# Drought Stress Tolerance of Two Wheat Genotypes

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**Abstract**: Biotic and abiotic stress effects can limit the productivity of plants to great extent. In Hungary, drought is one of the most important constrains of biomass production, even at the present climatic conditions. The climate change scenarios, developed for the Carpathian basin for the nearest future predict further decrease in surface water resources. Consequently, it is essential to develop drought stress tolerant wheat genotypes to ensure sustainable and productive wheat production under changed climate conditions. The aim of the present study was to compare the stress tolerance of two winter wheat genotypes at two different scales. Soil water regime and development of plants, grown in a pot experiment and in large undisturbed soil columns were evaluated. The pot experiments were carried out in a climatic room in three replicates. GK Élet wheat genotype was planted in six, and Mv Emese in other six pots. Two pots were left without plant for evaporation studies. Based on the mass of the soil columns without plant the evaporation from the bare soil surface was calculated in order to distinguish the evaporation and the transpiration with appropriate precision. A complex stress diagnosis system was developed to monitor the water balance elements. $ECH_2O$ type capacitive soil moisture probes were installed in each of the pots to perform soil water content measurements four times a day. The irrigation demand was determined according to the hydrolimits, derived from soil hydrophysical properties. In case of both genotypes three plants were provided with the optimum water supply, while the other three ones were drought-stressed. In the undisturbed soil columns, the same wheat genotypes were sawn in one replicate. Similar watering strategy was applied. TDR soil moisture probes were installed in the soil at various depths to monitor changes in soil water content. In order to study the drought stress reaction of the wheat plants, microsensors of 1.6 mm diameter were implanted into the stems and connected to a quadrupole mass spectrometer for gas analysis. The stress status was indicated in the plants grown on partly non-irrigated soil columns by the lower $CO_2$ level at both genotypes. It was concluded that the developed stress diagnosis system could be used for soil water balance elements calculations. This enables more precise estimation of plant water consumption in order to evaluate the drought sensitivity of different wheat genotypes.

**Keywords**: drought stress; wheat genotypes; gas metabolism; soil water content; stress diagnosis system

Plants are exposed to a large variety of biotic and abiotic stress effects, which limit their productivity (Hegedüs *et al.* 2004). In vitro selection for stress tolerance has a significant importance in the strategy of establishing plant systems with optimal stress reaction and productivity. In Hungary, drought is one of the most important constrains of biomass production (Várallyay 2005) even

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at the present climate (Farkas *et al.* 2005). The climate change scenarios, developed for the Carpathian basin for the nearest future predict further decrease in surface water resources (Bartholy *et al*. 2007). Hence, selection and development of new drought stress tolerant wheat genotypes that can adapt to the expected consequences of climate change is essential to ensure sustainable and productive wheat production in the future (Hagyó *et al*. 2007).

Drought and heat tolerance of different wheat genotypes are determined in stress diagnostic systems of different types (Pant *et al*. 1998; Djilianov *et al*. 2005). In the glasshouse stress diagnostic (Djilianov *et al*. 2005), a large number (hundreds) of pots are used, therefore the precise and continuous monitoring of soil water balance elements would be very expensive and time-consuming. On the other hand, the main disadvantage of plot-scaled field stress diagnosis systems (Pant *et al.* 1998) is that they are performed in few replicates and difficult to reproduce due to uncontrolled weather conditions. Hence, the harmonisation of the results, obtained from stress diagnosis systems carried out at different scales using various irrigation strategies and methods to determine the water use efficiency of the plants still calls for further attention.

Experiments on large soil columns can be viewed as an intermediate situation between the laboratory pot experiments and small-scale field plots, with the advantages and disadvantages of both. This experimental technique may be suitable for simulation of field conditions covering the whole lifetime of the selected crop. On the other hand, stress diagnosis systems functioning in climatic rooms under controlled conditions could provide precise complementary data on soil water balance elements (Hagyó *et al*. 2007).

The aim of the present study was to develop a multi-scale complex stress diagnostic system based on water balance calculation with smaller pot number to obtain supplementary data that would help the evaluation of the data obtained from glasshouse and field stress diagnostic systems. Further objectives were to link the gap between the water balance calculations from greenhouse experiments and the precise soil water balance measurement techniques. The advantage of the applied methods is that the stress tolerance of the individual wheat genotypes could be quantified using precise calculations of the water balance in the soil-plant system. In wildly used laboratory and greenhouse stress diagnosis systems the drought stress tolerance of the plants is characterised by either water saturation deficiency (WSD) calculated from the relative water content of either the soil (Gáspár *et al.* 2005) the plant (Wiśniewski & Zagdańska 2001) or relative drought index (proportion of actual and critical WSD values) (Kikuta 2005). Still, it does not allow precise comparison of the amounts of water, consumed by the plant because there is no account for evaporation from the soil surface. Moreover, the soil water content in such experiments is determined on mass and not volume base, because the bulk density of the soil in the pots is unknown.

This paper presents results of drought stress studies of different winter wheat genotypes obtained from a multi-scale stress diagnosis system incorporating large undisturbed soil monoliths and small pots placed in a climatic room. For the latter, precise water balance calculations were performed in order to quantify the drought stress tolerance of the different genotypes.

In the monoliths, gas metabolism of plants' reproductive stage (accumulation/consumption of respiratory gases inside plant tissues) was followed by a quadrupole mass spectrometric (QMS) method *in situ* and *in vivo* (Pártay *et al.* 2000; Lukács *et al.* 2005) and soil moisture was monitored (by the TDR method). In the smaller pot experiment precise water balance determination was executed in a climatic room under controlled conditions (Hagyó *et al*. 2007).

## MATERIAL AND METHODS

The multi-scale experiments were carried out on soil columns, taken from the Kecskés experimental station of the Cereal Research Nonprofit Company, Szeged, Hungary. The soil type was defined as Chernozem, with main soil properties given in Table 1. At the experimental site, preliminary measurements using electromagnetic induction probe were performed to select a homogeneous area for soil sampling.

For the large soil column experiments, ten undisturbed, 0.42 m diameter, 0.8 m long soil monoliths were prepared according to Németh *et al.* (1991). The monoliths were excavated at the selected field site and their cylindrical surfaces were coated with fibreglass cloth impregnated with a synthetic resin. The advantage of this technique is that it ensures

Table 1. Chemical and physical properties of the meadow Chernozem soil

| Genetic horizon | Depth (m) | pH ($H_2O$) | $CaCO_3$ (%) | OM (%) | EC (µS/cm) | CEC ($cmol_c$/kg) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|---|
| $A_{sz}$ | 0–0.18 | 8.24 | 7.7 | 3.16 | 191 | 17.34 | 22.7 | 22.6 |
| A | 0.18–0.30 | 8.24 | 12.1 | 2.58 | 198 | 15.87 | 22.9 | 24.0 |
| B | 0.30–0.54 | 8.39 | 13.8 | 1.37 | 192 | 11.74 | 21.8 | 29.7 |
| C1 | 0.54–0.92 | 8.69 | 30.9 | 0.31 | 312 | 7.66 | 24.1 | 19.8 |

EC – electrical conductivity measured in the saturation extract; CEC – cation exchange capacity; OM – organic matter content

a very close contact between the outer layers of the soil column and the material of the coating. Part of the coating imbibes the outer macrospores, creating a continuum between the soil and the coating, thus the wall effects are reduced.

The monoliths were transported to the greenhouse of the Research Institute for Soil Science and Agricultural Chemistry of HAS (RISSAC). Here further preparations were made: a tap was inserted into the lowest part of each column and then the bottoms of the monoliths were coated with fibreglass-resin. The monoliths firstly were saturated by slowly filling them up with deionised water through the built-in bottom tap and then were drained out to field capacity. Saturation was done with rising water level. For the first series of experiments four monoliths were used. In October 2005, 30 seeds of winter wheat (*Triticum aestivum* L.) were sown into each soil column. Two genotypes, Gk Élet and Mv Emese were used and grown as test plants till maturity. The GK Élet genotype is the breed of the Cereal Research Non-Profit Company. Its drought tolerance is medium. The Mv Emese is the breed of the Agricultural Research Institute of the Hungarian Academy of Sciences, with drought tolerance, classified as excellent. As winter wheat must go through a prolonged period of cold (vernalization) before flowering occurs, the monoliths were kept outside until the following spring (May 2006) to ensure conditions, close to natural ones. No irrigation was made during this period, but the columns received all the natural winter precipitation. In the meantime the number of plants/column had been reduced to five. At the time of heading, when the stems of the plants had reached sufficient thickness to ensure the implantation of the sensors for gas analysis, the monoliths were transported in the laboratory.

To ensure suitable for the plants conditions, sufficient light (21 000 lux) was ensured in 12 hours day/night cycles. Temperature of the air at various heights and in the soil at various depths (0, 0.10 and 0.35 m) was recorded daily. The soil moisture regime was determined by TDR (Time Domain Reflectometry) sensors (TDR multiplexer system) (Rajkai 2004), placed horizontally at 0.10, 0.30 and 0.50 m depths and vertically in the 0–0.20 m layer of each soil column. Irrigation was applied at the soil surface once a day on the basis of TDR data to ensure optimum soil water conditions except for columns subjected to drought stress. Gas concentrations of the soil and plants and laboratory air were continuously measured by the 20 channel QMS apparatus (Pártay *et al.* 2000; Lukács *et al.* 2005). Relative amounts of water vapor, nitrogen, oxygen, carbon-dioxide and argon were determined. Laboratory air served as standard, argon as control. Both the soil moisture and gas concentration measurements were made in 4-hour intervals.

The microsensors, inserted in the stems (Figure 1) were made of stainless steel tube of 0.20 m length and $1.65 \times 10^{-3}$ m diameter. One end of this tube is closed by soldering and perforated on two sides for 0.02 m length. A 0.02 m long tube of silicone rubber, which serves as a membrane, covers these perforations. The implantation of the micro-sensor into the stem of the wheat plant

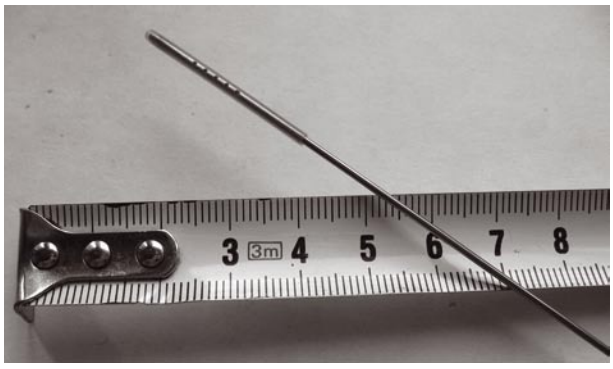


Figure 1. Microsensor used in QMS measurements

was preceded by the preparation of a channel in the plant tissue with the help of a punctuation needle of appropriate diameter. After the sensor had been inserted, the rim of the hole was packed with plastic material for airtight sealing and the sensor-tube was fixed to the stem of the plant to prevent later movement of the sensor. In each of the columns, four sensors (three inserted in the plants and one in the soil) were used.

In the laboratory pot experiment, the soil originated from the same sampling site as for the monolith experiment. In total, 14 identical plexi boxes with a volume of $7.2 \times 10^{-3}$ m$^3$ (0.15 m × 0.15 m × 0.32 m) were filled with air-dried soil at given dry soil bulk density ($1.18 \times 10^3$ kg/m$^3$). GK Élet wheat genotype was planted in six and Mv Emese in other six boxes. Two soil columns were left without any plants. An irrigation strategy was developed according to the hydrolimits, derived from soil hydrophysical properties (Štekauerová *et al.* 2002, 2006). The field capacity of the soil was 0.38, while the wilting point was found to be 0.06 m$^3$/m$^3$. In case of both genotypes, three plants were provided with optimum water supply (by ensuring soil water content between 0.6 FC and 1.0 FC, where FC is the field capacity) while the other three were drought-stressed (by keeping the soil water content around 0.2 FC). One of the soil columns without crop was irrigated according to the optimum, while the other one according to the drought-stressed irrigation strategy. The total amount of water in each pot was monitored by mass measurements 2–3 times per week. Soil water content was measured by 0.10 m long ECH2O capacitive soil moisture sensors (Campbell 2006), previously calibrated to the given soil. In each pot, two sensors were installed vertically into 0.05–0.15 and 0.20–0.30 m soil layers. The soil water content was recorded every 4 hours. The pots were placed in a climatic room with controlled temperature, air humidity, wind speed and light conditions. The air movement was permanent; it was equivalent to a wind velocity of 2–3 m/s. The air temperature and relative humidity of the air were registered every 30 minutes with a sensor placed at the height of the plants. The mean air temperature was 21.8°C and it ranged between 19.8°C and 24.5°C. The relative air humidity was evenly 83%. The potential evapotranspiration (PET) was determined by pan evaporation method (Szász 1997). Figure 2 (left) demonstrates the calculation of the daily average value of PET from the measured data.

The initial soil water content of the pots with non-stressed plants was preset by filling up the soil columns with water until saturation and then draining the water out of the boxes until reaching field capacity (FC). Since the initial water content of FC had been proved to be too high for obtaining stress during the experiment, the pots of the stressed plants were filled up with soil previously wetted to soil moisture content of 0.20 m$^3$/m$^3$ in average for the whole soil column.

Actual transpiration (TR) was determined from precise water balance calculations using the water balance equation written for the pots:

$$TR = I - E - \Delta w \times V \quad (1)$$

where:

$\Delta w \times V$ – change in the total amount of water in the soil column ($10^{-3}$ m$^3$)

$w$ – actual soil water content (m$^3$/m$^3$)

$V$ – volume of the soil column ($7.2 \times 10^{-3}$ m$^3$)

I – irrigation water amount calculated according to the irrigation strategy ($10^{-3}$ m$^3$)

E – actual evaporation from bare soil surface, calculated from Eq. (2) ($10^{-3}$ m$^3$)

TR – actual plant transpiration ($10^{-3}$ m$^3$)

$\Delta w \times V$ was calculated from both, the pot mass and the soil water content measurements. E was determined from the mass measurements of the soil columns without plants using the Varga-Haszonits empirical equation (Varga-Haszonits 1987):

$$E = \frac{PE}{1+e^{a+b\left(\frac{w}{w_{Max}}\right)}} \quad (2)$$

where:

E – actual evaporation from bare soil surface ($10^{-3}$ m$^3$)

PE – potential soil evaporation ($10^{-3}$ m$^3$)

$w$ – actual soil water content (m$^3$/m$^3$)

$w_{Max}$ – soil water content at saturation (0.42 m$^3$/m$^3$)

PE was determined from mass measurements of the pot that did not contain plant according to Figure 2 (right). The empirical coefficients $a$ and $b$ were chosen according to those, suggested by Varga-Haszonits for winter wheat (Varga-Haszonits 1987). Thus, $a$ and $b$ were equal to 4.2 and –8.6, respectively. TR was calculated as the remaining element of the water balance equation.

For the small-scale laboratory experiment, differences in water balance elements attributed to

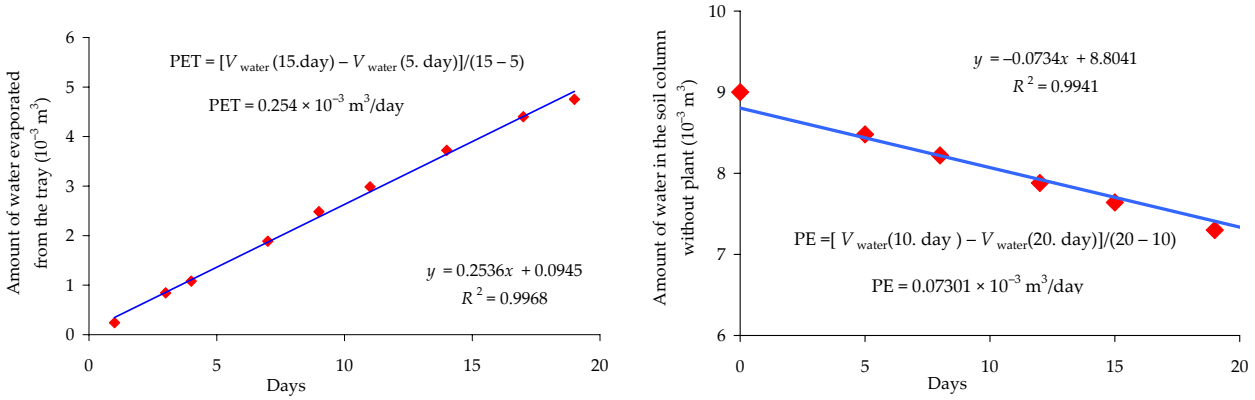


Figure 2. Calculation of the daily average potential evapotranspiration (PET, left) and daily average potential soil evaporation (PE, right) values from evapotranspiration tray and bare soil column mass measurements, respectively

different genotypes were analysed by ANOVA. The F statistics was used to separate significant differences in response parameters. Significance is indicated at $P < 0.05$.

## RESULTS AND DISCUSSION

### Large soil column experiments

The laboratory experiments on large undisturbed soil columns lasted 45 days – from the start of heading to the dying stage. Temporal changes in soil water content measured by TDR sensors for both wheat genotypes are shown in Figure 3. The irrigation of the stressed plants was stopped after the first week, resulting in 11 600 ml irrigation water deficit per column compared to the non-stressed treatment. The 0–0.20 m surface layer showed the highest drop of moisture content after the end of irrigation. Although the average temperature was 32°C in the air 1m above the soil surface and 29°C in the soil 0.1 m below the surface, the moisture level of the 0.1–0.5 m layers only slightly decreased. Thus, for the Mv Emese genotype the differences between the soil water contents, measured in the stressed and non-stressed columns at 0.3 and 0.5 m

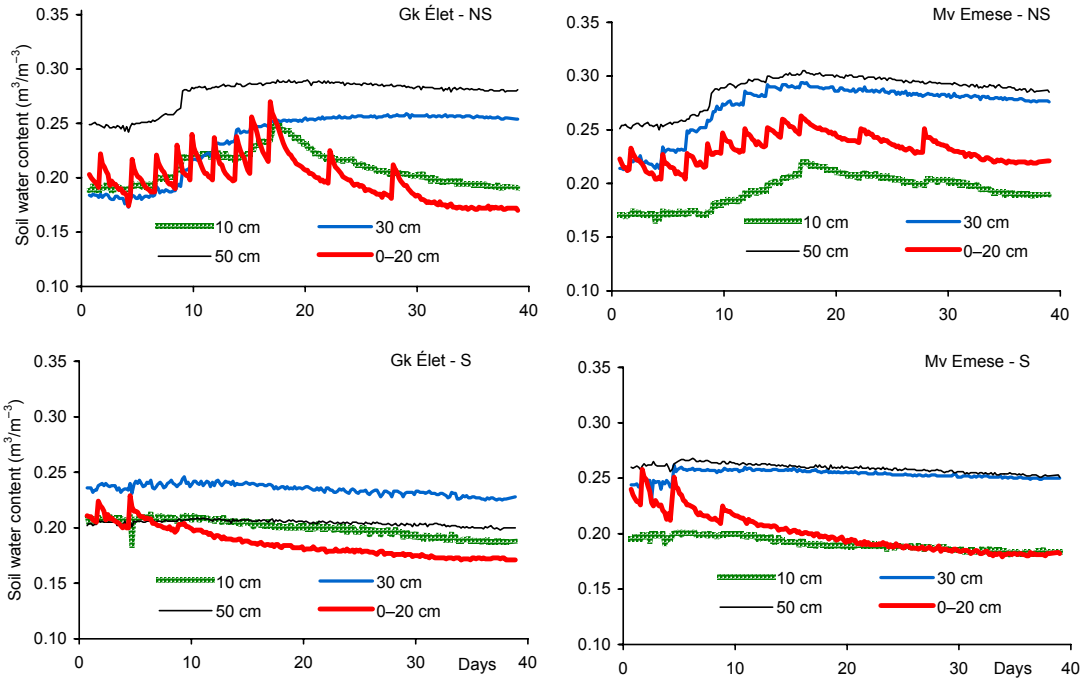


Figure 3. Soil water content dynamics ($m^3/m^3$) measured by TDR sensors in the irrigated (NS) and non-irrigated (S) large undisturbed soil monoliths with the two wheat genotypes

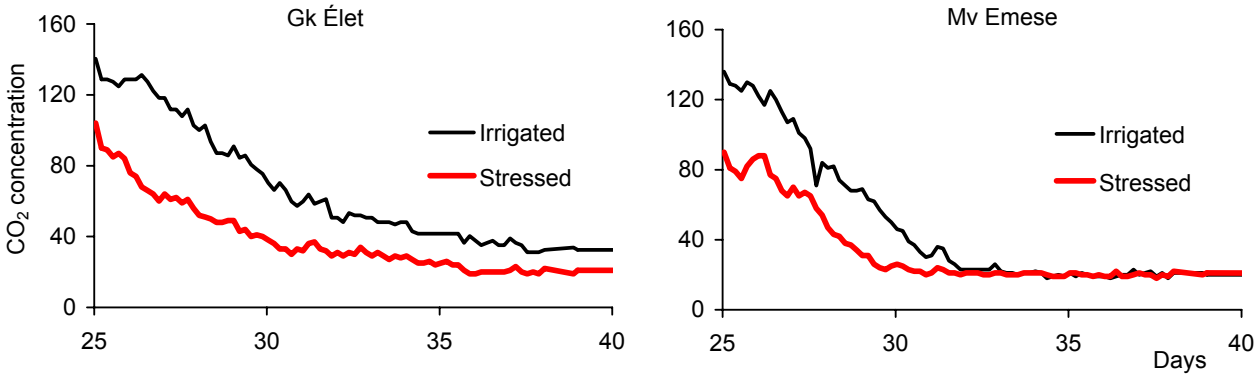


Figure 4. $CO_2$ concentration changes (in arbitrary units) in the stem of the irrigated (NS) and non-irrigated (S) test plants of Gk Élet and Mv Emese during the last two weeks of the experiment

depths were less than 0.05 $m^3/m^3$. Consequently, the water uptake of the plants from the soil was almost the same as in the non-stressed (irrigated) columns. We assume that capillary rise could supply sufficient amount of water for the plants in the non-irrigated treatments.

The $CO_2$ concentration changes in the plants as well as in the soil columns were measured using microsensors. Figure 4 shows the typical $CO_2$ curve of the last two weeks of the plants' life. When the $CO_2$ concentration dropped to the level of that measured in air, the plant died. In contradiction to the phenological observations, slight stress status was indicated in the plants grown on partly non-irrigated soil columns by the lower $CO_2$ level at both genotypes (Figure 4).

The concentration levels of the other gases measured in the plants were constant throughout the experiment with daily fluctuations of $O_2$. The order of gas concentrations was the following: water-vapor > $N_2$ > > $O_2$ > $CO_2$.

Our results indicate that the occurrence of drought stress can be detected by gas concentration measurements in the stem earlier, than any phenological changes could be observed.

### Laboratory pot experiments

The initial soil water content conditions, set up in the laboratory pot experiment, were different from those, used in the large monolith experiment. Since the pots were filled up manually, the initial soil water contents could precisely be fixed. Thus, when starting the laboratory pot experiment (1st day) the total amount of water (TSW) (Figure 5) in the non-stressed boxes (2360–2470 ml) was almost double of that in the stressed boxes (1260–1270 ml). Still, on Day 25 the total amount of soil water in the non-stressed boxes was less than in the stressed treatments probably because until that day the irrigation amount was similar in both the treatments to ensure stabile plant development until the tillering phase and because the root system was more developed under favourable non-stressed conditions. Consequently, the wheat development was better in the non-stressed (NS) treatments resulting in increased evapotranspiration compared to the plants in the stressed (S) treatments. After starting the irrigation, the total soil water in the NS pots was somewhat higher than in the S pots, but it was still much lower than the field capacity, most probably due to intensive evaporation and transpiration. In stressed and non-stressed treatments the observed differences in TSW were statistically significant mainly between days 12–25 and 29–40, respectively (Table 2). Thus, the processes governing the soil drying were different between the two wheat genotypes in the stressed treatments, probably because of observed differences in root distribution (Csorba 2007) and, consequently, plant water uptake. Once the soil water content was close to wilting point no differences between the TSW values of the stressed treatments were found. In treatments with optimal water supply no significant differences between the TSW during the long drying period were found, most probably because the initial soil water content was much higher in these pots and no drought stress occurred in the beginning of the experiment. However, statistically significant differences between the TSW of the soil columns under the two genotypes were found after the first irrigation event, which indicates, that the redistribution

Table 2. Mean values and statistical evaluation of the soil water balance elements determined for chosen days for the small-scale experiment in treatments with optimum water supply and in the stressed treatments

| Days | TSW ($10^{-3}$ $m^3$) 0–32 cm | | Soil water content ($m^3/m^3$) | | | |
|---|---|---|---|---|---|---|
| | | | 0–10 cm | | 20–30 cm | |
| | Gk Élet | Mv Emese | Gk Élet | Mv Emese | Gk Élet | Mv Emese |
| **Non-stressed treatments** | | | | | | |
| 1 | 2.36 a | 2.47 a | 0.37 a | 0.37 a | 0.34 a | 0.37 b |
| 5 | 1.96 a | 2.01 a | 0.36 a | 0.31 b | 0.32 a | 0.28 b |
| 8 | ***1.74*** a | ***1.81*** b | 0.36 a | 0.30 b | 0.31 a | 0.27 b |
| 12 | 1.45 a | 1.43 a | 0.34 a | 0.29 b | 0.29 a | 0.26 b |
| 15 | 1.15 a | 1.13 a | 0.32 a | 0.27 b | 0.27 a | 0.23 b |
| 19 | 0.91 a | 0.88 a | 0.29 a | 0.24 b | 0.24 a | 0.21 b |
| **25** | 0.72 a | 0.75 a | 0.25 a | 0.21 b | 0.20 a | 0.15 b |
| **29** | ***1.11*** a | ***1.06*** b | 0.23 a | 0.20 b | 0.18 a | 0.13 b |
| 32 | ***1.15*** a | ***1.31*** b | 0.34 a | 0.29 b | 0.26 a | 0.21 b |
| **35** | ***1.12*** a | ***1.24*** b | 0.34 a | 0.29 b | 0.27 a | 0.24 b |
| 40 | ***0.75*** a | ***0.85*** b | 0.30 a | 0.25 b | 0.26 a | 0.22 b |
| **42** | 1.33 a | 1.35 a | 0.30 a | 0.24 b | 0.27 a | 0.23 b |
| **45** | 1.15 a | 1.13 a | 0.27 a | 0.22 b | 0.23 a | 0.19 b |
| **48** | 1.05 a | 1.05 a | 0.30 a | 0.24 b | 0.27 a | 0.23 b |
| **52** | 0.59 a | 0.61 a | 0.28 a | 0.22 b | 0.25 a | 0.21 b |
| **55** | 1.15 a | 1.17 a | 0.28 a | 0.22 b | 0.25 a | 0.20 b |
| 59 | ***0.89*** a | ***0.85*** b | 0.23 a | 0.20 b | 0.26 a | 0.21 b |
| **Stressed treatments** | | | | | | |
| 1 | 1.26 a | 1.27 a | 0.24 a | 0.25 a | 0.13 a | 0.17 b |
| 5 | 1.23 a | 1.20 a | 0.24 a | 0.25 a | 0.13 a | 0.17 b |
| 8 | 1.17 a | 1.16 a | 0.23 a | 0.24 a | 0.11 a | 0.17 b |
| 12 | ***1.17*** a | ***1.14*** b | 0.24 a | 0.24 a | 0.10 a | 0.17 b |
| 15 | ***1.01*** a | ***0.93*** b | 0.23 a | 0.23 a | 0.10 a | 0.15 a |
| 19 | ***1.01*** a | ***0.93*** b | 0.22 a | 0.22 a | 0.10 a | 0.14 a |
| **25** | ***1.18*** a | ***1.00*** b | 0.22 a | 0.21 a | 0.13 a | 0.15 a |
| 29 | 0.86 a | 0.88 a | 0.22 a | 0.22 a | 0.13 a | 0.13 a |
| 32 | 0.78 a | 0.77 a | 0.22 a | 0.22 a | 0.13 a | 0.13 a |
| 35 | 0.69 a | 0.67 a | 0.21 a | 0.20 a | 0.12 a | 0.13 a |
| 40 | 0.61 a | 0.59 a | 0.20 a | 0.18 a | 0.12 a | 0.13 a |
| 42 | ***0.57*** a | ***0.52*** b | 0.20 a | 0.18 a | 0.12 a | 0.12 a |
| **45** | 0.57 a | 0.55 a | 0.18 a | 0.17 a | 0.12 a | 0.09 a |
| 48 | 0.49 a | 0.50 a | 0.19 a | 0.16 a | 0.11 a | 0.10 a |
| **52** | 0.45 a | 0.47 a | 0.17 a | 0.16 a | 0.11 a | 0.10 a |
| 55 | ***0.57*** a | ***0.61*** b | 0.17 a | 0.15 a | 0.11 a | 0.10 a |
| **59** | 0.60 a | 0.62 a | 0.14 a | 0.15 a | 0.09 a | 0.10 a |

TSW – total amount of water

Days printed in bold correspond to days with irrigation according to the irrigation strategy; in case of TSW, statistical differences between the two wheat genotypes are indicated by italics; mean values, corresponding to the same day but different wheat genotypes are significantly different at a probability level $P < 0.05$, if the same lower case letters do not follow them

of available water between the soil water balance elements could be different.

Variation in soil water contents in the stressed and non-stressed treatments could be observed in both the upper and the lower soil layers (Figure 6). The mean differences between the soil water contents in the 0.0–0.1 m layers of the stressed and non-stressed treatments after the 25th day (start of irrigation) of the experiment were 0.07 and 0.11 $m^3/m^3$ in the pots with Gk Élet and Mv Emese, respectively. In the 0.2–0.3 m layer these differences exceeded 0.08 and 0.15 $m^3/m^3$, correspondingly. Statistical evaluation of the data indicated, that the measured differences between the soil water contents under the two wheat genotypes were significant during the monitoring period (Table 2) in both the soil layers. Regarding the stressed treatments, the soil water content was close to the wilting point, the soil could not dry out more and no water from the poor irrigation exceeded the deeper soil layers. Consequently, no significant differences between the soil water regimes under the two different genotypes were found (Table 2).

In case of NS pots, the irrigation events could be identified not only in the topsoil, but in the 0.2–0.3 m soil layer as well, which indicates that the irrigation water reached the deeper soil horizons. Regarding the stressed treatments, the soil in the 0.2–0.3 m layer was very dry, reaching the wilting point by the end of the experiment.

Dissimilarities in soil water regimes observed in similar treatments of the two genotypes could be explained by differences in rooting depths and root distributions as well as in water consumption. Phenological differences between the two wheat genotypes could be observed in the length of each phenological stage as well as in the development of roots, leaves and ears (data not shown) (Csorba 2007). The observed differences between the soil water contents, however, could only be explained by precise soil water balance calculations.

Valuable differences between the soil water balance elements of the pots under the two different wheat genotypes were observed, especially for NS treatments (Table 2). Table 3 demonstrates the average results of the soil water balance elements, obtained for a 58-day period from the three replicates.

The evaporation from the soil surface (E) was lower (by 348 and 73 × $10^{-3}$ $m^3$) in pots with Mv Emese genotype in both, NS and S treatments. The calculated transpiration values (TR) were higher for the Mv Emese genotype compared to the Gk Élet genotype in all the cases. The amount of irrigation water (I), required to maintain optimum soil water conditions (NS case) was much smaller (by 360 × $10^{-3}$ $m^3$ in average) in case of Mv Emese genotype. Moreover, the TR/I ratio, that shows the efficiency of the crop to use the irrigation water was higher for the Mv Emese than for the Gk Élet genotype.

These results indicate that from the two studied winter wheat genotypes, Mv Emese has better drought stress tolerance.

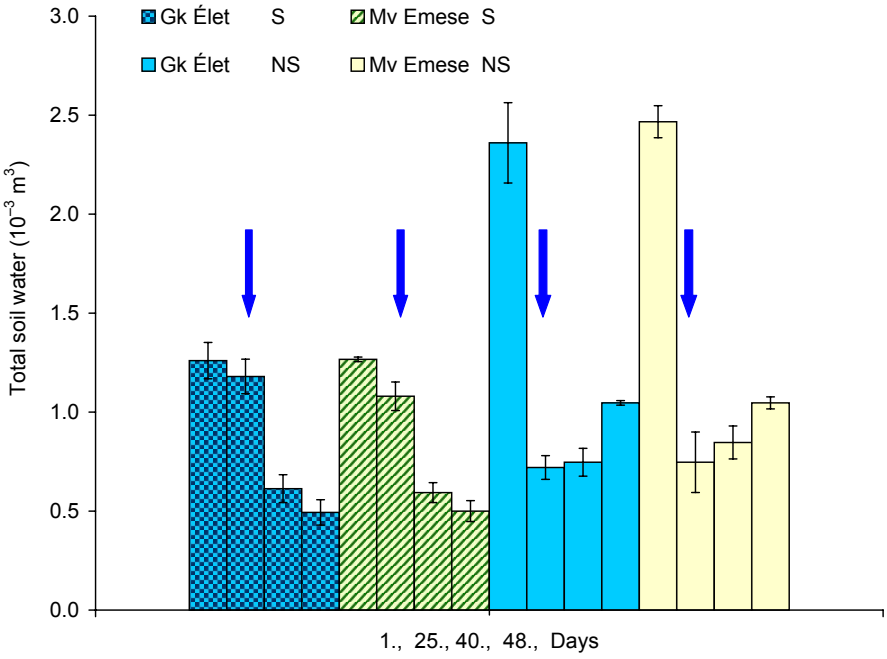


Figure 5. Total soil water content of the soil columns (ml, average and standard deviation), measured in the laboratory pot experiment at chosen days. The arrows refer to the start of the irrigation according to the irrigation strategy; NS refers to irrigated, S to non-irrigated plants

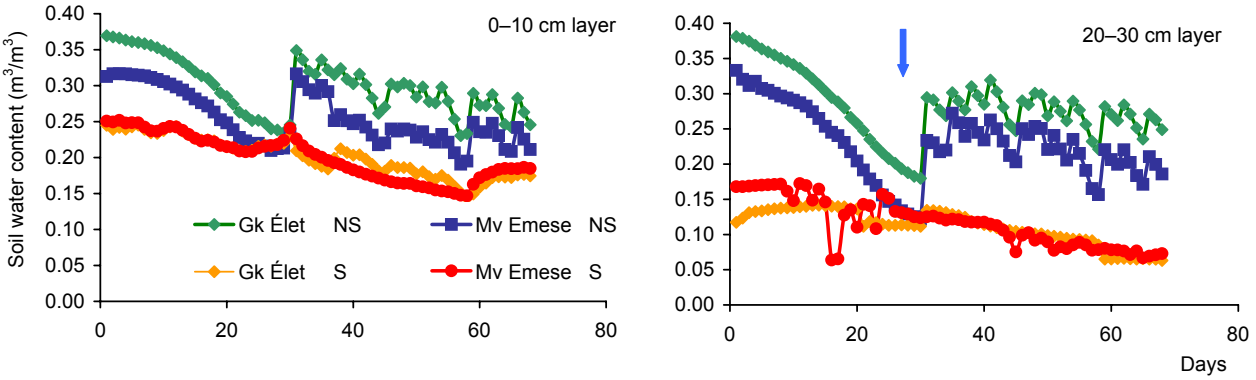


Figure 6. Soil water content dynamics ($m^3/m^3$, average of the three replicates) in the laboratory pot experiment; the arrows refer to the start of the irrigation according to the irrigation strategy; NS refers to irrigated, S to non-irrigated plants

## CONCLUSIONS

In the large soil column experiments the Gk Élet and Mv Emese wheat genotypes were able to compensate the water stress caused by the lack of irrigation due to high water conductivity and water retention of the Chernozem soil. Similarly and consequently there were no differences in the yield data. However, slight stress was indicated by the $CO_2$ concentration changes in the plants of the non-irrigated columns compared to the irrigated ones, indicating that the drought stress could be detected by stem gas analysis earlier than by phenological observations. No differences in $CO_2$ concentrations between the two genotypes were observed.

Table 3. Measured and calculated soil water balance elements in the not stressed (NS) and stressed (S) treatments of the two wheat genotypes

| Amount of water during 58 days (ml) | Gk Élet | | Mv Emese | |
|---|---|---|---|---|
| | NS | S | NS | S |
| PE | 4 234 | 4 234 | 4 234 | 4 234 |
| PET | 14 732 | 14 732 | 14 732 | 14 732 |
| PTR | 10 498 | 10 498 | 10 498 | 10 498 |
| E | 3 904 | 2 797 | 3 556 | 2 724 |
| TR | 7 099 | 1 252 | 7 262 | 1 323 |
| (E+TR)/PET | 0.75 | 0.27 | 0.73 | 0.27 |
| E/PE | 0.92 | 0.66 | 0.84 | 0.64 |
| TR/PET | 0.48 | 0.09 | 0.49 | 0.09 |
| TR/PTR | 0.68 | 0.12 | 0.69 | 0.13 |
| TR/I | 0.94 | 0.50 | 1.01 | 0.52 |
| I | 7 567 | 2 480 | 7 207 | 2 547 |

PE – potential evaporation from soil surface according to Figure 2 (right); PET – potential evapotranspiration as given in Figure 2 (left); PTR – potential transpiration, calculated as the difference between PET and PE; E – actual evaporation from soil surface obtained from Eq. (2); TR – transpiration, calculated from Eq. (1); I – irrigation

Statistically significant differences between the soil water balance elements, derived for the two different wheat genotypes, were obtained. The water consumption of the plants was different most probably due to the observed phenological differences. Our results, based on quantitative assessment proved the very good drought stress tolerance of the Mv Emese genotype. It was found, that the water use efficiency of the studied crops in proportion of the irrigation water amount was 94% and 101% in case of Gk Élet and Mv Emese, respectively. In general, the Mv Emese winter wheat genotype consumed all the irrigation water and used the water stored in the soil more efficiently, than the Gk Élet.

We concluded that the operation of the newly worked out complex stress diagnosis system was successful. The precise soil water balance element measurements carried out in the laboratory pot experiments appeared to be sufficient tools to estimate the amount of plant water uptake and to quantify the drought stress tolerance of the different genotypes. This enables more precise calculation of plant water consumption in order to evaluate the drought sensitivity of different wheat genotypes.

However, it is necessary to mention, that the development and water consumption of plants in a climatic room is rather different from those grown in the field. The obtained results are valid for special climatic conditions only and cannot

be directly implemented into large-scale plant production. Our results, however, give useful complementary information to the outcomes of glasshouse drought stress diagnosis systems.

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