and creates some transition zones.

The plot was ploughed for decades until 2001, after which minimum tillage has been applied. There were two intensive sampling campaigns performed during years 2002 – 2003. The first sampling date was chosen to ensure bare soil surface and low E_p rate (1 mm/day) to avoid significant water losses during the sampling period. On April 10th, 2002, the soil was sampled in a regular 20 x 20 m square grid. Soil samples were taken from the A horizon 0.10–0.15 m into the stainless cylinders of 100 cm^3 volume and 5 cm height. The ground water table was at a depth of 77 cm at this time. The meteorological characteristics were measured directly at the weather station in MSJ village. The actual soil water content was estimated by the gravimetric method and the drying branches of soil water retention curves were estimated in pressure chambers (Soil Moisture Equipment, Santa Barbara, California). The saturated hydraulic conductivity was determined in the laboratory on the same volume core samples using the falling head method. . The actual and saturated SWC as well as saturated hydraulic conductivities were estimated for each of 128 soil samples, while the retention curves were measured only for 43 samples selected evenly over the research plot.

The same sampling and SWC measurements were repeated on July 2nd, 2003 to compare the SWC distributions under markedly different boundary conditions; deeper GW table (in 2.5 m) and high E_p rate (6mm/day).

Rutzendorf experimental site

The field is situated in the Marchfeld area, 10 km from Vienna and soil and microclimate research commenced here in 2004. Daily evapotranspiration amounts were measured using digital ET Gage atmometers placed in 8 m, 20 m, and 80 m distances from the hedgerow in a lee from the main wind direction (Fig. 1). The results of the measurements correlate well with potential evapotranspiration calculated using Penman-Monteith and Turc (1961) equations within the period of measurement (R^2 = 0.64 for Penman and 0.71 for Turc). The meteorological station, representing field conditions without the hedgerow impact on wind speed, was placed at a distance of 80 m from the hedgerow. To identify the hedgerow effect on water stress occurrence the soil was assumed uniform along a transect from the hedgerow to 80-m distance from the meteorological station.

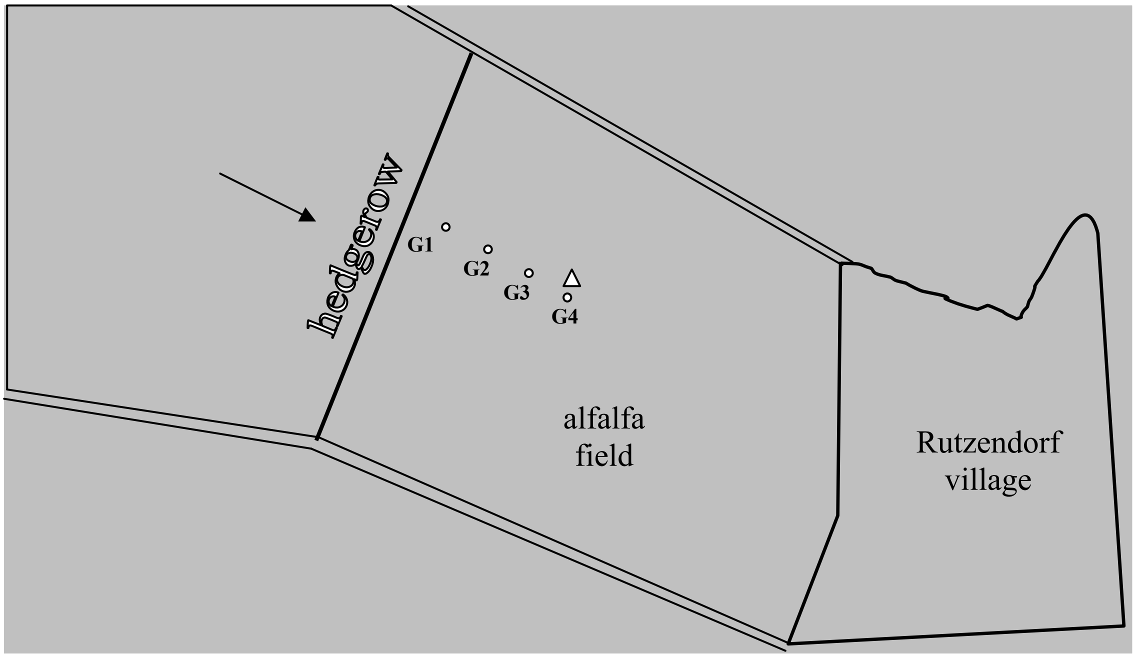

Figure 1. Field experiment near Rutzendorf. Transect measurements include ET Gage evaporimeters (G1-G4) and mobile meteorological station (triangle) to detect microclimatic impacts on different distances from a hedgerow. The arrow indicates the prevailing wind direction.

Methods

Calculation of critical SWC of limited availability, θ_{la}

For the 43 samples taken for soil water retention measurements the critical SWC of limited availability (θ_{la}) was calculated according to Novak (1989):

$$\begin{array}{lll} Et/E_p = 1 & \text{for } \theta_{la} < \theta & \\ Et/E_p = \alpha\,(\theta - \theta_{k2}) & \text{for } \theta_{k2} < \theta < \theta_{la} & (1) \\ Et/E_p = 1 & \text{for } \theta < \theta_{k2} & \end{array}$$

Taking the left side of (Eq. 1) equal to 1
it can be rewritten:

$$\theta_{la} = 1/\alpha + \theta_{k2} \qquad \text{for } \theta_{k2} < \theta < \theta_{la} \qquad (2)$$

$\theta_{k2} = 0.67 \text{ x } \theta_{wp}$ with θ_{wp} conventionally estimated from the soil water retention curve as θ(-1.5MPa). θ_{la} and α are highly variable depending mostly on evapotranspiration rate and other characteristics like the root system density and its spatial distribution. α for each sample is determined from:

$$\alpha = \alpha_m + (\alpha_1 - \alpha_m)\exp[-\delta(E_p - 1)] \qquad (3)$$

δ can be set to 0.25 for crops with dense root systems (Cowan, 1965; Sudnicyn, 1979) but α_m and α_l have to be calculated.

To calculate α_m we used (Eq. 2) substituting θ_{la} with the saturated SWC as its theoretical maximum value. α_l is the slope of equation (1) if Ep = 1 mm day^{-1} (Novák, 1989). Novák (1989) assumes ($\alpha_1 - \alpha_m$) is constant for each soil and equal to 12.3.

Geostatistical analysis of θ_{la}

The number of points with measured θ_{la} values (43 samples) is insufficient to perform direct interpolation. However, the database from the MSJ-experimental site also contains more intensely sampled variables, such as actual SWC or saturated SWC, which were estimated more intensely (128 samples) across the field. Both actual SWC and saturated SWC correlate significantly with θ_{la} (Fig. 2). Orfanus *et al.* (2008) reported the existence of SWC spatial organization across the MSJ-experimental field. Moreover, θ_{la} is a threshold value at which the mean value of actual SWC and its variability become directly proportional since the evapotranspiration becomes restricted by SWC and therefore smoothes its variability. The cross-correlated information contained in the secondary variable can therefore be reasonably added to interpolate unsampled θ_{la}. The actual SWC estimated gravimetrically on 100 cm^3 cylinders (sampled in a 20 x 20m grid) was used as the secondary variable in a cokriging interpolation (e.g. in Isaaks and Srivastava, 1989). θ_{la} data estimated from the MSJ-experimental site soil water retention curves were statistically analysed (Table 1) and then specifically interpolated for each soil textural class to ensure stationarity.

Results and Discussion

How soil texture determines the limits of water availability and the occurrence of water stress potential

Although interpolation produced somewhat higher mean values and a smoothed variance in loamy sand when compared to the original data (compare Fig. 3 and Tab. 1), the geostatistical analysis revealed 4 distinct regions inside the 4.5 ha MSJ experimental field, which apparently have different demands for water supply to saturate the soil above θ_{la} (Fig. 3). Regions *R1* and *R3* have similar water availability limits, but R2 and *R4* differ substantially from all other regions. Considering that a change of SWC by 1% volumetric equates to a 10 mm water input into the 1–m deep soil layer, the difference in average θ_{la} of 8.5 % vol. (during day with high E_p) and 6% vol. (when E_p is low) over such small area is significant. For a homogeneous soil profile, avoidance of water stress during days with high E_p means that in region *R4* 850 m^3/ha more water must be supplied into the 1-m thick soil horizon compared to region *R2*. Region R4 covers practically all the clay loam part of the experimental field, so this difference in water demand can be related to soil texture.

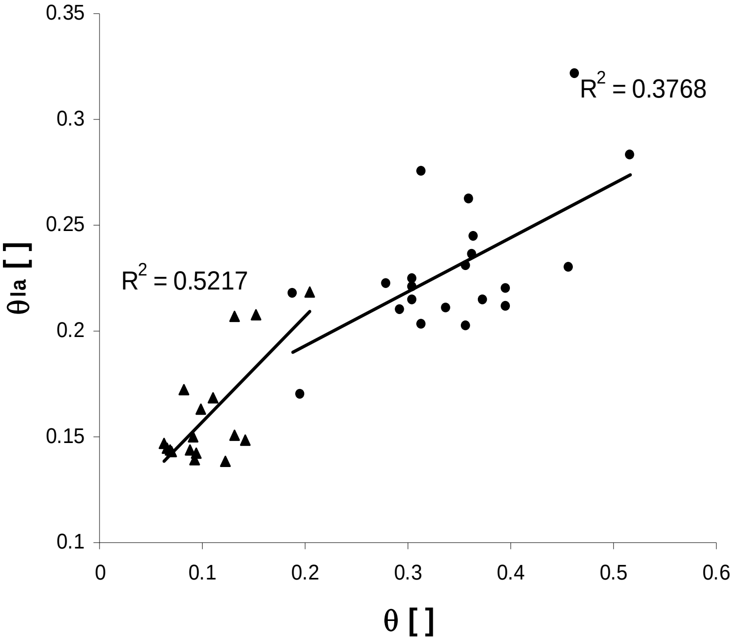

Figure 2. The correlation between critical SWC of limited availability (θ_{la}) and actual SWC estimated at April 10th, 2002 in MSJ experimental field approves cokriging as reasonable interpolation method. The triangles represent the loamy sand data while the circles relate to clay loam data.

Table 1. Descriptive statistics of permanent wilting point (θ_{WP}), field capacity (θ_{FC}) and SWC of limited availability (θ_{la}) estimated for two textural classes and two evapotranspiration rates, in MSJ-Field experimental site. All variables are in % volumetric.

	CLAY LOAM				LOAMY SAND			
	θ_{WP}	θ_{FC}	θ_{la} (E_{p-max})	θ_{la} (E_{p-min})	θ_{WP}	θ_{FC}	θ_{la} (E_{p-max})	θ_{la} (E_{p-min})
Mean	12.9	35	24.9	15.2	3.497	21.1	16.1	8.9
Standard Error	1.44	1.29	0.97	0.967	0.876	1.88	0.602	0.587
Median	10	35.43	23	13.3	1.43	19.9	14.9	9.58
Standard Deviation	6.29	6.3	4.22	4.22	3.82	8.2	2.62	2.62
Sample Variance	40	39.9	17.8	17.8	14.6	67	6.89	6.89
Kurtosis	0.568	0.924	0.568	0.568	0.769	-1.098	0.0698	0.769
Skewness	1.156	0.511	1.156	1.156	1.368	0.098	1.368	1.368
Range	23	27.4	15.4	15.4	12.4	26.3	7.97	7.97
Minimum	4	23.2	18.9	9.25	0. 1	7.8	13.9	7.33
Maximum	27	50.6	34.4	24.7	12.5	34.1	21.8	15.3
Count	19	19	19	19	19	24	24	24
Conf. Level (95.0%)	3.03	2.67	2.03	2.03	1.84	3.95	1.26	1.23

The statistics for field capacity $\theta_{fc,}$ are also given in Table 1, with the corresponding pressure heads for field capacity set to -10 kPa for loamy sand and -33 kPa for clay loam. Although θ_{la} correlates well with θ_{fc} and they sporadically overlap for high evapotranspiration rates (Fig. 4), these two characteristics (hydrolimits) are not convertible.

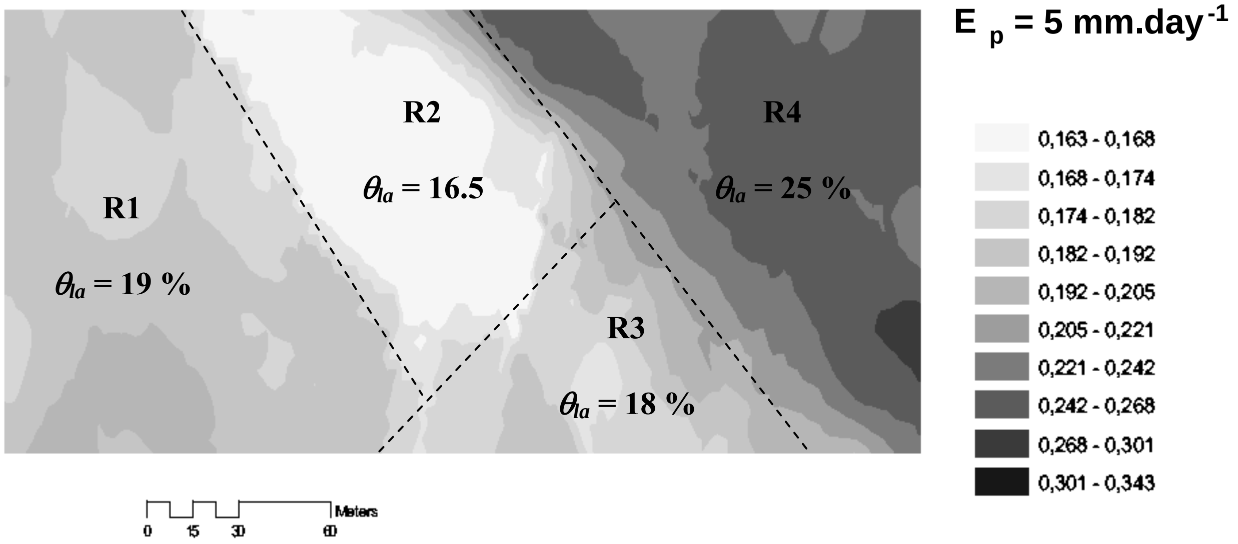

Figure 3. Field-scale spatial variability of θ_{la} [$cm^3.cm^{-3}$] related to high evaporative demand, as influenced by textural heterogeneity of soil in locality Moravsky Sv. Jan in western Slovakia.

How evapotranspiration determines the limits of soil water availability and the occurrence of water stress potential

Besides soil texture, evapotranspiration intensity further modifies the critical value of SWC for which the water availability for plant use starts to be limited (Slatyer, 1967; Hillel, 1980; Novák and Havrila). Hatfield (1985) and Amer and Hatfield (2004) showed that the slope of the canopy resistance increase with decreasing available soil water depends on solar radiation intensity. For higher radiation intensities the increase of canopy resistance with decreasing available soil water is milder. It was shown in the last section that for high $E_{p,}$ θ_{la} can reach similar values to θ_{fc} in loamy sand soil. The statistical analysis (Table 1) shows that during the vegetation season 2002 the mean θ_{la} (calculated from eq. 2 and 3) in the clay loam part of the MSJ-experimental site was 0.249 during the day with highest evapotranspiration (E_{p-max} = 5.1 mm day^{-1}) and 0.152 during the day when evapotranspiration was lowest (E_{p-min} = 0.97 mm day^{-1}). The corresponding values for loamy sand were 0.161 and 0.089, respectively. It follows from the results that the temporal changes in average θ_{la}, due to seasonal variability of evaporative demand, can reach 6 - 9% volumetric SWC. This is the same as a 60 - 90 mm of water layer in a one-meter thick soil layer, assuming a homogeneous soil profile.

Moreover, the potential evapotranspiration rate at field scale can change not only in time (i.e. during the vegetation season), but also in space (e.g. owing to different relief or landscape structures, such as the 8-m high hedgerow in the Rutzendorf experimental site). In Fig. 6 the course of accumulated evapotranspiration measured by the ET Gage evaporimeters during a period of 10 consecutive days with mostly clear summer weather conditions, are compared with the Penman-Monteith and Turc (1961) equation. As would be expected, the evaporimeters at different distances from the hedgerow show the impact of reduced wind speed in the lee. Closer to the hedgerow the measured evaporation was lower due to lower wind speed. The evaporimeter at 20 m distance from the hedgerow measured significantly lower evaporation rates than at 80 m distance (Fig. 4-5). However, the ET Gage measurement at 80 m distance from the hedgerow did not reach the calculated evapotranspiration rates for an alfalfa canopy at 2 m height, probably because the ET Gage evaporimeters measured evaporation close to canopy height where reduced wind speed and higher air humidity was observed (Eitzinger *et al*., 2010). The hedgerow-induced variability of evapotranspiration manifests itself further in the calculated values of θ_{la} (Eq. 1-2). During days with low E_p rates the effect was small ($\Delta\theta_{la}$ was only about 0.5% vol.), but during days with high evaporative demand of the atmosphere it can reach up to 19 % vol. over the distance of 80 m from the hedgerow. This means that during days with high E_p rates the field-scale variability of θ_{la} can exceed its seasonal variability. Even if we assumed homogeneous soil along the transect, the difference in θ_{la} caused by the shadowing effect of the hedgerow can represent a water layer that was hundreds of millimeters over a one–meter thick soil layer that covers the distance of 80 m to the hedgerow. This finding is supported by Vivoni *et al*. (2008), who also found that the impact of vegetation on soil moisture can induce much greater spatial than temporal differences within a research plot.

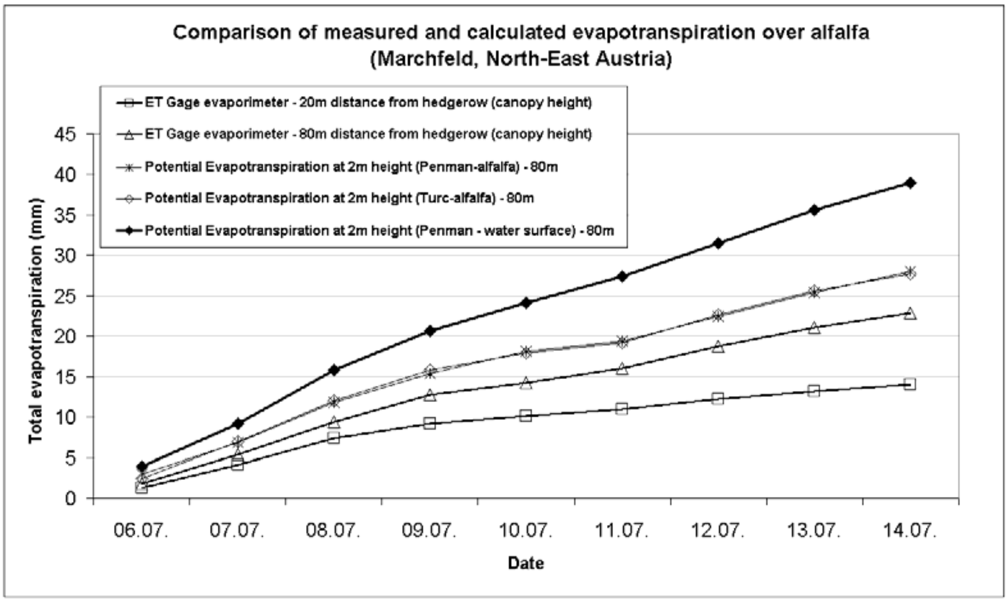

Figure 4. Measured and calculated cumulative evapotranspiration during 9 consecutive days at different distances to a hedgerow in Rutzendorf experimental site.

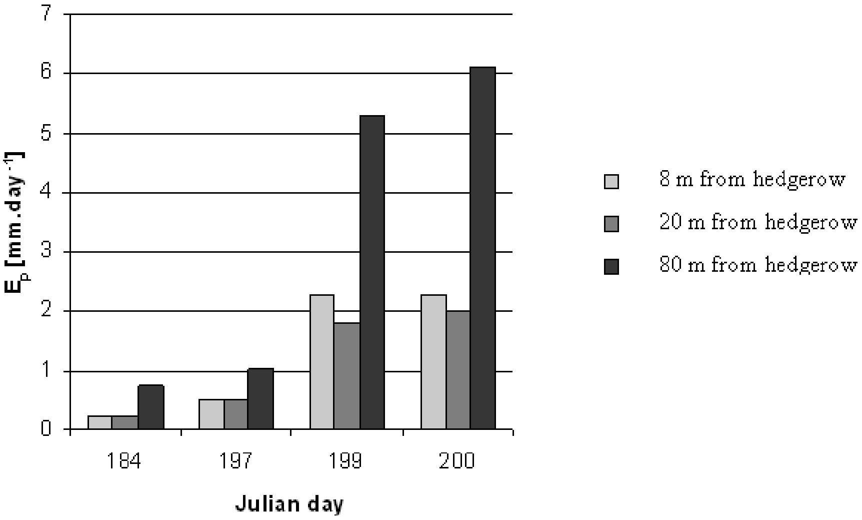

Fig. 7 Measured evapotranspiration rates at different distances to a hedgerow in Rutzendorf experimental site during days with highest and lowest evaporative demand of atmosphere (E_p).

Conclusions

Two regions with contrasting soil texture and significantly different water demands to eliminate water stress were distinguished in the 4.5 ha MSJ experimental field. The differences in average θ_{la} between clay–loam and loamy sand soil can reach 8.5% vol. (850 m^3 ha^{-1} of water). This is the extra amount of water, which must be supplied to avoid water stress in the finer textured soil. We conclude that texturally induced spatial variability of θ_{la} has an impact at field scale that can be as greater as the seasonal range of θ_{la} (6–9% vol.) in texturally homogeneous soil.

The effect of the biological factor (hedgerow) on spatial variability of θ_{la} can be even greater than the effect of soil texture. During days with low E_p rates this effect is negligible ($\Delta\theta_{la}$ only about 0.5% vol. over 80–m distance from hedgerow) but during days with high evaporative demand of the atmosphere the spatial variability can increase almost 40 times, 2–3 times exceeding the seasonal variability. Hedgerow can safe almost 2000 m^3 ha^{-1} of water mostly by its shadowing effect against wind.

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Abstrakt

Obsah vody v pôde môže byť chápaný ako integrálna súčasť obehu vody v prírode a to v celej škále časových a priestorových mierok. Koncept poľnej vodnej kapacity je nevhodný pre stanovenie limitov optimálnych vlhkostných podmienok pre rast rastlín a preto v tejto práci bol použitý koncept kritického obsahu vody v pôde zodpovedajúceho zníženej dostupnosti pôdnej vody pre rastliny (θ_{la}). Takýto obsah vody v pôde je fyzikálne a fyziologicky jasne definovaný, ako vlhkosť pôdy, pri ktorej process evapotranspirácie začína byť limitovaný obsahom vody v pôde a relatívna evapotranspirácia klesá pod hodnotu 1. θ_{la} nie je stabilnou vlastnosťou pôdy, ako sa pôvodne uvažovalo, ale závisí na potenciálnej hodnote evapotranspirácie E_p v danom čase na danom mieste. To znamená, že pri vyššej hodnote potenciálnej evapotranspirácie je potrebný vyšší obsah vody v pôde, aby rastliny stačili napĺňať atmosferický deficit vodných pár. Aby boli zachované optimálne podmienky pre vývoj rastlín a zabezpečená maximálna produkcia biomasy, inými slovami, aby bolo zabránené výskytu vodného stresu, je treba udržovať obsah vody v pôde v ideálnom rozmedzí nad hodnotou θ_{la} prinajmenšom v kritických ontogenetických fázach vývoja rastlín.

Vplyvy dvoch faktorov, pôdnej textúry a 8-m vysokého vetrolamu (pásu drevín) na fluktuácie θ_{la} v mierke poľa boli študované na západnom Slovensku pri obci Moravský Sv. Ján (MSJ) a v severovýchodnom Rakúsku pri obci Rutzendorf. Na poli pri MSJ hodnoty θ_{la} reflektovali textúrnu heterogenitu pôdy. Rozsah hodnôt vo vnútri populácie ílovitohlinitej molickej čiernice $\Delta\theta_{la}$ bol 0.15 $m^3. m^{-3}$, zatiaľčo v hlinitopiesočnatej kultizemnej regozemi to bolo iba 0.08 $m^3.m^{-3}$. Rozdiel v priemerných hodnotách θ_{la} medzi týmito dvoma pôdnymi druhmi bol 0.06 – 0.09 $m^3.m^{-3}$ v závislosti na potenciálnej evapotranspirácii. Maximálne $\Delta\theta_{la}$ spôsobené textúrnymi zmenami na 4.5 ha poli bolo 0.18 $m^3.m^{-3}$. Na porovnanie, sezónna variabilita (rozsah hodnôt) $\Delta\theta_{la}$ v roku 2002 dosahovala 0.06 – 0.09 m^3 m^{-3}, v závislosti na pôdnom druhu.

Vetrolam v poli pri Rutzendorfe mal počas dní s nízkou potenciálnou evapotranspiráciou len malý efekt na priestorovú variabilitu θ_{la}. $\Delta\theta_{la}$ bolo nižšie ako 0.01 $m^3.m^{-3}$ ak potenciálna evapotranspirácia bola nižšia ako 1 mm/day. Avšak počas dní s vysokou potenciálnou evapotranspiráciou (6 mm day^{-1}) $\Delta\theta_{la}$ dosiahlo až 0.19 m^3 m^{-3} počas leta 2004. Výsledky svedčia o tom, že aj malé úpravy v poľnohospodárskej krajine môžu mať veľmi významný efekt pri plnení jej vodohospodárskej a produkčnej funkcie. Pri aplikovaní precízneho závlahového poľnohospodárstva, samozrejme tam kde je to možné, je možné ušetriť stovky až tisícky metrov kubických na 1 hektár pôdy.

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