Method to estimate the critical soil water content of limited availability for plants

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Abstract: This contribution contains a proposal to estimate the critical soil water content of limited availability for plants, below which transpiration starts to decrease due to limited water availability for roots, which is frequently noted as "the point of limited soil water availability". The method is based on the fact, that soil water content at which transpiration rate is starting to decrease is followed by the biomass production decrease. The method is using the relationship between the relative transpiration and the average soil water content of the soil root zone, and the linear relation between biomass production and transpiration, published earlier.

Key words: soil water content, soil water availability for plants, critical soil water content of limited availability

Introduction

Soil water availability concept emerged under conditions of limited water resources needed for plant irrigation, when it was necessary to save as much water as possible. The oldest known civilisations were located in the arid regions, with limited precipitation during the vegetation period. Therefore, to secure agricultural production, irrigation has to be applied. Quantitative approach to this concept was introduced in 20$^{\text{th}}$ century, when limited water resources required rational approach to their exploitation. First known conception (Veihmeyer & Hendrickson, 1927) declared equal soil water availability in the wide range of soil water content between the "permanent wilting point" and the "field capacity". Soil water content corresponding to the "field capacity" is not clearly quantitatively declared. One of the definitions used is (Veihmeyer & Hendrickson, 1949; ICID, 1996): "Field capacity – the amount of water held in the soil after the excess of gravitational water has drained away and after the rate of downward movement of water has materially decreased."

The term "permanent wilting point" is defined as the "water content of the soil below which a plant cannot effectively obtain water from the soil; water content at –1.5 MPa water tension; available soil water is nil" (ICID, 1996). This definition is based on the term "wilting coefficient" of Briggs and Shantz and was published by Veihmeyer & Hendrickson (1927). The above definition is based on results of numerous pot experiments. Plants were grown in pots under condition of ideal availability of water and nutrients; at some growing stage plants were ceased to be irrigated. Numerous experiments confirmed the reproducibility of this procedure for different plants (Kutílek & Nielsen, 1994). Another procedures of "wilting point" estimation can lead to quite different soil water potential. Adaptation of plants to continuously decreasing soil water content (SWC) in the field led up to the values –3.0 MPa, water tension without symptoms of wilting (Jordan & Ritchie, 1971).

The range of plant available water is between the field capacity (FC) and the permanent wilting point (PWP). Veihmeyer & Hendrickson (1927) claimed equal availability of soil water to plants in this range, but Richards & Waldleigh (1952) proposed the concept of decreasing availability as the soil water content decreases in this range. A contemporary approach is represented by the researchers who suggested the existence of a "critical soil water content" below which a significant decrease of water extraction by plant as well as the decrease of yield can be observed (Bielorai, 1973).

From results of research it follows, that the plant starts to decrease the transpiration rate before the water content or the soil water potential corresponding to the permanent wilting point is reached. This value was assigned as the "point of limited availability of soil water for plants" or simple point of limited availability. Exact definition does not exist, but there are some approximative characteristics of this term because of its great importance for practical purposes, mainly for irrigation scheduling. Irrigation should be applied, when this limit is reached. Two of definitions are the following:

1. Point of limited availability of soil water for plants defines such soil water content, when soil water transport rate decreases with unfavourable influence of it on the plant growth. It corresponds to the soil water potential pF = 3.0–3.3. From the above mentioned it follows, that the "point of limited availability" is treated as a characteristic of the soil only.

2. In principle, the root extraction rate of soil water is changing according to the soil water potential gradient and the hydraulic conductivity of the soil, adjacent to roots. From this point of view, "availability" of soil water depends on the rate of root extraction which is necessary to cover the plant transpiration needs. Transpiration rate is determined also by meteorological characteristics of the adjacent layer of atmosphere. Water can be "available" at low transpiration rate and "unavailable" at relatively high transpiration rate, at the same soil water content (soil water potential).

To overcome the ambiguity in definition, widely accepted and published empirical information can be used, expressing biomass production (yield) as proportional to the canopy transpiration in general (Hsiao, 1993) and to the transpiration total during the vegetation period in particular (Hanks & Hill, 1980; Vidovič & Novák, 1987; Merta et al., 2006). This empirical relationship is valid for given canopy type, and a particular site (soil) with defined agrotechnology. Therefore, transpiration total during the vegetation period is an important factor of biomass production.

Aim of this study is to propose the method for the critical soil water content estimation, at which biomass production is starting to decrease below its potential value; to introduce the rational definition of the term "point of limited availability for plants".

Material and methods

Three types of soil were used for measurement and calculation – loess soil (Trnava site), loamy soil (Most pri Bratislave) and sandy soil (Láb). All sites are located in the south-western Slovakia lowland (48°–49°N, 17°–18°E, 130–145 m a.s.l.). Saturated hydraulic conductivities were measured in laboratory using falling head permeameter and average values of them in the soil profile were used. The field capacity (FC) was estimated by measurement in the field, the SWC corresponding to the wilting point was estimated by the use of the retention curve as corresponding to the soil water potential –1.5 MPa. Relationship between soil water potential and SWC were evaluated from measurements using the pressure plate apparatus, and were approximated by the van Genuchten's equation (van Genuchten, 1980), assuming $n = 1 - 1/n$.

Empirically estimated linear relationship between seasonal transpiration totals and biomass production is widely accepted as an approximation and was estimated for numerous agricultural canopies. Review of them was published by Hanks & Hill (1980). It can be expressed in the form

$$Y = k_t E_t - y_0 \quad (1)$$

Table 1. Characteristics of the three types of soils used.

Parameter	Site		
	Trnava	Most	Láb
θ_v [cm^3 cm^{-3}]	0.14	0.18	0.04
θ_{fc} [cm^3 cm^{-3}]	0.37	0.35	0.30
θ_s [cm^3 cm^{-3}]	0.45	0.40	0.37
θ_{k2} [cm^3 cm^{-3}]	0.09	0.13	0.027
K_s [m s^{-1}]	1.2×10^{-7}	5.6×10^{-7}	2.2×10^{-6}
α [cm^{-1}]	0.0336	0.0577	0.0327
n [–]	1.158	1.299	2.147
θ_r [cm^3 cm^{-3}]	0.07	0.09	0.02

θ_v – volumetric soil water content corresponding to the wilting point [cm^3 cm^{-3}], θ_{fc} – soil water content corresponding to the "field capacity" [cm^3 cm^{-3}], θ_s – water content of the saturated soil [cm^3 cm^{-3}], θ_{k2} – critical soil water content, according to the Eq. (6) [cm^3 cm^{-3}] K_s – hydraulic conductivity of the soil saturated with water (saturated hydraulic conductivity) [m s^{-1}], α [cm^{-1}] and n [–] – van Genuchten's equation coefficients, θ_r – residual soil water content [cm^3 cm^{-3}].

where Y is the biomass density (per unit area, i.e. hectare) ML^{-2}, coefficient $k_t = \Delta Y/\Delta E_t$ [ML^{-3}] is the slope of the linear relationship $Y = f(E_t)$ and is frequently noted as a coefficient of transpiration utilisation efficiency (Hillel & Guron, 1973), [ML^{-2}L^{-1}], E_t is transpiration total of the given canopy during the vegetation period, expressed in height of water layer [L^{3}L^{-2}], y_0 is the intercept.

The transpiration is frequently used as an indicator of the soil water resources. Relative transpiration as an index of the soil water resources state was proposed by Budagovskij & Grigorieva (1991) to be the ratio of transpiration E_t and potential transpiration E_{tp}:

$$\eta_p = E_t / E_{tp} \quad (2)$$

The ratio is characterizing the relative availability of soil water in the range (0; 1).

The next step should be to express transpiration ratio as a function of the soil root zone water content (soil water potential). It seems to be obvious – from a pragmatic point of view – that volumetric soil water content is easy to be estimated and is suitable for the routine use. Relationship between evapotranspiration (transpiration) and soil water content is frequently used to calculate the evapotranspiration (transpiration) from their potential values. Relationships were estimated by measurements (Denmead & Shaw, 1962; Feddes et al., 1978; Novák, 1990), or by mathematical modelling (Novák et al., 2005). The problem is to estimate the "critical" soil water content at which transpiration ratio is starting to decrease, followed by the biomass production decrease too.

This, in principle continuous relationship can be formally divided into three intervals of soil water content (Fig. 1); the first is between saturated soil and the so called "critical" SWC (θ_s, θ_{k1}); here the transpiration is not – limited by SWC of the soil root zone (usually, one meter soil layer is used). The second SWC interval is between (θ_{k1}, θ_{k2}), where transpiration rate is decreasing nearly to zero at SWC θ_{k2}. Transpiration in the SWC (third) interval below θ_{k2} is supposed to be zero in this approximation. There is one limitation – not important for our aim- there is a SWC interval (θ_a, θ_s), the so called "anaerobic range", where soil aeration is limiting roots functioning due to lack of the oxygen (Feddes & Raats, 2004).

The relation between the transpiration and the potential transpiration at SWC θ in the range (θ_{k1}, θ_{k2}) can be expressed by the equation

$$E_t = E_{tp} a(\theta - \theta_{k2}) \tag{3}$$

where a is the slope of the above-mentioned linear relationship, θ is volumetric SWC [$L^3\ L^{-3}$]. Eq. (4) is expressing the conditions needed to estimate $\theta_{k1} = \theta_{la}$ where actual and potential transpiration are equal (θ_{la} is the critical SWC, where transpiration rate is starting to decrease, L^3L^{-3}):

$$E_t/E_{tp} = 1 \tag{4}$$

Solution of Equations (3) and (4) for θ is expressed by Eq. (5). The critical SWC θ_{k1}, where transpiration rate is starting to decrease, allows interpretation of the term "water content of limited availability" of the soil water for plants. It is SWC corresponding to this critical SWC when transpiration is starting to decrease below potential transpiration rate. In this way, the term water content of limited availability of soil water for plants is physically and physiologically defined. It can be expressed by the empirical equations published earlier (Novák, 1990):

$$\theta_{la} = \theta_{k1} = \frac{1}{a} + \theta_{k2} \tag{5}$$

$$\theta_{k2} = 0.67 \cdot \theta_v \tag{6}$$

$$a = -2.27\ E_{tp} + 17.5 \tag{7}$$

where θ_{k1}, θ_{k2} are the so called "critical" SWCs indicating the beginning and the end of the transpiration decrease rate range, θ_v is SWC of the permanent wilting point (Kutílek & Nielsen, 1994). Coefficient a depends on the potential evapotranspiration (transpiration) rate E_{tp}, and was estimated for three agricultural canopies; it is believed to be valid for wide variety of them. It follows, that SWC corresponding to the critical soil water content of limited availability for plants depends on the soil properties, but it is also strongly influenced by the transpiration rate.

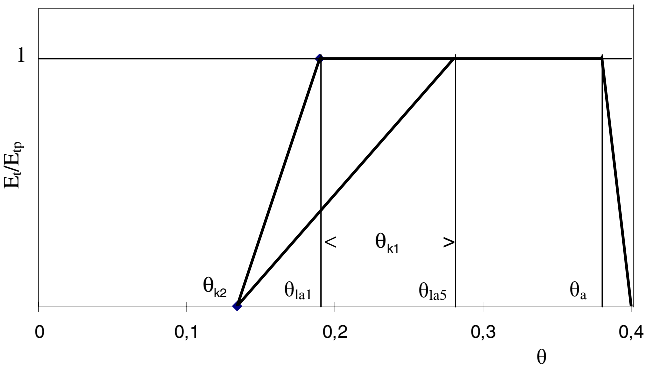

Fig. 1. Relative transpiration and the soil water content of the upper one meter soil layer $E_t/E_{tp} = f(\theta)$, where $\theta_{la5} - \theta_{la1}$ is the range of the "critical soil water contents of limited availability" for plants, θ_{k1}, for the range of daily transpiration totals $1 \leq E_t \leq 5$ mm/day at the site Most pri Bratislave.

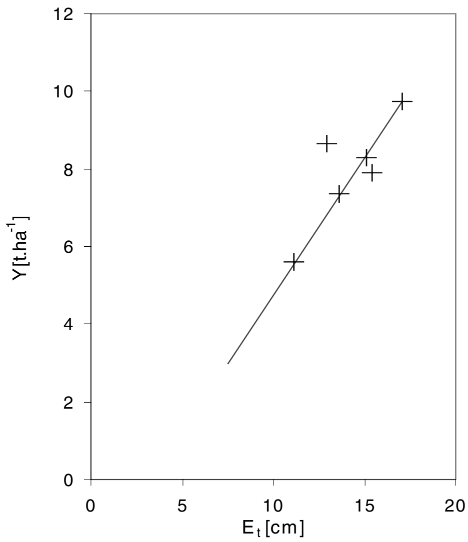

Fig. 2. Mass of maize dry grain yield (Y) and transpiration total during the vegetation period (E_t) for site Most pri Bratislave, Slovakia.

Results and discussion

The proposed and described method estimation of the "critical soil water content of limited water availability for plants" (θ_{la}) is illustrated by its application to the three types of soils with different texture. A linear relationship between mass of the maize dry grain (Y) and transpiration total during the vegetation period (E_t) for the site Most pri Bratislave is shown in Fig. 2. Pairs of data (Y_i; E_{ti}) were assessed by estimation of the maize grain weight, transpiration was calculated by the simulation model GLOBAL (Majerčák & Novák, 1992) using the modified Penman-Monteith method (Monteith, 1965; Tesař et al., 2006).

Relative transpiration and the soil water content of the upper one meter soil layer $E_t/E_{tp} = f(\theta)$, for the site Most pri Bratislave is in Fig. 1. The range of the "critical soil water contents of limited availability" to plants, for the range of daily transpiration totals $1 \leq E_t \leq 5$ mm/day, covers relatively broad range of soil water contents, in this particular case the $\Delta\theta_{la} = \theta_{la5} - \theta_{la1}$ represents 0.47 of the range of the soil water available for plants – $\Delta\theta_{la}/(\theta_a - \theta_{la1})$. The critical soil water content θ_{k2}, was calculated according to the Eq. (7), the SWC corresponding to an "anaerobic point" θ_a was estimated as the difference between θ_s and θ corresponding to the zero soil water pressure of retention curve.

Figure 3 presents SWC corresponding to the critical soil water content of limited availability to plants for the three soils as they depend on the transpiration rate $\theta_{la} = f(E_t)$. From the analysis it follows a strong dependence of critical SWC of the limited availability for plants θ_{la} on the transpiration rate and increase of

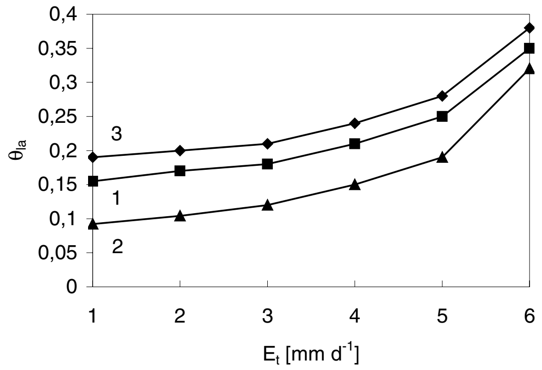

Fig. 3. Critical soil water content of limited availability to maize θ_{la}, corresponding to the transpiration rate E_t of the three soils, parameters of which are in Table 1. Trnava (1), Láb (2), Most pri Bratislave (3).

its value with it. It is a fact, that decrease of daily transpiration rate during days with maximum energy input (hot days) limited by lack of the soil water is limiting biomass production much more significantly than during cold days. The θ_{la} values corresponding to $E_t = 6$ mm/day can be observed during midday of hot days, when even canopies grown on moist soil are not supplied by water adequately.

Proposed estimation method for the critical SWC of limited availability for plants θ_{la} is physically and physiologically clearly interpreted and can be easily calculated using equations (5–7).

For practical purposes it is possible to use the critical SWC (θ_{la}) corresponding to the daily average transpiration rates.

Conclusions

The "critical soil water content of limited water availability" (θ_{la}) is characterising an average soil water content of the upper, (one meter) soil layer at which intensity of transpiration starts to decrease followed by the biomass production decrease. The core of the method is based on the fact, that the ratio of transpiration and assimilation is fairly constant for particular plant and on empirical linear relationship between the relative transpiration rate and average soil water content of the root zone.

The "critical soil water content of limited water availability" (θ_{la}) can be estimated using equations (5–7) as corresponding to the "critical soil water content" θ_{k1} containing known or easy measurable soil characteristics, as permanent wilting point (θ_v) and average daily transpiration ratio E_t/E_{tp}.

Critical soil water content of limited soil water availability (θ_{la}) is thus physiologically clearly defined.

Characteristic "critical soil water content of limited water availability" is not determined by the soil properties only; an important factor is the transpiration rate too. It is recommended for practical purposes to use θ_{la} values corresponding to the average daily transpiration rates.

Critical soil water content of limited water availability (θ_{la}) can be used as an indicator for irrigation scheduling, to secure yield close to maximum.

Proposed method of the "critical soil water content of limited water availability" estimation is illustrated by the data acquired by the measurements in soil – plant – atmosphere continuum with maize canopy.

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