The Actual Consumption of Water by Selected Cultivated and Weed Species of Plants and the Actual Values of Evapotranspiration of the Stands as Determined Under Field Conditions

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Abstract: In the years 2005 to 2008, the consumption of water by selected cultivated and weed species under the field conditions and the values of the actual evapotranspiration in selected stands of cultivated crops were evaluated. The values of the transpiration flow were measured with a T4.2 EMS Brno (CZ) 12 channel sap-flow meter, and the actual evapotranspiration by BREB method (Bowen Ratio-Energy Balance) using the equipment of the same firm. The recording of the values obtained during the measurements was carried out in 10-min intervals. The sap flow was measured on the following weed plants *Amaranthus retroflexus*, *Artemisia vulgaris*, *Cirsium arvense*, *Conyza Canadensis*, and *Lactuca serriola* as weeds in the cultivated crops of *Brassica napus* and *Zea mays*. The actual evapotranspiration using the BREB method was determined over the stands of *Beta vulgaris*, *Brassica napus*, *Hordeum vulgare*, *Medicago sativa*, and *Zea mays*. On the basis of the measurements carried out, the average daily values of the sap flow of the evaluated plants ranged from 0.016 to 0.193 kg/day of water per plant. The maximum daily values ranged from 0.025 to 0.309 kg/day of water per plant. The average daily value of the evapotranspiration flow in *Hordeum vulgare* during the period under observation amounted to 2.9 mm, while the daily values ranged from 1.2 to 4.6 mm H_2O/day. In the other evaluated plants, the daily values of evapotranspiration ranged from 0.9 mm to 5.9 mm/day of water, on average 3.4 mm/day of water (*Beta vulgaris*), and from 1.7 mm to 5.2 mm/day of water, on average 3.2 mm/day of water (*Brassica napus*).

Keywords: transpiration; evapotranspiration; *Brassica napus*; *Beta vulgaris*; *Hordeum vulgare*; *Medicago sativa*; *Zea mays*; weeds; global solar radiation; vapour pressure deficit; sap flow; BREB

The water consumption of plants represents a significant part of the landscape water balance (Merta *et al.* 2001). An important factor influencing the water balance of the plant stands on agricultural soil and thereby in the countryside is the species composition of phytocoenosis. Within the framework of phytocoenosis, the cultivated plants and weeds take share in influencing the water balance. The knowledge of the actual evapotranspiration values of cultivated crops is a prerequisite for the understanding of the influence of agriculture on the environment as well as the basis for the elimi-

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nation of negative effects of agriculture on the environment and its water balance. Furthermore, the exchange of CO_2 and water vapour between plant crops and the surrounding air play an important role in the photosynthetic assimilation and, consequently, in the biomass production. From the practical point of view, the knowledge of the evapotranspiration demands can be used for the water balance optimisation through the finally structured crop and growing phases duration and growth access periods (San José *et al.* 2003). The crop transpiration depends on the management, such as the supply of nutrients (Shepherd *et al.* 1987), seeding day (Connor *et al.* 1992), and the plant species or cultivars (Eastham & Gregory 2000). Additionally, the energetic fluxes and the water use efficiency (e.g. Corbeels *et al.* 1998; Asseng & Hsiao 2000) as well as the dissipation of the energy within the landscape (Ripl 1995) are evaluated. The energy balance components are strongly affected by the leaf area index and plant height during all developmental stages of the canopy, especially the sensible heat flux. The results have shown that the dry matter weight is totally independent of the energy partitioning (Cleber *et al.* 2008). Also important for the estimation and verification of the crop coefficients values is the actual evapotranspiration assessment (Inman-Bamber & McGlinchey 2003; Hanson & May 2006; Kato & Kamichika 2006). The crop coefficients are classified as single or dual (Allen *et al.* 1998). The current knowledge of the plant species moisture requirements has been obtained predominantly within the framework of the study of forest communities while the transpiration values are known in wood species (Schulze *et al.* 1985; Čermák *et al.* 1992, 1995; Jech *et al*. 2003). The information on the moisture requirements of the herbal species, particularly their determination under natural conditions, are relatively, on the basis of literature survey, is not so abundant (Bethenod *et al.* 2000; Merta *et al.* 2001). From the point of view of the determination of the individual moisture requirements, the sap flow-meter can be used, which is based on the principle of heat dispersal in the herbal or woody stems (Kučera *et al.* 1977). The evaporation of plant stands can be determined by the BREB method (Bowen ration and energy balance), which uses the determination of the ratio of the sensible and latent heats in the close vicinity of the evaporating surface. The water flow in a stem – sap flow – just like the water output of the whole plant stand, depends primarily on the evaporation demands of the adjacent layer of the atmosphere, which are represented by e.g. the vapour pressure deficit and also by the input of energy given e.g. by the global solar radiation energy (Woodward & Sheehy 1983). The relation between the maize plants transpiration and the meteorogical influence of the stand under the field conditions has also been investigated by Pivec and Brant (2006). In respect of the moisture requirements of cultural plants, Brant *et al.* (2007a) point out the differences between the moisture requirements of the line and hybrid varieties of winter rapeseed. The transpiration values of selected weed species of the *Asteraceae* family have also been determined within the framework of the field experiments (Brant *et al.* 2007b). The aim of this study is to compare the moisture requirements of selected stands of field crops and weed species, determined under the field conditions on the basis of the present experiments.

MATERIALS AND METHODS

The use of the heat balance method is based on the relation (1) between the entering heat amount and the increase in temperature within a defined space (Kučera *et al.* 1977; Tatarinov *et al.* 2005):

$$P = Q \times dT \times c_w + dT \times z \tag{1}$$

where:
P – heat energy input (W)
Q – sap flow (kg/s)
dT – temperature difference within the measured space (K)
c_w – specific heat of water (J/kg/K)
z – coefficient of the heat losses in the measured space (W/K)

During our experiments that took place from 2005 to 2008, the sap flow values were evaluated in the selected cultivated and weed plants under the field conditions. The Q values were measured with a 12-channel T4.2 flow meter destined for the stems of 6 to 20 mm diameter, which was made by the EMS Brno (CZ) firm. The values obtained during the measurements were recorded in 10-min intervals during the entire period of the individual measurements. The measurements point was always located on the base of the plant or stalk (selected stalks of the *Artemisia vulgaris*

Table 1. Specification of localities, dates of measurements, BBCH phase, and species in which the sap flow was measured

Plant species	Date of measurement	BBCH	*n*	Location	Notes
Amaranthus retroflexus (Common amaranth)[W]	2. 8.–27. 8. 2006	69–75	2	Praha-Suchdol	measured in solitary plants
Artemisia vulgaris (Mugwort)[W]	2. 8.–27. 8. 2006	67–73	7*	Praha-Suchdol	measured in solitary plants
	19. 7.–17. 8. 2007	67–75	7*		
Brassica napus (Winter rape)[AC]	9. 6.–22. 7. 2005	71–88	6	Červený Újezd	measured in the stand of winter rape
	5. 6.–25. 7. 2006	75–97	6		
	26. 4.–29. 6. 2007	64–86	24		
	29. 5.–14. 7. 2008	71–87	17		
Cirsium arvense (Creeping thistle)[W]	2. 8.–8. 8. 2005	63–65	1*	Červený Újezd	measured in the stand of maize
Conyza canadensis (Canadian fleabane)[W]	2. 8.–27. 8. 2006	69–89	6	Praha-Suchdol	measured in solitary plants
	19. 7.–17. 8. 2007		9		
Lactuca serriola (Prickly lettuce)[W]	2. 8.–27. 8. 2006	67–81	9	Praha-Suchdol	measured in solitary plants
	19. 7.–17. 8. 2007	63–85	8		
Zea mays (Maize)[AC]	15. 7.–3. 9. 2008		11	Červený Újezd	measured in the stand of maize

n = number of measured plants or stalks, [AC]– arable crop, [W]– weed, *– stalks

and *Cirsium arvense* plants were measured). Table 1 documents the evaluated plant species, locations, and the time of the measurements. The developmental phases are described by the BBCH scale (Table 1). The BBCH-scale is a scale used to identify the phenological development stages of a plant. Officially, the abbreviation BBCH derives from Biologische Bundesanstalt, Bundessortenamt and CHemical industry. The field measurements were carried out at the localities Červený Újezd (GPS coordinates: 50°04'34.45"N, 14°09'22.351"E – WGS 84) and Prague-Suchdol (GPS coordinates: 50°7'35.845"N, 14°22'32.72"E – WGS 84). In the years of 2005, 2007, and 2008, the measurements were carried out on *Brassica napus* plants, Navajo variety, and in 2006 on Jasper and Spirit varieties. In 2008, the measurements were performed on *Zea mays* plants (Maize), Rivaldo variety. The crops of *Brassica napus* and *Zea mays* were cultivated on ploughed soils. At the time of the measurements, the evaluated weed varieties were in the phases ranging from the start of flowering to the start of seed ripening. BBCH phases in the weed species were classified according to Hess *et al.* (1997) and in the cultivated crops according to Meier (2001). The following supplementary meteorological characteristics were measured: temperature (T) and air humidity (r) – on the basis of which the vapour pressure deficit (d) was determined, and then the global solar radiation (Rg) and precipitation (P).

The values of the actual evapotranspiration were measured under the field conditions at the localities Červený Újezd (GPS coordinates: 50°04'34.45"N, 14°09'22.351"E – WGS 84) and Budihostice (GPS coordinates: 50°18'46.374"N, 14°15'21.256"E – WGS 84). At the Červený Újezd locality, the values of the actual evapotranspiration were measured in the stand of *Brassica napus* (winter rape, Navajo variety) in 2008 and in that of *Zea mays* (maize, Rivaldo variety). At the Budihostice locality, the values of the actual evapotranspiration were measured in *Hordeum vulgare* (spring barley, Jersey

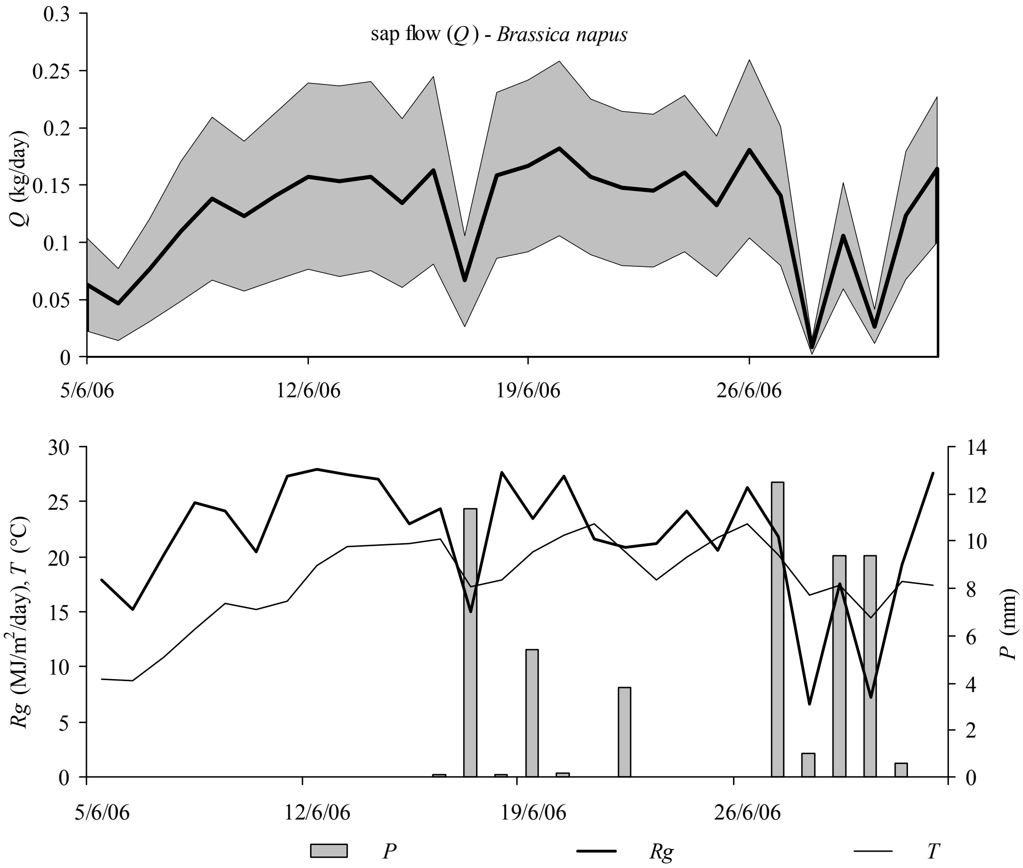

Figure 1. Average daily sap flow values (Q, kg/day) of winter rape (average of 6 plants) for the period of 5. 6. to 2. 7. 2006 and the daily course of global solar radiation values (Rg, MJ/m^2/day), air temperature at 2 metres over the ground (T, °C) and the daily precipitation totals (P, mm) for the same period

variety) in 2007, in *Beta vulgaris* (sugar beet, Julieta variety) in 2008, and in *Medicago sativa* (alfalfa, Oslava variety, in the first year of growth). The minimum size of the area on which the evapotranspiration was measured was 1 ha. Ploughing was the basic treatment of the areas evaluated. The values of the actual evapotranspiration in the stands of *Hordeum vulgare* were measured from 21. 04. to 18. 07. 2007 (BBCH 22–91), of *Beta vulgaris* from 12.06. to 08. 07. 2008 (BBCH 31–49), of *Brassica napus* from 06. 06. to 11. 07. 2008 (BBCH 75–86), of *Medicago sativa* from 23. 07. to 17. 10. 2008 (BBCH were not assessed), and of *Zea mays* from 15. 07 to 3. 9. 2008 (BBCH 61–71). BBCH phases were classified according to Meier (2001).

The linear (arithmetic row) and non-linear (geometric row) dependences expressed by the relation (2) – (Kučera, personal communication) were used for the approximation of the transpiration process (records in 10 min intervals and average daily values) by means of the global solar radiation and vapour pressure deficit:

$$Y = aX_1/(X_1 + b) \times X_2/(X_2 + c) \qquad (2)$$

where:

a, b, c – parameters
Y – water flow through the plant – transpiration
X_1 – global solar radiation
X_2 – vapour pressure deficit

By means of this approximation is it possible to determine exactly the clearly phenological BBCH phase, which corresponds to the ending of the growth phase of a species. At this point, the progress of the actual measured value of transpiration intersects with the approximated one, determined only by the input values of the global solar radiation and vapour pressure deficit.

The BREB method is based on the precondition of the coefficients of the apparent and latent heat being equal, when it is possible to determine the ratio of the sensible and latent heats by measuring the gradients of the air temperature and humidity over the evaporating surface (Woodward & Sheehy 1983):

$$\beta = \frac{H}{\lambda E} = \gamma \frac{dT}{de} \tag{3}$$

where:
H – flow of sensible heat
λ – specific heat of the water vapour
E – evapotranspiration
γ – psychrometric constant 0.66 hPa/°C
dT/de – temperature/humidity gradient of air at two levels over the evaporating surface

The lower/upper levels of measurements were at 0.65/2.15 m over the ground for *Hordeum vulgare*, 1.90/3.10 m for *Brassica napus*, 0.40/2.00 m for *Beta vulgaris*, 0.55/2.2 m for *Medicago sativa*, and 1.9/3.1 m for *Zea mays*, respectively.

If the radiation balance is $Rn = H + \lambda E$, then

$$E = \frac{Rn}{\lambda(1+\beta)} \tag{4}$$

The radiation balance measured directly with the SCHENK (AU) balance meter was corrected by means of a component of the energy amount that flows into the soil under the active surface of the observed plant stand as measured with the HUXEFLUX (NL) sensors.

RESULTS AND DISCUSSION

The average daily values of the sap flow determined in our experiments, including the daily averages of the energy received and the sums of precipitation for the observed period, are outlined in Table 2. In respect of the moisture requirements of a plant, interesting is also the determination of the maximum daily values of the sap flows as the highest border line values of an interval in which the Q values were present.

The lower border line of this interval has obviously been determined by a near zero value, which was recorded during very cloudy and rainy weather. In Figure 1 is documented the positive relation between the values of the sap flow of a plant and the energy input expressed by means of global solar radiation on the basis of similarity with the progress of the above outlined quantities. The sun radiation energy received, however, is not the only factor that governs the transpiration. Together with the accessibility of water in the soil (this was not measured), aerodynamic conditions (not measured) and evaporation demands of the

Table 2. Averages of daily values of sap flow (Q, kg/day of water), their maxima (Q_{max}, kg/day of water), and standard deviation Q_{max} (SD × Q_{max}) for the evaluated plant species and the average daily sums of global solar radiation (Rg, MJ/m^2/day) and daily totals of precipitation (P, mm) for the period under observation

Plant species	Date of measurement	Q	Q_{max}	SD × Q_{max}	Rg	P
Amaranthus retroflexus	2. 8.–27. 8. 2006	0.018	0.080		14.104	99.0
Artemisia vulgaris	2. 8.–27. 8. 2006	0.077	0.150	0.062	14.104	99.0
	19. 7.–17. 8. 2007	0.084	0.157	0.092	17.777	79.0
Brassica napus	9. 6.–22. 7. 2005	0.044	0.121	0.033	17.077	174.8
	5. 6.–25. 7. 2006	0.092	0.187	0.074	22.342	65.1
	26. 4.–29. 6. 2007	0.030	0.079	0.055	19.548	195.9
	29. 5.–14. 7. 2008	0.085	0.203	0.061	19.642	107.5
Cirsium arvense	2. 8.–8. 8. 2005	0.016	0.025		14.801	20.6
Conyza canadensis	2. 8.–27. 8. 2006	0.046	0.116	0.043	14.104	99.0
	19. 7.–17. 8. 2007	0.078	0.174	0.051	17.777	79.0
Lactuca serriola	2. 8.–27. 8. 2006	0.068	0.153	0.102	14.104	99.0
	19. 7.–17. 8. 2007	0.025	0.093	0.041	17.777	79.0
Zea mays	15. 7.–3. 9. 2008	0.080	201	0.043	15.625	104.0

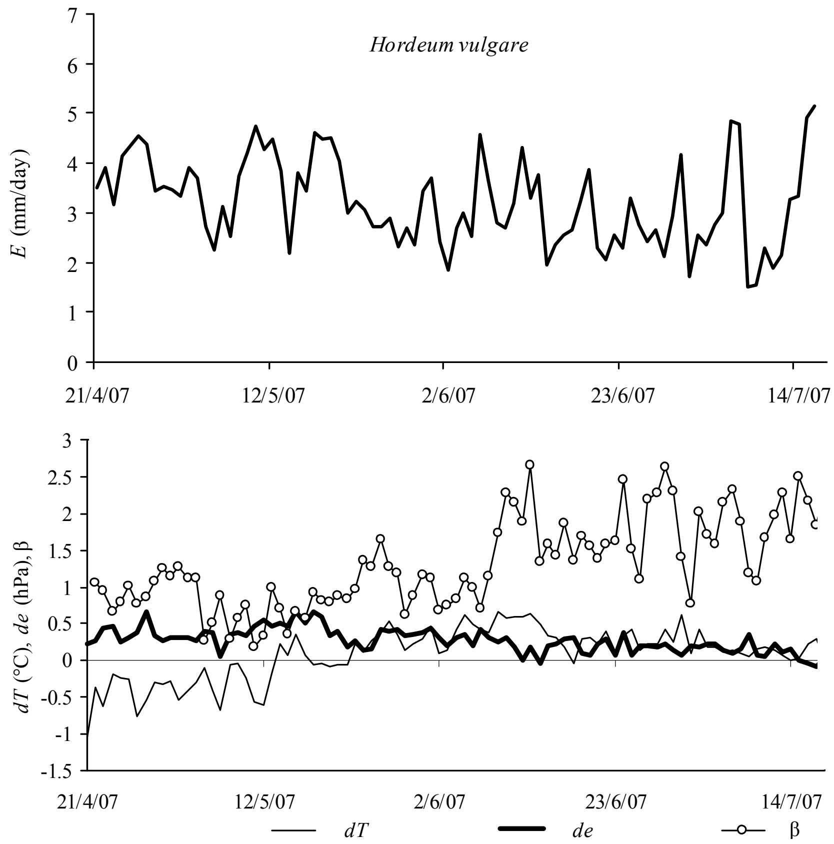

Figure 2. Daily totals of *Hordeum vulgare* evapotranspiration (*E*, mm), and the average temperature gradient (*dT*, °C), air humidity (*de*, hPa), and Bowen ratio (β) for the period of 21. 4. to 18. 7. 2007

atmosphere in the zone of the active surface of vegetation, expressed by e.g. vapour pressure deficit, the environment of the evaporation process of water from the ecosystem into the atmosphere is the decisive abiotic factor (Kučera *et al.* 1977; Pivec & Brant 2006).

On the basis of the measurements carried out, the average daily values of the sap flow ranged from 0.016 to 0.193 kg/day of water. The maximum daily values ranged from 0.025 to 0.309 kg/day of water. However, in respect of the determination of the moisture requirements of a stand or vegetation growth, it is necessary to determine the value of the sap flow per unit area of the plant stand. This value is, on one hand, given by the number of individuals of the cultivated plant per unit area and comes from the requirements for the optimum structure of the growth and, on the other hand, by the intensity of weed infestation, i.e. the abundance of weeds and the spectrum of the species, including the biomass production.

If, in our experiments, the number of *Brassica napus* plants ranged from 30 to 50 plants per m^2, then we could determine, on the basis of the estimate of the transpiration requirements of the plant stand coming out from the average daily value of Q = 0.063 kg/day/plant (average value of the measurements carried out from 2005 to 2008), that the average daily consumption of water by the plant stand can range from 1.65 to 2.75 kg/day/m^2. This is valid in the case that the given estimate does not include the values of the sap flow of weeds. In respect of the transpiration requirements of weeds, this concerns not only the influence on the moisture requirements of the vegetation growth, but also the competitive relations between the cultivated and weed plants to water.

If, for example, we compare the transpiration requirements of the *Brassica napus* plants and those of *Lactuca serriola*, which can become a weed in the stands of *Brassica napus*, we will find out that they resemble each other. We can then express the assumption that the occurrence of one plant of *Lactuca serriola* per unit area of the *Brassica napus* stand has the same effect on the transpiration requirements of the stand and competitive relations to water as the increase in the numbers of individuals of *Brassica napus* per the given area unit by one plant. A more distinct effect on the transpiration requirements of the growth stand will be found if we evaluate the influence of the occurrence of *Artemisia vulgaris* plants in the stands of *Brassica napus*. If the daily average value of the sap flow in *Artemisia vulgaris* reaches 0.077 to 0084 kg of water per a single stalk, then with the average number of stalks, which can range from 3 to 7 in *Brassica napus*, the moisture requirements of this weed are considerably higher in comparison with a single plant of *Brassica napus*.

The results of measuring the actual evapotranspiration of spring barley using the BREB method during the period observed are best illustrated by Figure 2. The hourly values of evapotranspiration reached the values of up to 0.81 mm/h, on average 0.13 mm/h. The daily sums of evapotranspiration ranged from 1.2 mm to 4.6 mm of water, on average 2.9 mm. The lower part of Figure 2 documents the daily average of the temperature gradient between the lower and upper levels of measurements from –1.0°C to +0.66°C, the average gradient of +0.087°C, and air humidity from –0.07 to +0.67 hPa, the average gradient of +0.27 hPa. The progress of both gradients corresponds with the progress of the Bowen ratio ranging from 0.177 to 2.64, with the average value of 1.3, which means that the average consumption of heat to warm up the air through convection by 30% exceeded the consumption of heat for evaporation. In the other crops evaluated, the daily values of evapotranspiration ranged from 0.9 mm to 5.9 mm/day of water, on average: 3.4 mm/day of water (*Beta vulgaris*), and from 0.6 mm to 6.1 mm/day of water, on average: 2.5 mm/day of water (*Medicago sativa*), Figure 3. In *Beta vulgaris* and *Medicago sativa* similar values of evapotranspiration were estimated in the second half of the vegetative period (Figure 3). An evapotranspiration decrease was observed in *Beta vulgaris* at the end of the vegetative period due to abiotic factors changes. The decline of *Medicago sativa* evapotranspiration was influenced by the crop cutting (Figure 3), according to the results of Asseng and Hsiao (2000). The transpiration ability of these crops in the second half of the growing season is important not only in view of the water flux through the ecosystem, but also in view of energy balance stabilisation. In particular, cultivated crops such as *Beta vulgaris*, *Medicago sativa*, and *Zea mays* contribute to the cooling of the ground level atmosphere due to the evapotranspiration process, where a higher amount of latent heat energy is utilised. It is important to ensure a high proportion of cereal crops and of *Brassica napus* in the crop rotations. As a result of the maturation phase of these cultivated crops coming at the turn of summer and subsequent crop harvest, the Bowen ratio increased in the plots, as illustrated in Figure 2. Daily values of evapotranspiration by *Brassica napus* plant fluctuated from 1.7 mm to 5.2 mm/day of water, on average: 3.2 mm/day of water, and by *Zea mays* 2.2 mm/day of water on average. Figure 4 illustrates the daily totals of transpiration/evapotranspiration measured by the sap flow/BREB technique in *Brassica napus* and *Zea mays* plants. *Q* values of *Zea mays* achieved 35% of *E* values. The amount of water passing

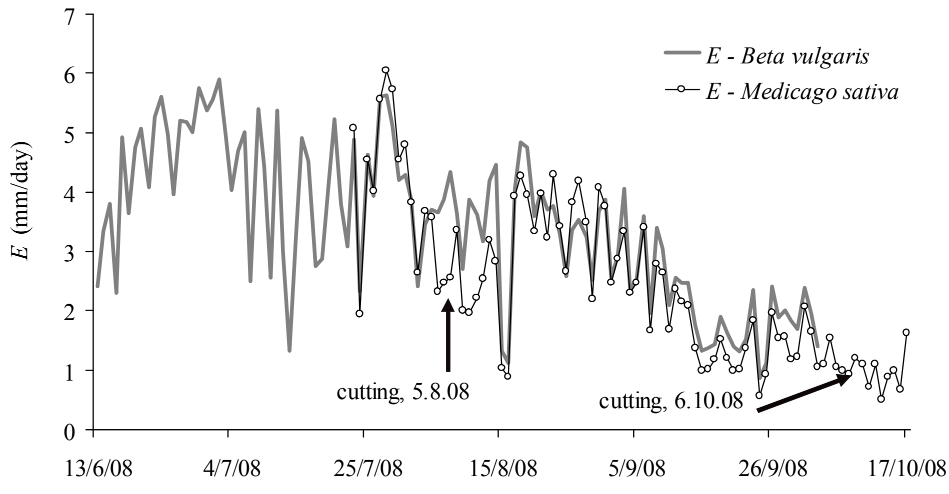

Figure 3. Daily values of *Beta vulgaris* and *Medicago sativa* (*E*, mm) evapotranspiration during 2008; in *Medicago sativa* crops the dates of the shoot biomass cutting are labelled

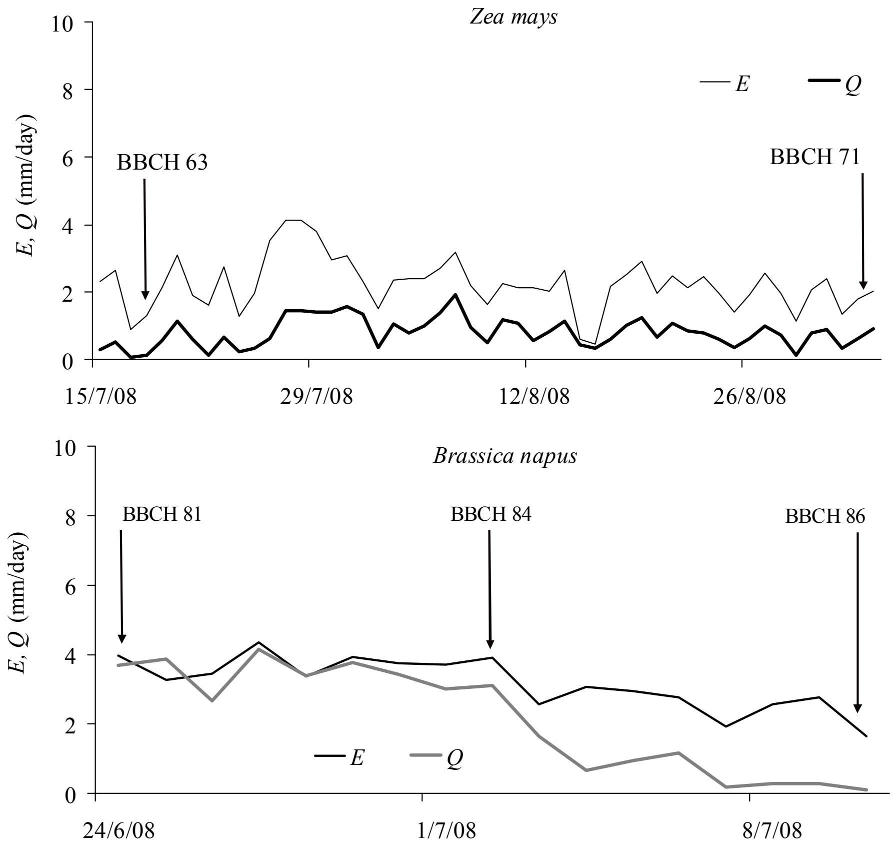

Figure 4. Daily values of evapotranspiration (E, mm) and sap flow (Q, mm) of *Zea mays* and *Brassica napus* plants. The average number of individuals in *Zea mays* was 96 000 ha^{-1} and in *Brassica napus* 42 individuals m^{-2}

through the *Zea mays* plant stems on 1 m^2 of crop as measured by the sap flow, when compared with the evapotranspiration values measured by BREB technique, denotes a higher evaporation than we expected. This suggests that the heat balance method of the sap flow rate measurement can be disputed as concerns *Zea mays* plants, which are monocotyledonous and in which, therefore, the water flow runs across the whole cross-section of vascular bundles in the stem. On the other hand, *Zea mays* is a representative of C4 plants with a smaller water consumption and a higher water use efficiency than revealed by C3 plants. In any case, the study of *Zea mays* will require a much greater effort and more detailed observation since there are few literature references on this subject. From Figure 4 is it clear that *Brassica napus* transpiration rates decline with the advancing maturation stage (BBCH phase 84) according to the results of Pivec *et al.* (2009). After the maturation stage, the crop transpiration still drops and the values of evapotranspiration are probably influenced by evaporation.

CONCLUSIONS

The measured values have demonstrated that the consumption of water by agricultural plants as well as by weeds is a significant component of the water balance in an agri-industrial areas. Some weed species (*Cirsium arvense*) transpire less than 0.1 l of water daily, others, due to the branched out system of stalks in a single individual (*Artemisia vulgaris*) and the stalk water flow, which is comparable with that of the main farm crop, represent a distinct competition for water in agricultural ecosystems as significant, changeable landscape forming elements. When we consider that this concerns tens of tonnes of water from a single hectare per day, then, during the vegetative period, this amount is comparable with the forest stands which, however, transpire even outside the main vegetation period. The most crucial conclusion of this work is a comparison of actual evapotranspiration values measured both by the BREB method and the sap flow. Simultaneous use of these methods provides also the verification of the results obtained.

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.

Asseng S., Hsiao T.C. (2000): Canopy CO_2 assimilation, energy balance, and water use efficiency of an alfalfa crop before and after cutting. Field Crops Research, **67**: 191–206.

Bethenod O., Katerji N., Goujet R., Bertolini J.M., Rana G. (2000): Determination and validation of corn crop transpiration by sap flow measurement under field conditions. Theoretical and Applied Climatology, **67**: 153–160.

Brant V., Pivec J., Bečka D. (2007a): Line and hybrid varieties of the winter rape transpiration in dependence on the selected abiotic factors of the environment. In: Symposium Book: Vliv abiotických a biotických stresorů na vlastnosti rostlin. ČZU, Praha, 123–126. (in Czech)

Brant V., Pivec J., Neckář K., Venclová V. (2007b): Actual water consumption by the chosen weeds of *Asteraceae* family on the mature stage of development depending on environmental conditions. In: 14th European Weed Research Society Symposium. Hamar, Oslo.

Cleber B. de Souza, Bernardo B. da Silva, Pedro V. de Azevedo, Vicente de P.R., da Silva (2008): Energy fluxes and development of pineapple crop. Revista Brasileira de Engenharia Agrícola e Ambiental, **12**: 400–407.

Connor D.J., Theiveyanathan S., Rimmington G.M. (1992): Development, growth, water-use and yield of a spring and a winter wheat in response to time of sowing. Australian Journal of Soil Research, **43**: 493–516.

Corbeels M., Hofman G., Van Cleemput O. (1998): Analysis of water use by wheat grown on a cracking clay soil in a semi-arid Mediterranean environment: weather and nitrogen effects. Agricultural Water Management, **38**: 147–167.

Čermák J., Cienciala E., Kučera J., Hällgren J.E. (1992): Radial velocity profiles of water flow in trunks of Norway spruce and oak and the response of spruce to severing. Tree Physiology, **10**: 376–380.

Čermák J., Cienciala E., Kučera J., Lindroth A., Bednářová E. (1995): Individual variation of sap-flow rate in large pine and spruce trees and stand transpiration: a pilot study at the central NOPEX site. Journal of Hydrology, **168**: 17–27.

Eastham J., Gregory P.J. (2000): The influence of crop management on the water balance of lupin and wheat crops on a layered soil in a Mediterranean climate. Plant and Soil, **221**: 239–251.

Hanson B.R., May D.M. (2006): Crop coefficients for drip-irrigated processing tomato. Agricultural Water Management, **81**: 381–399.

Hess M. , Barralis G. , Bleiholder H. , Buhr L. , Eggers T. , Hack H. , Stauss R. (1997): Use of the extended BBCH scale – general for the descriptions of the growth stages of mono- and dicotyledonous weed species. Weed Research, **37**: 433–441.

Inman-Bamber N.G., McGlinchey M.G. (2003): Crop coefficients and water-use estimates for sugarcane based on long-term Bowen ratio energy balance measurements. Field Crops Research, **83**: 125–138.

Jech D., Havlíčková K., Weger J. (2003): Crop function of the fast-growing wood species in the landscape. In: Weger J. (ed.): Biomass – Renewable Resources of Energy in the Landscape. VÚKOZ, Průhonice. (in Czech)

Kato T., Kamichika M. (2006): Determination of a crop coefficient for evapotranspiration in a sparse sorghum field. Irrigation and Drainage, **55**: 165–175.

Kučera J., Čermák J., Penka M. (1977): Improved thermal method of continual recording the transpiration flow rate dynamics. Biologia Plantarum, **19**: 413–420.

Meier U. (ed.) (2001): Growth Stages of Mono-and Dicotyledonous Plants. BBCH Monograph, 2nd Ed., Federal Biological Research Centre for Agriculture and Forestry, Braunschweig.

Merta M., Sambale C., Seidler C., Peschke G. (2001): Suitability of plant physiological methods to estimate the transpiration of agricultural crops. Journal of Plant Nutrition and Soil Science, **164**: 43–48.

Pivec J., Brant V. (2006): Comparison of the corn sap flow dependency on the site environmental conditions. In: Symposium Book: Vliv abiotických a biotických stresorů na vlastnosti rostlin 2006. ČZU, Praha, 279–283. (in Czech)

Pivec J., Brant V., Bečka D. (2009): The influence of weather conditions on the sap flow of *Brassica napus* L. during the fructification and maturation stages. Ekológia (Bratislava), **28**: 43–51.

Ripl W. (1995): Management of water cycle and energy flow for ecosystem control – the Energy-Transport-Reaction (ETR) Model. Ecological Modelling, **78**: 61– 35.

San José J.J., Bracho R., Montes R., Nikonova N. (2003): Comparative energy exchange from cowpeas (*Vigna unguiculata* (L.) Walp cvs. TC-9-6 and M-28-6-6) with differences in canopy architectures and growth durations at the Orinoco llanos. Agricultural and Forest Meteorology, **116**: 197–219.

Shepherd K.D., Cooper P.J.M., Allan A.Y., Drennan D.S.H., Keatinge J.D.H. (1987): Growth, water use and yield of barley in Mediterranean-type environments. Journal of Agricultural Science, **108**: 365–378.

Schulze E.D., Čermák J., Matyssek R., Penka M., Zimmemann R., Vašíček F. (1985): Canopy transpiration and water fluxes in the xylem of the trunk of *Larix* and *Picea* trees – a comparison of xylem flow, porometer and cuvette measurements. Oecologia, **66**: 475–483.

Tatarinov F.A., Kučera J., Cienciala E. (2005): The analysis of physical background of tree sap flow measurement based on thermal methods. Measurement Science and Technology, **16**: 1157–1169.

Woodward F.I., Sheehy J.E. (1983): Principles and Measurements in Environmental Biology. Butterworth & Co., Ltd., London.

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