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Calculation of available water supply in crop root zone and the water balance of crops

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Abstract: Determination of the water supply available in soils for crops is important for both the calculation of water balance and the prediction of water stress. An approach to calculations of available water content in layers of the root zone, depletion of water during growth, and water balance, with limited access to data on farms, is presented. Soil water retention was calculated with simple pedotransfer functions from the texture of soil layers, root depth, and depletion function were derived from observed data; and the potential evapotranspiration was calculated from the temperature. A comparison of the calculated and experimental soil water contents showed a reasonable fit.

Key words: water shortage, root system, depletion, soil water capacity, texture, evapotranspiration

1. Introduction

Drought poses a serious problem for farmers in a large part of the world. Under the transitional (maritime/continental) climatic conditions of the Czech Republic, fluctuations in precipitation often causes water shortages at critical stages of crop growth. During yield formation of annual crops winter supply of water is often exhausted, and precipitation is not sufficient to cover high transpiration demand. Farmers have asked for innovations from agricultural research to apply effective measures for reducing the negative impacts of drought. It is evident that the approach for a solution must be complex. An optimal root system and the utilization of the water reserve from the root zone are recognized as important factors in the effort (*Himmelbauer et al., 2008; Haberle et al., 2014; Kirkegaard et al., 2007; Kong et al., 2013; Svoboda et al., 2014*). Further, deep roots absorb nitrate and other nutrients leached from top soil, an important function in the effort for reduction of water pollution (e.g. *Kuhlmann et al., 1989*).

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Calculation of the available soil water supply for a crop is a starting point for a reliable water balance and for predictions of the onset of water stress occurrence. This supports adoption of the relevant agronomic measures on both the short- and long-term scale. However, farmers have no tool to estimate the amount of available water in their fields nor its depletion during the growth period.

For farmers, water balance considering a specific crop, actual status of canopy, a local field, meteorological conditions, and the actual state of the crop may be more helpful; while various drought monitoring systems on the state-wide scale inevitably come from more general data. Numerous agro-climatological and crop models are used for water balance; however, they mostly demand input data, which is hardly available on farms without special equipment, knowledge, or services.

On farms, a simplified approach for estimations of the available water supply for a specific crop and field must be used as a compromise between demands for detailed hydro-pedological, physiological, and vegetative input data and the capabilities and facilities of farmers. However, a farmer must be involved, and is expected to exert some effort to get, at minimum, the basic data for the calculation. Today's introduction of the common simple on-line automatic meteorological stations on farms establishes a good base for a reliable calculation of potential evapotranspiration and water balance. We developed a method of water balance calculation performed within an on-line programme (`http://svt.pi.gin.cz/vuzt/koreny.php`); a simple expert system (*Haberle et al., 2015*). The system also supplies the user with input data to be used in the case of their lack, or when a user intends to test the impact of environmental and agronomical conditions on the water supply and the occurrence of water stress.

The aim of the study was i) to review the procedure of calculation of crop water balance with limited input data, and ii) to compare the calculated and observed available water contents in the root zone.

2. Materials and methods

Calculation of available water content and balance consists of the following steps:

A. Calculation of available water capacity of the soil layers;
B. Estimation of crop root depth and water depletion from the root zone;
C. Calculation of potential evapotranspiration from the air temperature;
D. Estimation of the crop coefficient from field observation of the crop canopy;
E. Calculation of the water balance in the root zone.

This method of calculation was tested with data from farms and experimental fields sampled in years 2012–2014.

A. Calculation of available water capacity of soil layers, and determination of soil water content at the start of spring growth

Soil texture, including stone (>2 mm) content, was determined in twelve fields of nine sites with different soil-climate conditions (Fig. 1, Table 1). The soil was sampled to depth of 130 cm at 10 cm (top layer) and 20 cm increments. The textures of profile layers are shown on the background of

Fig. 1. Location of sites.

Table 1. Experimental sites.

Experimental site	Meteorological station (distance to exp. site)	Altitude	Year average temp.	Year rainfall	Year potential ET
		m a.s.l.	°C	mm	mm
Ivanovice na Hané	Ivanovice na Hané (0.6 km)	225	8.9	542	723.0
Ruzyně I	Praha-Ruzyně (0.1 km)	340	8.3	520	706.7
Ruzyně II	Praha-Ruzyně (2.3 km)	364	8.4	510	706.8
Lukavec u Pacova	Košetice, Křešín (6.9 km)	612	6.9	633	566.2
Valečov I	Havlíčkův Brod (7.0 km)	532	7.4	684	520.5
Valečov II	Havlíčkův Brod (7.9 km)				
Čáslav	Čáslav (0.7 km)	263	8.9	630	566.5
Chrášťany u Rakovníka I	Heřmanov (6.8 km)	356	7.4	508	592.3
Chrášťany u Rakovníka II	Heřmanov (7.4 km)				
Ústí n. Orlicí - Dl. Třebová	Ústí n. Orlicí (4.1 km)	410	7.2	705	510.6
Mostek, Sudslava	Ústí nad Orlicí (12.4 km)	385			
Horní Dobrouč-Lanšperk	Ústí nad Orlicí (3.9 km)	420			

a soil triangle (Fig. 2). Soil volume weight was determined by the standard method; samples were excavated with a special soil sampler from deep subsoil layers.

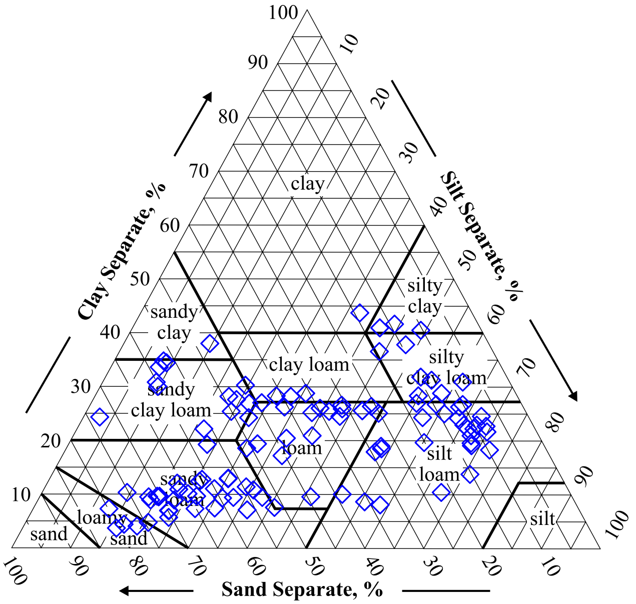

Fig. 2. Texture of soil layers of monitored fields.

The available water capacity (AWC) of soil layers was calculated as AWC = FC – WP, where FC is the field capacity and WP is the wilting point (in vol. %). The FC and WP were calculated as an average of the outputs of several pedotransfer functions, which demand only the proportion of clay (< 0.01 mm or < 0.001 mm) and silt or sand (see *Haberle et al., 2014; Vlček et al., 2014*).

We recommend starting the calculation at emergence or spring regeneration (winter crops), with water content at 90% of AWC but after dry winters, especially on soil with a high AWC, the amount must be reduced. We suggest to determine directly soil moisture which can be done without special equipment. Here, the observed early spring soil moisture was used as the input value for the calculation.

B. Crop root depth and depletion of water from the root zone

The same method of root distribution examination was used in the experiment and in previous studies. The roots were sampled after flowering, during seed filling and tuber growth (the stage of the expected maximum root depth), with a soil corer, at 10 cm segments to a depth of 10–20 cm under the layer where the last roots were visible. The roots were separated with water on sieves, cleaned, and the root length was calculated according to *Tennant (1975)*. The ranges of root depth of the selected crops (Table 2), based on the experimental data from the experiment as well as long-term investigations of the authors are presented (e.g., *Haberle and Svoboda, 2014;*

Table 2. The range of crop root depths.

	Conditions for root growth		
Crop	unfavourable	common	favourable
Winter cereals	60–80	80–100	100–140
Winter oilseed rape	60–80	80–110	110–160
Spring barley	40–50	50–80	80–110
Spring wheat, oats	50–70	70–100	100–120
Poppy	40–60	60–80	80–110
Pea	30–40	40–60	60–80
Potatoes	30–40	40–50	50–80
Maize	60–70	70–100	100–150
Sugar beet	80–90	90–130	130–180
Sunflower	70–100	100–130	130–200

Svoboda and Haberle 2014a,b). Here, the average root depths for sites were used for the calculations, with the intent to reproduce the conditions of limited input data access on farms.

For the calculation of maximum (potential) water depletion from layers of the crop root zone, an empirical approach was used, based on literature data (e.g., *Kong et al., 2013*), previous studies (*Haberle and Svoboda, 2012; Svoboda and Haberle, 2014a*), and field observations of apparent depletion of soil water. Before long, depletion of water is shifted to deeper sparsely rooted subsoil layers when the upper zones are exhausted. The process is proceeding along with root growth to increased depth and gradual colonization of the layers with the available water reserves. Hence, in the framework of the simplified approach, there is no need to calculate the progressive increase of the root zone due to the growth of roots to greater depth. The whole root zone is represented by one layer (pool). Only water to maximum root depth is assumed to be potentially available for the plants. As root growth to greater depth ceases after flowering and during yield formation, the water is exhausted under lack of precipitation, and water stress aggravates plant growth.

From our data and the literature we generalize that up to 90% of water available from the arable layer with a high root density can be utilized by crops. The level of the wilting point is hardly reached under field conditions. In the subsoil layers, possible water depletion also reaches 90% of the available supply under conditions of sufficient root density ($> 1 \text{ cm} \cdot \text{cm}^{-3}$), and it decreases from crop specific depth to the bottom of the root zone. Data on root density distribution are not attainable on farms; however, for annual crops, an exponential like decrease of root density is typical (e.g., *Haberle and Svoboda, 2014; Zuo et al., 2013; Zhang et al., 2012*). We observed the type of distribution in all crops and sites (Fig. 3). Our results suggest the zone of low root density ($< 0.5-1.0 \text{ cm}\cdot\text{cm}^{-3}$) is longest in those crops with the deepest root systems. Thus, for the calculation, the maximum possible water depletion decreases within the deepest part (approximately, the last tenth to the last third of root depth, depending on crop) linearly, from 90% to 10% of the water content at AWC.

C. Calculation of potential evapotranspiration (ET)

ET was calculated from daily average temperatures according to the method

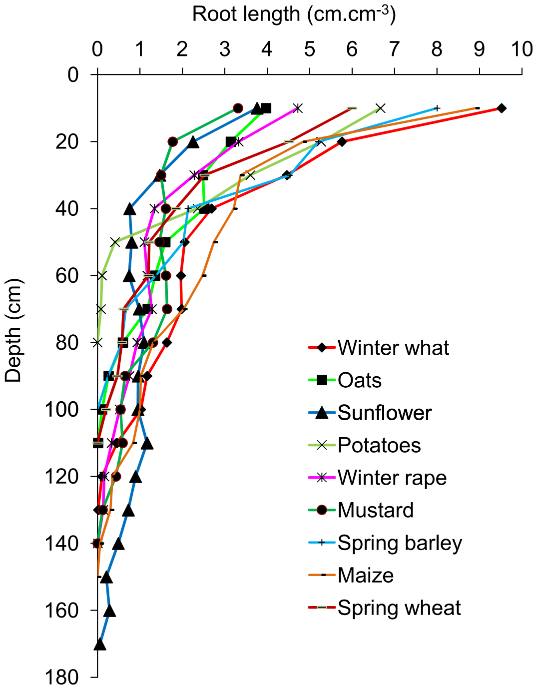

Fig. 3. The example of root distribution of selected crops growing on deep fertile soils.

of Blaney-Criddle, modified by *Schrödter (1985)*. The analysis showed a satisfactory agreement with ET calculated according to *Allen et al. (1998)*, in comparison with several other calculation methods (*Kohut M. – not published)*.

D. Estimation of the crop coefficient

Instead of constant terms (date, stage of development, or sum of effective temperatures), a subjective approach was selected. The key points, the cover of 80% percent of the soil with leaves and the start of green leaf area decline are estimated by a user. The crop coefficient, which determines the rate between potential and actual evapotranspiration increases from 0.3 (30% of ET) at bare soil (and at the start of emergence) to values between 0.8–1.1 after filling the canopy; and it decreases again towards 30% at maturity. The approach enables a user to take into consideration different development of the crop stand and canopy, possible delay or damage caused by frost, or uneven emergence. Here, for calculation, the key points were specified according to observation. The value of the crop coefficient is reduced when the amount of water in the root zone drops under a crop specific level (50%–30% of the content at AWC); at 10% of available water the depletion ceases. When precipitation increases the soil moisture of the upper layer, the crop coefficient temporarily increases to a higher level (without considering the entire root zone moisture) until the water is again exhausted.

E. Calculation of water balance in the root zone

Water balance in the root zone was calculated according to the presented approach in daily steps. Precipitation should be corrected (reduced) according to on-site observation, in cases when strong rains or thawing snow on frozen soil cause surface water out-flow. Percolation of water under the root zone during growth is accounted for by neglecting the increase of water content over FC.

The calculated and observed available water contents in the root zone were compared (Fig. 4). The content of water in the root zone during seed filling or about maturity was determined; in several cases the soil moisture was also assessed during growth (Fig. 5).

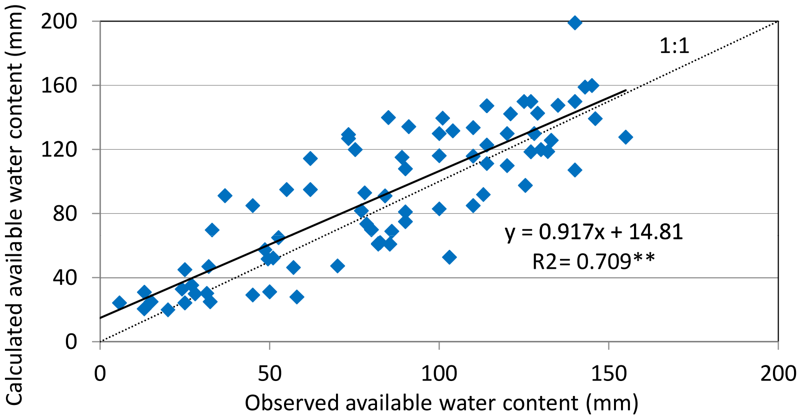

Fig. 4. The comparison of calculated and observed content of available water in root zone of crops.

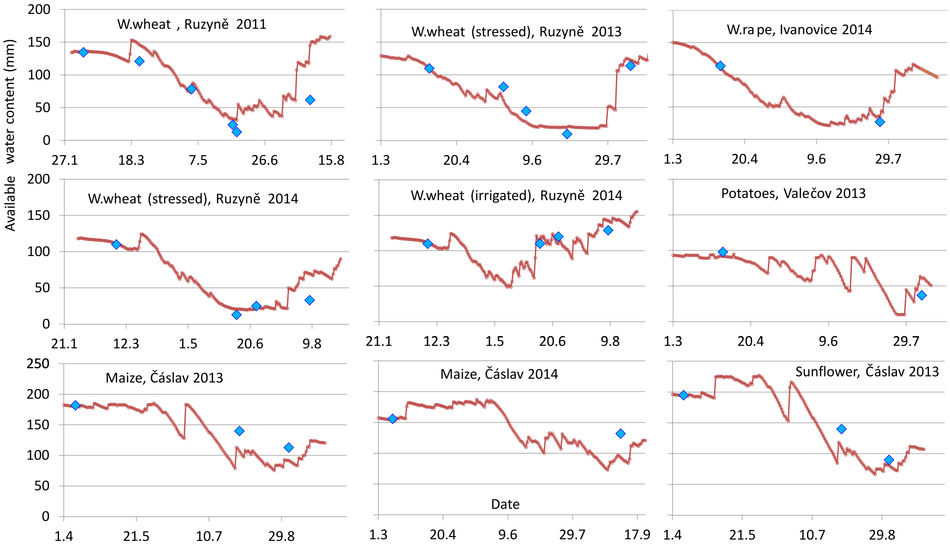

Fig. 5. The example of changes of calculated content of available water during growth. Points are observed water contents.

3. Results and discussion

Comparisons of the observed and calculated content of available water in the root zone showed a satisfactory fit, the correlation coefficient of linear regression was highly significant ($r = 0.84$, $p < 0.001$) (Fig. 4). The fit was worsened by several values, mostly of maize (the only C4 species of observed crops), where observed water contents were higher than calculated one, probably due to lower water consumption than indicated by long duration of green canopy and the corresponding crop coefficient.

The calculation was based on several assumptions and simplifications, allowing it to be used with the limited access to input data on farms. The main aim of the method and linked online programme was not a detailed simulation of water depletion, but rather to give the user an idea about the key factors determining the available water supply and its depletion by crops during growth. The programme allows one to modify input values and to test the impact of alternative plants, soils and weather conditions. The programme also provides a description of simple, field methods to determine or estimate soil texture, moisture, or root depth. Sets of daily data for combinations of cold/warm and dry/wet weather are also supplied within the programme.

One of the possible sources of error is the calculation of AWC of the soil layers by pedotransfer functions (PTF). We found a good agreement between the maximum water content in the 130 cm zone, observed (mostly) in early spring of years 2012–2014 and the water content at field capacity (FC) calculated as the average of several simple PTFs (*Haberle et al., 2014*). The observed content was 0% to 17% lower than the calculated one, which agreed with the loss of water due to evaporation from the topsoil. In the programme, WP and FC are calculated according to *Váša (1960)* and *Novotný et al. (1990)*, to simplify input data, but it may be easily supplemented by other PTFs (*Saxton et al., 1986; Vlček et al., 2014*).The programme also calculates WP and FC from estimated soil type (texture class), however, users are encouraged to leave the analysis of the texture to expert services.

Farmers do not have the relevant equipment nor expertise to determine the exact root depth or root length density distribution. The programme suggests ranges of root depths for crops under more-or-less favourable soil conditions. A user is advised to check the root depth with the use of a soil trench or a common hole corer. Inspection of the soil profile, especially in fields with obstacles to root growth (soil hardpan, layers of impermeable clay or pebbles, anoxic soil layers due to stagnant water) may improve the realistic estimation of the extent of root zone and explain any unexpected effect of drought or excessive precipitation on the crops.

An exact simulation of the distribution of water depletion from a soil profile in relationship to root development is a difficult task, even for crop models (e.g. *Hao et al., 2005; Himmelbauer et al., 2008*). In agroclimatological calculations of water balance, it is greatly simplified or neglected. The farmer is chiefly interested in situations where the precipitation is insufficient, the topsoil water is exhausted, and the crops show symptoms of water stress; surviving thanks only to subsoil water reserves. The situation most often comes during the main growth stage and seed filling or tuber growth, when the roots have already occupied a great volume of the soil, and root penetration is near its limit as the growth is none or only minor after flowering. Thus we can assume water of the whole root zone is potentially accessible for a crop. An empirical reduction of water depletion from the deepest layers (with a low root density) also reflects the aspect of time; individual root axes reach the depth at late periods of plant growth. We commonly observed that in the deepest layers the available water was not fully exhausted (*Haberle and Svoboda, 2012*) (Fig. 6). Exceptionally, under specific year conditions, in soils with a high AWC, well developed canopy and root systems, several weeks without precipitation and gradual exhaustion of water, apparent depletion of water under root depth was observed (Fig. 6). The integration of the water reserve into the calculation of the water balance would demand more experimental data.

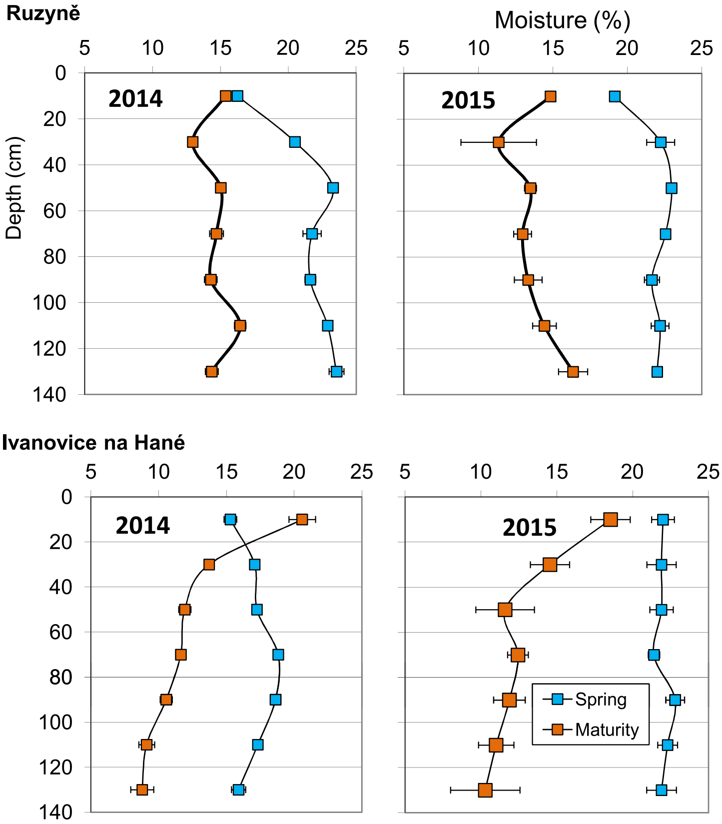

Fig. 6. Soil moisture under winter wheat at early spring and at maturity in dry years 2014 and 2015 on sites with a deep soil. Average of three different treatments in long-term experiments.

The estimation of intervals of the crop coefficient changing during growth is another factor affecting calculation of water depletion. However, the shift of a few days does not play a great role due to the slow rate in the increase and decrease of the coefficient. Further, under conditions of water shortage, a bit faster or slower rate of depletion will result in a similar low level of soil water. If the shift is considerable it may adversely affect the agreement with field data.

The calculation of potential evapotranspiration from temperature alone is somehow compensated by taking measurements directly at the site, near a monitored field. National systems of drought monitoring use meteorological data, often from stations tens of kilometres distant. The programme may be improved with a more sophisticated calculation, utilizing data from on-farm meteorological measurement. Accounting for local precipitation variability, possible surface water out-flow, and direct farmer inspection may also improve the calculation of the water balance, compared with regionally-based systems.

4. Conclusions

The presented approach for calculation of the available water supply and its depletion by crops on farms with limited access to input data reproduced reasonable observed water contents. The calculation may be easily upgraded with more sophisticated algorithms. The use of the programme should stimulate farmers and agronomists to consider the factors affecting the available water supply, and to take appropriate measures.

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References

Allen R. G., Pereira L. S., Raies D., Smith M., 1998: Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, United Nations, Rome, I., 300 p.

Haberle J., Svoboda P., 2014: Impacts of use of observed and exponential functions of root distribution in soil on water utilisation and yield of wheat, simulated with a crop model. Archives Agron. Crop Sci., **60**, 1533–1542.

Haberle J., Svoboda P., 2012: Distribution of wheat roots in soil profile and available water and nitrogen supply (Distribuce kořenů pšenice v půdním profilu a využitelná zásoba dusíku a vody). Úroda, **60**, 79–84 (CD). (in Czech with English abstract).

Haberle J., Svoboda P., Kohút M., Kurešová G., 2014: The comparison of calculated and experimentally determined available water supply in the root zone of selected crops. In: Rožnovský J., Litschmann T. (eds): Mendel a bioklimatologie, 3–5. 9. 2014 Brno, 122–133 (CD). ISBN 978-80-210-6983-1.

Haberle J., Vlček V., Kohut M., Dostál J., Středa T., Svoboda P., 2015: Water balance and the determination of available water content in root zone of crops (Bilance a určení dostupné zásoby vody v kořenové zóně plodin). ISBN 978-80-7427-173-1. VÚRV, v.v.i., 36 p., available also online at `<http://www.vurv.cz>`, (in Czech with English abstract).

Hao X., Zhang R., Kravchenko A., 2005: Effects of root density distribution models on root water uptake and water flow under irrigation. Soil Sci., **170**, 167–174.

Himmelbauer M. L., Novák V., Majerčák J., 2008: Sensitivity of soil water content profiles in the root zone to extraction functions based on different root morphological parameters. J. Hydrol. Hydromech., **56**, 34–44.

Kirkegaard J. A., Lilley J. M., Howe G. N., Graham J. M., 2007: Impact of subsoil water use on wheat yield. Aust J. Agr. Res., **58**, 303–315.

Kong L., Si J., Sun M., Feng B., Zhang B., Li S., Wang Z., Wang F., 2013: Deep roots are pivotal for regulating post-anthesis leaf senescence in wheat (Triticum aestivum L.). J. Agron. Crop Sci., **199**, 209–216.

Kuhlmann H., Barraclough P. B., Weir A. H., 1989: Utilization of mineral nitrogen in the subsoil by winter wheat. Z. Pflanzenernaehr. Bodenk., **152**, 291–295.

Novotný M., Kervališvili D. M., Šanta M., 1990: Irrigation of field and special crops (Závlaha poľných a špeciálnych plodín). PRÍRODA, Bratislava 2012, 312 p. ISBN 80-07-00267-7. (in Slovak).

Saxton K. E., Rawls W. J., Romberger J. S., Papendick R. I., 1986: Estimating generalized soil-water characteristics from texture. Soil Sci. Soc. Am. J., **50**, 1031–1036.

Schrödter H., 1985: Verdunstung. Anwendungsorientierte Messverfahren und Bestimmungsmethoden. Springer, Berlin-Heidelberg. 186 p. 978-3-540-15355-9.

Svoboda P., Haberle J., 2014a: Available supply of water in soil in relation to depth and distribution of roots in selected crops (Dostupná zásoba vody v půdě ve vztahu k hloubce a distribuci kořenů vybraných plodin). In: Vliv abiotických a biotických stresorů na vlastnosti rostlin (ed. Hnilička F.), 10–11. 9. 2014, Zvolen, SK, 2014, 210–214. ISBN 978-80-213-2475-6. (in Czech with English abstract).

Svoboda P., Haberle J., 2014b: Root depth of crops (Hloubka kořenů polních plodin). Úroda, **62**, 12, 433–436 (CD). (in Czech with English abstract).

Svoboda P., Haberle J., Kurešová G., 2014: Root growth and depletion of nitrogen from root zone of winter wheat under drought and ample water supply. 13th Alps-Adria

Scientific Workshop (28.4.–3.5. 2014, Villach, Austria). CD 299–302. (ISSN 0546-8191).

Tennant D., 1975: A test of a modified line intersect method of estimating root length. J. Ecol., **63**, 995–1001.

Vlček V., Hybler V., Hladký J., Pospíšilová L., 2014: Selected pedotransfer functions and their suitability for indicative hydro-physical characteristics of soils (Vybrané pedotransferové funkce a jejich vhodnost pro orientační hydrofyzikální charakteristiku půd). Úroda, **62**, 12, 453–456 (CD). (in Czech with English abstract).

Váša J., 1960: Soil moisture characteristics (Půdní vláhové charakteristiky). Vodohospodársky časopis SAV, **8**, 235–243. (in Slovak).

Zhang X, Shao L, Sun H, Chen S, Wang Y., 2012: Incorporation of soil bulk density in simulating root distribution of winter wheat and maize in two contrasting soils. Soil Sci. Soc. Am. J., **76**, 638–647.

Zuo Q, Zhang R., Shi J., 2013: Characterization of the root length density distribution of wheat using a generalized function. In: Timlin D., Ahuja L. R. (eds). Advances in agricultural systems modelling. Chapter 4. Enhancing understanding and quantification of soil-root growth interactions, 93–117. ISBN: 978-0-89118-339-6.