Water use of winter cereals under well-watered and drought-stressed conditions

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ABSTRACT

A reduction in the water available to plants will lend increasing importance to the dynamics of water uptake and to the water use efficiency (WUE) of cereals. The effect of drought on the water use efficiency of winter cereals was investigated in a greenhouse experiment in the Centre for Agricultural Research. The effect of water deficiency on the water use properties was studied by measuring changes in the grain weight, thousand-kernel weight and aboveground biomass. The water use efficiency of wheat varieties generally ranged from 1.5–2.3 kg/m^3 and 1.06–2.0 kg/m^3 in the case of optimum and limited water supplies, respectively, while these figures were 1.4 kg/m^3 and 0.8 kg/m^3 for winter barley and 0.8 kg/m^3 and 0.5 kg/m^3 for winter oat. Investigation on the relationship between harvest index (HI) and WUE was found that the harvest index is only one indicator of drought tolerance; but the stability of HI under non-optimum environmental conditions also needs to be determined.

Keywords: water uptake; water use efficiency; harvest index; water shortage

The Mediterranean effect is becoming increasingly felt in the climate of the Carpathian Basin, so the region will probably suffer from more frequent droughts in the late spring and summer months (Bartholy and Pongrácz 2007). Shifts in rainfall occurrence and increasingly frequent incidence of water deficiency will be decisive for the development and yield of winter cereals in Central Europe (Barnabás et al. 2008, Brázdil et al. 2009, Jäger 2010).

Maximising water use efficiency (WUE) will be essential in areas where water is the most limiting factor for wheat production (Oweis et al. 2000). Yields can largely be maintained and product quality can be improved in some cases, while substantially reducing the level of water use (Zhang and Oweis 1999). The impact of soil moisture deficit on crop yields depends on the phenological stage of the crop, and the most sensitive stage was found to vary from region to region (Singh and Chauhan 1991) but the grain-filling period has an outstanding importance both for the yield and for WUE (Qiu et al. 2008).

On a global scale the WUE of wheat ranges typically from 0.4 to 2.0 kg/m^3, but there are substantial differences between the regions. While in Texas WUE values of around 0.4 kg/m^3 were recorded under rainfed conditions (Xue et al. 2006), values of 0.5–1.5 kg/m^3 were reported for irrigated fields (Howell et al. 1995). According to Sun et al. (2006), WUE values on the North China Plain are typically 0.97–1.83 kg/m^3.

In the present study the WUE of winter cereals was investigated with the aim of (1) determining the WUE of various species on the basis of the yield and the quantity of water taken up during the growing season; (2) analysing differences in water use in the case of optimum water supplies and simulated drought stress, and (3) revealing how WUE and harvest index (HI) could be utilised to provide a characterisation of the drought tolerance of varieties.

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MATERIAL AND METHODS

Plant materials. Five winter wheat (*Triticum aestivum* L.) genotypes (Mv Toborzó (TOB); Mv Mambo (MAM); Bánkúti 1201 (BKT); Plainsman (PLA) and Cappelle Desprez (CAP)), one winter barley (*Hordeum vulgare* L.) variety (Hanzi (HAN)) and one winter oat (*Avena sativa* L.) variety (Mv Hópehely (HOP)) were examined in greenhouse experiments at the Agricultural Institute, Centre for Agricultural Research in Martonvásár, Hungary. The exact water uptake of the plants was monitored with a digital scale (Mettler Toledo, Budapest, Hungary) from sowing to the final harvest. After 42 days of vernalisation, 8 seedlings were planted in pots containing 10 000 cm^3 of a 3:1:1 (v/v) mixture of soil, sand and humus. Nutrient solution was provided once a week using Volldünger Classic water-soluble fertilizer (Kwizda Agro Ltd., Vienna, Austria). The drought stress was generated by total water withholding for 7 days from the 5^{th} day after heading (Madani et al. 2012, Varga et al. 2012). Weight of the pots was constant at the end of the stress treatments, as the result of which the volumetric soil water content measured using 5TE soil moisture sensors (Decagon Devices Ltd., Pullman, USA) dropped from the control value of 20–25% to 3–5%. The soil water content of the pots given optimum water supplies was maintained at 60% of the water-holding capacity (WHC) of the soil, while the stress-treated plants were watered to 30% of WHC after the 7-day treatment till the final harvest.

Analysis. The effect of water deficiency was studied by measuring changes in the grain weight (GW), thousand-kernel weight (TKW) and aboveground biomass (B). Harvest index (HI) was calculated by dividing the grain yield (kg) by the total aboveground biomass (kg). Water uptake was equivalent to the transpiration of the plants, as the soil was covered with plastic film to prevent evaporation. The water use efficiency (WUE; kg/m^3) was calculated by dividing the grain yield (kg) by the water used during the vegetation period (m^3). One-way analysis of variance was used to determine significant differences among the treatments.

RESULTS

The yield parameters of plants grown with normal water supplies are presented in Table 1. When the water supplies were limited the grain yields of MAM, PLA, CAP and HAN were statistically on par. The grain yields of TOB and BKT were considerably below the wheat average, and HOP had the significantly lowest yield, 50% less than that achieved under optimum conditions (Table 2).

Water withholding caused the greatest yield reduction for the BKT, and the smallest reduction

Table 1. Yield parameters of plants grown with normal water supplies ($\bar{x}$ ± SD)

Plant material	GW/pot		TKW/pot		B/pot		HI/pot	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
MAM	62.71^{a}	3.67	53.83^{a}	6.39	121.7^{a}	10.94	51.68^{a}	3.16
PLA	50.59^{b}	0.91	33.7^{b}	1.1	97.18^{b}	2.52	52.07^{a}	1.04
CAP	58.75^{ab}	9.97	25.03^{c}	4.66	173.95^{c}	15.52	33.66^{b}	3.58
TOB	44.07^{bd}	1.87	41.57^{d}	3.04	77.73^{d}	6.06	56.8^{c}	2.33
BKT	75.87^{c}	5.98	46.01^{e}	1.65	167.32^{c}	13.69	45.35^{d}	0.52
HAN	79.03^{c}	13.16	37.53^{b}	1.7	202.0^{f}	19.68	38.98^{e}	3.42
HOP	39.77^{d}	6	23.53^{f}	0.47	212.0^{f}	2.23	18.74^{f}	2.73
Mean	58.68		37.31		150.27		42.47	
$LSD_{0.05}$	9.35		3.84		15.03		3.35	

Winter wheat genotypes: TOB – Mv Toborzó; MAM – Mv Mambo; BKT – Bánkúti 1201; PLA – Plainsman; CAP – Cappelle Desprez. Winter barley variety: HAN – Hanzi. Winter oat variety: HOP – Mv Hópehely. GW – grain weight (g); TKW – thousand-kernel weight (g); B – aboveground biomass (g); HI – harvest index (%). Values with the same letters within each column did not differ significantly

Table 2. Yield parameters of plants grown with limited water supplies

Plant material	GW/pot		TKW/pot		B/pot		HI/pot	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
MAM	38.30[a]	2.63	41.23[a]	2.84	73.04[a]	7.57	52.63[a]	3.40
PLA	34.38[a]	1.55	26.15[b]	2.45	71.26[a]	3.21	48.25[b]	1.18
CAP	35.97[a]	6.11	24.73[b]	3.36	146.28[b]	4.72	24.52[c]	3.38
TOB	28.29[b]	10.5	33.30[c]	3.16	57.49[a]	4.13	49.28[ab]	1.78
BKT	25.46[b]	6.97	25.13[b]	6.74	90.45[c]	7.80	27.89[c]	5.41
HAN	34.60[a]	5.76	37.17[ac]	3.97	149.80[b]	8.39	23.03[d]	2.91
HOP	19.96[c]	4.02	20.43[e]	0.76	142.90[b]	36.41	14.23[e]	2.11
Mean	30.99		29.73		104.46		34.26	
$LSD_{0.05}$	4.723		4.663		16.144		3.795	

Winter wheat genotypes: TOB – Mv Toborzó; MAM – Mv Mambo; BKT – Bánkúti 1201; PLA – Plainsman; CAP – Cappelle Desprez. Winter barley variety: HAN – Hanzi. Winter oat variety: HOP – Mv Hópehely. Values with the same letters within each column did not differ significantly, figures in bold indicate a significant difference from the values recorded under optimum conditions. GW – grain weight (g); TKW – thousand-kernel weight (g); B – aboveground biomass (g); HI – harvest index (%)

in grain yield was recorded for PLA (32%), but the decrease was less than 40% for all the wheat varieties.

HAN proved to be sensitive to environmental stress, as the yield loss at limited water supplies was 56% compared with the control. Water deficit in the late stages of development caused a significant reduction in TKW for all the varieties with the exception of CAP and HAN.

The TKW of the BKT declined to the greatest extent (45.4%), while the reduction ranged from 19.9–23.4% for the other varieties.

With the exception of MAM, water withholding led to a significant decline in HI. This extremely adaptable variety had better HI under dry conditions even than the drought-tolerant control. Under optimum conditions TOB had an extremely high value of HI, and the 13.2% reduction observed in the case of water withholding was not significantly different from the results recorded for PLA and MAM. The HI values of BKT exhibited an even greater reduction (38.5%) than the drought-sensitive control (27.2%). The relative decline in HI was greatest for the HAN (40.9%), the value of which fell to 23%. The HI of HOP, which was low even under optimum conditions, fell by a further 24% to a value of 14.23% under dry conditions (Table 2).

Analysis of water use parameters. In the case of both water supplies, water uptake of HAN and HOP significantly surpassed that of the wheat varieties (Figure 1). The least water was used in the course of plant development by TOB, which absorbed 24.7% less water than the mean value for the wheat varieties.

When unlimited water was available, the varieties utilised 14.1–17.2% of their total water requirements to the first node appearance. The only exceptions were BKT, where this figure was only 9.7%, and HOP, which utilised 26.1% of the

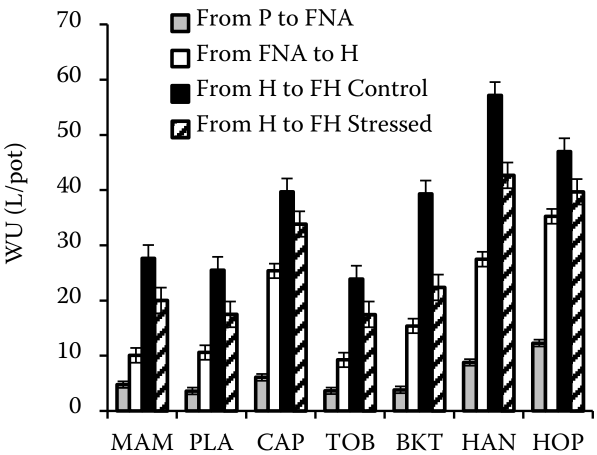

Figure 1. Cumulated water uptake (WU) of cereals in various developmental phases in the case of optimum and limited water supplies. P – planting; FNA – first node appearance; H – heading; FH – final harvest. Winter wheat genotypes: TOB – Mv Toborzó; MAM – Mv Mambo; BKT – Bánkúti 1201; PLA – Plainsman; CAP – Cappelle Desprez. Winter barley variety: HAN – Hanzi. Winter oat variety: HOP – Mv Hópehely

total water quantity during this period. By heading most of the wheat varieties had utilised 36.4–41.5% of their total WU, though a value of 63.9% was obtained for CAP (Figure 1).

When the absolute water quantities were considered it was found that BKT took up almost 54% more water during this period than the mean for MAM, PLA and TOB, while this figure was 154% for CAP. HOP used up 75% of the total water consumption by the heading stage, thus substantially exceeding the ratios recorded for wheat or barley.

As a consequence of water withholding, the water uptake of the wheat varieties over the whole vegetation period dropped by 14.1–42.2%. In the case of HAN and HOP, the decline in water uptake amounted to 23.8% and 16.4%, respectively.

Compared with the water uptake over the whole vegetation period, the quantity consumed up to first node appearance was 30% for HOP, while all the other varieties had values between 17.1% and 23.8% when exposed to drought during the generative phase of development. By heading, stress-treated plants of CAP and HOP had already used up a substantial part of their total water uptake (75% and 88.8%, respectively). The best results were obtained for MAM and TOB: even in the case of stress, these varieties only consumed 50% of their total water uptake by the heading stage. For the varieties PLA, BKT and HAN this value ranged from 60.5–68.8% (Figure 1).

An analysis of the WUE in the case of optimum water supplies showed that MAM had a significantly higher efficiency (2.29 kg/m^3) than the mean for the wheat varieties (Figure 2a). No significant difference was observed between PLA, BKT and TOB, which had WUE values of 1.97, 1.88 and 1.86 kg/m^3, respectively. The WUE of CAP and HAN was considerably poorer than that of the best wheat varieties (1.48 and 1.39 kg/m^3, respectively), while HOP had the significantly lowest value of WUE (0.84 kg/m^3) (Figure 2a). Water deficit after heading led to a significant reduction in WUE, except for the variety PLA (Figure 2b). Despite the significant decrease in the WUE of MAM, the value recorded under dry conditions did not differ significantly from that of PLA. Among the wheat varieties, the greatest reduction in WUE was observed for BKT. In the case of HAN and HOP water withholding led to a further significant reduction in WUE: 41.7% and 40.5%, respectively, compared with the control.

DISCUSSION

Among the environmental factors, water deficit during the reproductive phase of development is the most important limiting factor for winter cereals (Blum 2009). However, if reproductive development is to be successful, it is essential for the plants to maintain their water regime during the generative phase, irrespective of the quantity of biomass achieved during the vegetative phase (Kato et al. 2008). It was established by Morell et al. (2011) that, compared to the water uptake over the whole vegetation period, the ratio of water taken up by winter barley prior to anthesis varied over a wide range, from 31–85%. In the present experiment considerable differences

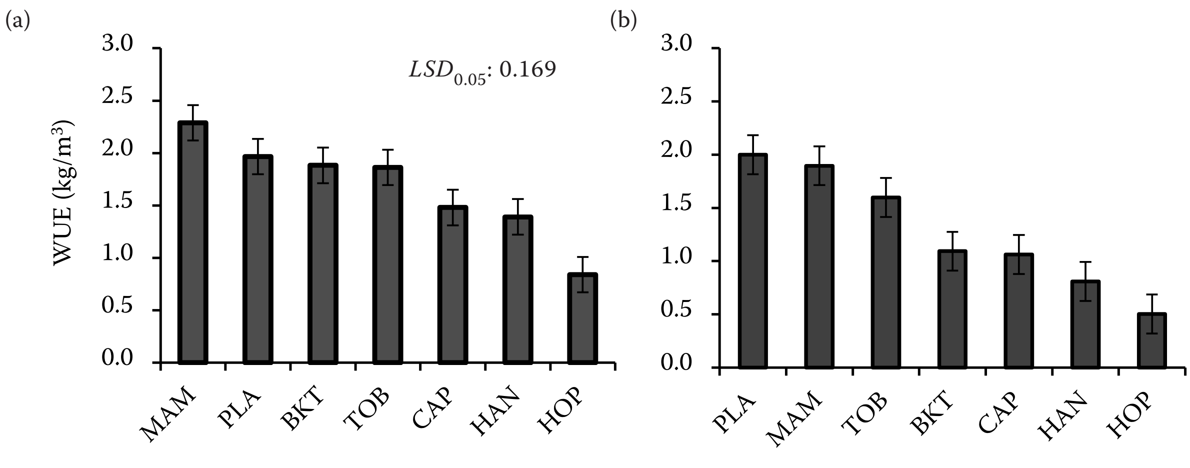

Figure 2. Water use efficiency (WUE) of cereals with optimum (a) and limited (b) water supplies. Winter wheat genotypes: TOB – Mv Toborzó; MAM – Mv Mambo; BKT – Bánkúti 1201; PLA – Plainsman; CAP – Cappelle Desprez. Winter barley variety: HAN – Hanzi. Winter oat variety: HOP – Mv Hópehely

were found between the varieties both at the first node appearance and at heading, regardless of the water supply level.

Araus et al. (2003) reported the presence of a negative correlation between drought tolerance and WUE in the case of limited water supplies. The present results, however, suggest that varieties with good WUE under optimum water supplies have better tolerance of water withholding during the anthesis period, while poor drought tolerance is associated with a substantial drop in WUE.

As drought became more severe and water use declined, there was an increase in WUE, i.e. water deficit resulted in higher WUE values (Peuke et al. 2006). The present results, however, show that this correlation cannot be demonstrated when drought occurs during the later phases of development. As the plants have already taken up a large proportion of the water required for their development, regardless of the variety, and as drought stress results in a considerable decline in yield, the WUE values are typically lower.

Kang et al. (2002) found that WUE increased linearly with HI. When water supplies were withheld, increasing values of HI resulted in better WUE. However Zhang et al. (2008) investigated the correlation between water supplies and HI in winter wheat; they found a reduction in HI parallel to an increase in the water supplies. The present results indicated that, in the case of wheat varieties, changes in HI and WUE paralleled each other, so that HI declined to varying extents in response to water withholding, except for the most drought-tolerant varieties. The drop in HI caused by water withholding in winter barley and winter oats was considerably greater than the change in WUE.

Based on the yield data, Qiu et al. (2008) calculated WUE values of 1.1–2.1 kg/m^3 for winter wheat and stated that the seed-setting and milky ripe stages were the most critical in terms of WUE. The variability in WUE may be substantial even within a variety, primarily due to environmental effects (Angus and van Herwaarden 2001, Sun et al. 2006, Lin et al. 2012). In the case of optimum water supplies and simulated drought at heading, the WUE figures obtained for wheat varieties in the present experiment ranged from 1.5–2.3 kg/m^3 and 1.06–2.0 kg/m^3, respectively, while these values were 1.4 and 0.8 kg/m^3 for winter barley and 0.8 and 0.5 kg/m^3 for winter oats.

It was concluded by Reynolds and Tuberosa (2008) that, as previously suggested by Passioura (1996), water uptake, WUE and HI are all drivers of yield. Blum (2009), on the other hand, while agreeing that WU and HI are drivers of yield, stated that WUE was just a passenger. In the present experiments, the decline in biomass in response to water withholding was less pronounced for some varieties (CAP, HAN, HOP), thus maintaining a high level of water uptake despite the substantial reduction in grain yield. This suggests that the harvest index is an important indicator of drought tolerance and WUE in cereals, but that the stability of HI under sub-optimum environmental conditions should also be investigated if the adaptability of individual varieties is to be determined.

In conclusion, (1) WUE of the wheat varieties equalled or in some cases even exceeded that of the drought sensitive control genotype. WUE of the old Hungarian genotype and the modern varieties was similar under optimum irrigation, but the WUE dropped to the level of the drought sensitive control as the result of water shortage. WUE of winter barley and especially of winter oat was significantly lower than that of the winter wheat varieties. (2) Water shortage simulated after heading resulted in a decrease in WUE. Winter barley and winter oat utilized the major proportion of the total water use by the end of the vegetative phase, so in the case of dry period there is not only a loss of yield but also an intense decrease in the soil moisture available to subsequent crops. (3) It was concluded that the HI should be determined at different water supply levels to characterise the drought tolerance of the genotypes. Results showed that modern varieties with a good WUE at optimal water supply have the best drought tolerance when stress is occurring in the period of the anthesis.

REFERENCES

Angus J.F., van Herwaarden A.F. (2001): Increasing water use and water use efficiency in dryland wheat. Agronomy Journal, *93*: 290–298.

Araus J.L., Villegas D., Aparicio N., García del Moral L.F., El Hani S., Rharrabti Y., Ferrio J.P., Royo C. (2003): Environmental factors determining carbon isotope discrimination and yield in durum wheat under Mediterranean conditions. Crop Science, *43*: 170–180.

Barnabás B., Jäger K., Fehér A. (2008): The effect of drought and heat stress on reproductive processes in cereals. Plant, Cell and Environment, *31*: 11–38.

Bartholy J., Pongrácz R. (2007): Regional analysis of extreme temperature and precipitation indices for the Carpathian Basin from 1946 to 2001. Global and Planetary Change, *57*: 83–95.

Blum A. (2009): Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Research, *112*: 119–123.

Brázdil R., Trnka M., Dobrovolný P., Chromá K., Hlavinka P., Žalud Z. (2009): Variability of droughts in the Czech Republic, 1881–2006. Theoretical and Applied Climatology, *97*: 297–315.

Howell T.A., Steiner J.L., Schneider A.D., Evert S.R. (1995): Evapotranspiration of irrigated winter wheat – Southern high plains. Transactions of the ASAE, *38*: 745–759.

Jäger K. (2010): Simultaneous water withholding and elevated temperature alters embryo and endosperm development in wheat. Acta Agronomica Hungarica, *58*: 91–95.

Kang S., Zhang L., Liang Y., Hu X., Cai H., Gu B. (2002): Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. Agricultural Water Management, *55*: 203–216.

Kato Y., Kamoshita A., Yamagishi J. (2008): Preflowering abortion reduces spiklet number in upland rice (*Oryza sativa* L.) under water stress. Crop Science, *48*: 2389–2395.

Lin Y., Zeng Z., Ren C., Hu Y. (2012): Water use efficiency and physiological responses of oat under alternate partial root-zone irrigation in the semiarid areas of Northeast China. Procedia Engineering, *28*: 33–42.

Madani A., Makarem A.H., Vazin F., Joudi M. (2012): The impact of post-anthesis nitrogen and water availability on yield formation of winter wheat. Plant, Soil and Environment, *58*: 9–14.

Morell F.J., Lampurlanés J., Álvaro-Fuentes J., Cantero-Martínez C. (2011): Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization. Soil and Tillang Research, *117*: 76–84.

Oweis T., Zhang H., Pala M. (2000): Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. Agronomy Journal, *92*: 231–238.

Passioura J.B. (1996): Drought and drought tolerance. Plant Growth Regulation, *20*: 79–83.

Peuke A.D., Gessler A., Rennenberg H. (2006): The effect of drought on C and N stable isotopes in different fractions of leaves, stems and roots of sensitive and tolerant beech ecotypes. Plant, Cell and Environment, *29*: 823–835.

Qiu G.Y., Wang L., He X., Zhang X., Chen S., Chen J., Yang Y. (2008): Water use efficiency and evapotranspiraton of winter wheat and its response to irrigation regime in the north China plain. Agricultural and Forest Meteorology, *148*: 1848–1859.

Reynolds M., Tuberosa R. (2008): Translational research impacting on crop productivity in drought-prone environments. Current Opinion in Plant Biology, *11*: 171–179.

Singh R.V., Chauhan S.P.S. (1991): Response of barley to the levels and sources of nitrogen with and without zinc in relation to yield and water use under dryland conditions. Bhartiya Krishi Anusandhan Patrika, *6*: 43–48.

Sun H.Y., Liu C.M., Zhang X.Y., Shen Y.J., Zhang Y.Q. (2006): Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. Agricultural Water Management, *85*: 211–218.

Varga B., Janda T., László E., Veisz O. (2012): Influence of abiotic stresses on the antioxidant enzyme activity of cereals. Acta Physiologiae Plantarum, *34*: 849–858.

Xue Q., Zhu Z., Musick J.T., Stewart B.A., Dusek D.A. (2006): Physiological mechanisms contributing to the increased water-use efficiency in winter wheat under deficit irrigation. Journal of Plant Physiology, *163*: 154–164.

Zhang H., Oweis T. (1999): Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agricultural Water Management, *38*: 195–211.

Zhang X., Chen S., Sun H., Pei D., Wang Y. (2008): Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. Irrigation Science, *27*: 1–10.

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