Hungarian University of Agriculture and Life Sciences

DETERMINATION OF WATER USE AND WATER-USE EFFICIENCY OF CEREALS IN DIFFERENT EXPERIMENTAL SYSTEMS

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Introduction and the objectives of the dissertation

The achievements of the industrial revolution not only enabled rapid population growth but also brought with them the large-scale burning of fossil energy carriers, which contributed to the increase in atmospheric carbon dioxide concentration, from the initial 278 ppm to approximately 417 ppm today. If the rate of CO_2 emissions does not change, the atmospheric concentration may reach 550 ppm level within 30 years. Carbon dioxide is a natural component of our atmosphere and is necessary for the assimilation of plants. Due to its almost doubling level over the last couple of centuries, it has become one of the most significant greenhouse gases. The increased CO_2 level has positive effects on photosynthesis, reduces water uptake, and improves the growth and production of plants. An increase in CO_2 level can reduce stomatal resistance, thereby improving water uptake. In C3 plants, elevated CO_2 concentration can stimulate net CO_2 assimilation leading to higher biomass production and yield. The positive effect of carbon dioxide on C3 plants is a well-known phenomenon, but this effect is highly environmental effects-dependent, such as air temperature or the nutrient and water content of the soil.

According to the forecasts, we can expect more and more intense periods of drought in many agricultural areas in the coming decades. Drought stress is one of the most important abiotic stresses, which significantly reduces plant production and affects up to 40-60% of crop areas.

Water-use efficiency (WUE) is an important metric, as it sheds light on the relationship between carbon and water turnover and is therefore an indicator of drought tolerance. Determining the WUE is important in the study of plant responses to climatic change, which metric shows significant differences between species and influences many environmental factors. In the course of our work, we examined the WUE of winter cereals in different experimental systems.

The main objectives if the thesis:

- Examination of the abiotic stress tolerance of winter cereals (barley, oat, wheat).
- Determination of water uptake and water-use efficiency in various experimental systems.
- Comparison of different WUE-calculating methods.

In order to achieve our goals, we used different experimental systems in order to take advantage of the methods available to us and provide practice-oriented results to both breeders and farmers. The experimental greenhouse system under controlled climatic conditions ensured the elimination of effects of possible unfavourable meteorological and soil conditions, we could examine the water circulation effects of targeted stress treatments and evaluate the plants' stress responses in the light of water circulation. The outdoor lysimeter system for scientific purposes is currently the most precise system for simulating field conditions, which, in addition to determining the water uptake of plants during the growing season, is also suitable for determining the dynamics of water circulation within a day, however, adaptation to environmental conditions is necessary in this case, and due to the high cost of the investment, the examination of large populations it is not viable in this system. The advantages of the mentioned methods primarily provide information at the basic level, but for farmers, it is a strategic question of how efficiently they manage the available water resources, and how much productivity they have with the different field conditions. In order to do this, we conducted our experiments in two different growing seasons at three field sites with different climatic and soil properties. Our aim was based on combining the three experimental systems in such a way that the experiments, based on each other and complementing each other, provide the most accurate information possible about the water circulation and water-use efficiency of winter cereals. Hence the different cereals have different developmental attribution and habitus in our experiments we included our most important winter wheat also winter barley and winter oat.

Materials and methods

<u>*Greenhouse system*</u>

Experimental design

In the climate-controlled greenhouse experiment, we investigated four winter wheat varieties: ‘Mv Ikva’, ‘Mv Nádor’, ‘Mv Nemere’, and ‘Mv Kolompos’; one winter barley variety: ‘Mv Initium’ and one winter oat variety: ‘Mv Hópehely’. The experimental design included three treatments, three carbon dioxide levels, and six varieties. The control (C) plants were watered three times a week with tap water. The optimal irrigation level was 60% of the maximum water-holding capacity of the used soil mixture. As stress treatments, drought was simulated by the third of the plants at the tillering developmental stage (T) (BBCH 21), and by the third of the plants at the heading developmental stage (H) (BBCH 55). The water content of the soil was monitored, and the stress treatment was stopped when the water content of the soil mixture decreased to a 5 v/v% levels. The treatments were repeated at three different carbon dioxide levels: ~400 ppm, 700 ppm and 1000 ppm.

Four vernalised plants were planted in plastic buckets and the surface of the soil was covered with black foil to minimalize evaporation. After full maturity, we measured the dry above-ground biomass (BM), we determined the number of spikes (SN), the yield (GY) and thousand kernel weight (TKW). The exact water uptake of the plants was determined on a digital scale. The water consumption during the growing season (WU) was obtained by summing up the registered amount of irrigation. After the harvest, the above-ground biomass was dried for 48 hours at 70 °C in a drying cabinet and was weighed by a digital scale.

The water-use efficiency was calculating by first equation,

$$WUE = \frac{GY}{WU} \quad (1),$$

where *WUE* is water-use efficiency ($g \cdot L^{-1}$), *GY* is grain yield (g) and *WU* is water use (L).

The harvest index was calculating by second equation,

$$HI = \frac{GY*100}{BM} \quad (2),$$

where *HI* is harvest index (%), *GY* is grain yield (g), *BM* is above-ground biomass (g).

Relative changes of the different parameters to elevated carbon dioxide level were calculated using the third equation,

$$\frac{Ex}{A} \text{ vagy } \frac{Ey}{A} \quad (3),$$

where A is the different parameters' values on ~400 ppm CO_2 level, Ex is the different parameters' values at 700 ppm CO_2 level and Ey is the different parameters' values at 1000 ppm CO_2 level.

The experimental design involved four winter wheat, one winter barley and one winter oat variety, three watering treatments and three CO_2 levels in three replicates. A multi-way ANOVA was performed to determine the effects of the tested factors (variety, water supply and CO_2) and Tukey's post hoc test was used to compare means. The SPSS 16.0 program (IBM, Armonk, NY, USA) and Microsoft Excel (Microsoft, Redmond, WA, USA) were used for the statistical analysis and visualization. The significance level was set at $P \leq 0.05$.

Field experimental system

Experimental design

In our field experiments, we used in the greenhouse system examined species and varieties. We set up the experiments at three sites: CER, Agricultural Institute in Martonvásár, CER, Institute for Soil Sciences in Pusztaegres, University of Debrecen, Institutes for Agricultural Sciences and Educational Farm in Nyíregyháza. The experiments were conducted on clay loam soil in Martonvásár and Pusztaegres, and on sandy soil in Nyíregyháza. We set up our experiments in the same layout in two growing seasons (2019/2020 and 2020/2021). Plants were sown in small plots with number of 4.5 million seedlings/ha. In Martonvásár and Pusztaegres, the experiment included six repetitions per variety, and in Nyíregyháza in three repetitions. After processing of the plants, the precipitation-use efficiency of the plants was determined the fourth equation.

$$PUE = \frac{GY}{P} \quad (4),$$

where PUE is precipitation-use efficiency ($g \cdot mm^{-1}$), GY is grain yield (g) and P is precipitation in the growing season (mm). During the determination, we did not take into consideration the water movements below the soil surface.

The experimental design involved four winter wheat, one winter barley and one winter oat variety, three production sites, two growing seasons, six or three replications. A multi-way ANOVA was performed to determine the effects of the tested factors (variety, production site and growing season) and Tukey's post hoc test was used to compare means (variety and production site) and t-probe (growing season). The SPSS 16.0 program (IBM, Armonk, NY, USA) and Microsoft Excel (Microsoft, Redmond, WA, USA) were used for the statistical analysis and visualization. The significance level was set at $P \leq 0.05$.

Experimental lysimeter system

Experimental design

In our lysimeter experiments, we used in the greenhouse and field system examined species and varieties. We set up the experiments at three production sites: CER, Agricultural Institute in Martonvásár. The depth of the lysimeter cylinders is 2 m, the surface is 1 m^2. At the end of the experiment, the harvested spikes were threshed with Wintersteiger Hege 16 laboratory threshing machine and the grain yield was determined using a digital scale.

The water-use efficiency was calculating by the fifth and sixth equation,

$$WUE_y = \frac{GY}{ET} \quad \text{és} \quad WUE_{BM} = \frac{BM}{ET} \qquad (5) \text{ and } (6),$$

where WUE_y is water-use efficiency calculating by grain yield ($g \cdot mm^{-1}$), *GY* is grain yield (g) and *ET* is evapotranspiration (mm) and WUE_{BM} is water-use efficiency calculating by above-ground biomass ($g \cdot mm^{-1}$), *BM* is above-ground biomass (g).

The precipitation-use efficiency was calculating by the seventh equation,

$$PUE = \frac{GY}{P} \qquad (7),$$

where *PUE is* precipitation-use efficiency ($g \cdot mm^{-1}$), *GY* is grain yield (g) and *P* is precipitation in the growing season (mm). During the determination, we did not take into consideration the added and extracted water amount.

The agronomical constant (K_a) was calculated by the eight equations,

$$K_a = \frac{ET_{act}}{E_{act}} \qquad (8),$$

where K_a is agronomical constant, ET_{act} is the evaporation (mm) and E_{act} is evaporation (mm).

The lysimeter cylinders were sown by hand on 10th October 2019 and 26th October 2020, with seeding density of 4.5 million seedlings/ha. On the day after sowing in the lysimeters, border (Mv Initium barley variety) was sown by hand (scattered sowing) around the cylinders. The experiment was harvested with scissors on 2nd July 2019 and 6th June 2020. During the experiment, no fertilization or irrigation took place in the area.

The experimental design included four winter wheat varieties, one winter barley and one winter oat variety, two growing season and one replication in each season. We used Microsoft Excel (Microsoft, Redmond, WA, USA) to visualize our data.

Results and discussions

Investigation of the production and water use of cereals in the greenhouse experiment

The effects of CO_2 concentration and simulated water deficit on plant phenological parameters

At the current atmospheric carbon dioxide level (~400 ppm), except for the 'Mv Kolompos' winter wheat variety, both stress treatments (water withdrawal at BBCH 21 ('T') or at BBCH 55 ('H') growing stage) significantly reduced biomass by all tested genotypes compared to the control plants. When the plants were grown at 700 ppm CO_2 level, we observed significant differences between all treatments ('C', 'T' and 'H') by the barley, oat and two wheat varieties ('Mv Ikva' and 'Mv Kolompos'). The simulated drought stress at BBCH 55 stage reduced the biomass in every tested variety. At 1000 ppm CO_2 concentration compared to the optimal watering, early-stage drought stress reduced the biomass of 'Mv Ikva' and 'Mv Kolompos' wheat varieties and late-stage drought reduced this parameter by 'Mv Hópehely', 'Mv Nemere' and 'Mv Kolompos'. The increase in the carbon dioxide level had a positive effect on biomass production by the tested barley variety, which effect was only detectable in stressed plants.

At the current atmospheric carbon dioxide concentration, early-stage drought stress significantly increased the number of spikes in 'Mv Nemere' (30%) and in 'Mv Nádor' (18%) wheat varieties, but this treatment caused a 13% decrease in the tested winter barley variety. Drought during the heading also reduced the SN of the tested barley variety by 13% and a significant decrease (24%) was also observed in the 'Mv Ikva' wheat variety. At 700 ppm CO_2 concentration, we observed that the spikes number of 'Mv Ikva' was significantly decreased and significantly increased in 'Mv Nemere' and 'Mv Initium' genotypes as the result of the BBCH 21 stage stress. The simulated heading stage drought resulted in an increase (43%) of SN by the 'Mv Nádor' wheat variety but by 'Mv Ikva' spikes number was decreased (12%) because of it. When the plants were grown at 1000 ppm CO_2 concentration the water withdrawal increased the number of spikes at the early-stage by the 'Mv Nemere' wheat variety (30%), while the water deficit at the heading-stage increased this parameter by the 'Mv Ikva' wheat genotype.

The increase in the carbon dioxide level had a positive effect in regard to the spikes number, we observed a significant negative CO_2 reaction at 1000 ppm level only in the optimal irrigation treatment and in stress treatments by 'Mv Ikva'.

At the current atmospheric CO_2 level, the tillering-stage drought reduced the thousand kernel weight by 'Mv Nádor' and 'Mv Ikva' varieties (20% and 16%)

and the heading-stage water stress reduced the TKW of ‘Mv Nádor’, ‘Mv Hópehely’ and ‘Mv Initium’ genotypes (by 16%, 8% and 7%). There were significant differences between the two stress treatments for all testes varieties, Expect for ‘Mv Kolompos’ wheat variety. In the case of the ‘Mv Initium’, ‘Mv Hópehely’ and ‘Mv Nemere’ varieties, the TKW decreased to a greater extent as a result of the late-stage drought. At 700 ppm carbon dioxide level, the thousand kernel weight of the tillering-stage stressed plant decreased by all investigated varieties except the barley. As a result of the late drought, we determined higher TKW values by ‘Mv Initium’ (28%) and ‘Mv Kolompos’ (21%) varieties, but this treatment significantly reduced the TKW of ‘Mv Hópehely’ (58%) and ‘Mv Nádor’ (28%) wheat varieties. The thousand kernel weight of the optimal watered and by early-stress treatment plants was significantly lower at both elevated carbon dioxide levels (700 ppm and 1000 ppm) than by current atmospheric level grown plants and the decrease was more severe at 700 ppm level. On the other hand, we observed increased TKW values by heading-stage stress treatment on 700 ppm compared to the current CO_2 level. Compared to the CO_2 level at 700 ppm, the thousand kernel weight was significantly reduced in all three treatments by the tested oat genotype furthermore the late-stage stress caused a significant decrease at the 700 ppm level.

The effects of CO_2 concentration and simulated water deficit on the yield

At the current CO_2 level, both drought stress treatments reduced the grain yield of all tested cultivars, with the exception of the ‘Mv Kolompos’ wheat variety. Compared to the optimal irrigation treatment, the most significant changes were observed by the tested oat variety, the early-stage stress resulted in a 24% decrease in GY, and the simulated drought stress at the heading stage resulted in a 54% decrease in this parameter. By ‘Mv Initium’, ‘Mv Ikva’ and ‘Mv Hópehely’ varieties, significant differences emerged between the two stress treatments; the effect of the late-stage drought led to a greater reduction in yield. At an elevated carbon dioxide level (700 ppm), the tillering-stage water withdrawal reduced the GY of ‘Mv Hópehely’ (47%), ‘Mv Ikva’ (20%), ‘Mv Nádor’ (12%) and ‘Mv Nemere’ (10%) varieties. The heading-stage stress reduced the grain yield of the tested oat and the wheat varieties, compared to the optimal irrigation treatment. The greatest decrease (77%) was observed by the ‘Mv Hópehely’ oat cultivar. In the case of ‘Mv Kolompos’, ‘Mv Nádor’, ‘Mv Nemere’ and ‘Mv Hópehely’ varieties, there were differences between the two stress treatments; the late-stage stress resulted in a significantly lower yield. At 1000 ppm carbon dioxide level, the tillering stress treatment significantly reduced the grain yield only by the ‘Mv Ikva’ wheat variety (15%), but the heading-stage stress resulted in a significant yield reduction in all tested cultivars except for 'Mv Kolompos' variety. The greatest decrease (64%) was also observed by the tested oat genotype. There was also a significant difference between the two stress treatments in the case of the tested barley and oat varieties, the effect of the late-stage drought led to a more drastic yield reduction in both varieties.

The tested barley variety ('Mv Initium') reacted significantly positively to the increase in carbon dioxide levels in all applied treatments, but we could observe a greater grain yield increase in the stress-treated plants. We observed an opposite trend by the tested oat variety ('Mv Hópehely'); carbon dioxide fertilisation, typically at the level of 1000 ppm, significantly reduced the grain yield of this genotype, however, this trend was not detectable by the optimal irrigation treatment at the 700 ppm CO_2 level. 'Mv Ikva' wheat variety also showed a negative CO_2 reaction, which, however, was only significant by the control treatment. The other tested varieties mostly responded positively to CO_2-fertilisation. Compared to the atmospheric CO_2 concentration, the elevation to the 700 ppm level resulted in an increase in yield by 'Mv Nemere' and 'Mv Kolompos' varieties by the control treatment and by the early-stress treatment. In the case of the 'Mv Kolompos' wheat variety, positive reactions were observed in the control plants and in the late drought stress treatment, when the CO_2 concentration was raised to 1000 ppm level. The grain yield of the 'Mv Nádor' wheat variety was reduced by the late-stage drought stress at both elevated CO_2 concentrations (compared to the current atmospheric CO_2 Level), this significant decrease was detectable at 1000 ppm CO_2 level in the case of 'Mv Nemere' wheat variety.

The effects of CO_2 concentration and simulated water deficit on harvest index

At the current atmospheric CO_2 concentration, the tillering-stage stress reduced the harvest index of the tested oat variety by 15% and increased the HI of 'Mv Kolompos' by 8%. The heading-stage drought reduced the HI of 'Mv Hópehely' (45%) and increased it of the tested barley variety by 7%. In the case of the 'Mv Hópehely' variety, we also observed significant differences between the three treatments, the lowest HI values resulted from the late-stage stress treatment, while the most favourable value was measured by the optimal irrigation treatment. At 700 ppm CO_2 concentration in the early developmental phase, water deprivation significantly increased the harvest index of 'Mv Ikva' (9%), 'Mv Nemere' (4%) and 'Mv Nádor' (4%) wheat varieties and reduced the íhi values by 'Mv Hópehely' (31%) and 'Mv Initium' (8%) varieties. Drought stress at the heading developmental stage reduced the HI by all tested cultivars, the largest measurable decrease (62%) was found by the oat variety. Water deficit induced by the heading stage reduced the HI by ‘Mv Nádor’, ‘Mv Initium’, ‘Mv Kolompos’, ‘Mv Ikva’ and ‘Mv Nemere’ (19%, 18%, 16%, 15% and 8%) compared to the control. There were significant differences between all three treatments at 700 ppm carbon dioxide level; the late drought reduced the grain yield of the plants to a greater extent than the biomass, so the decrease visible in the HI values was even more intense. At 1000 ppm CO_2 concentration, the drought stress induced in the early development phase had no significant effect on the HI tested of the cultivars, but the water withdrawal applied in the generative phase significantly reduced the HI of ‘Mv Hópehely’ (43%), ‘Mv Nádor’ (15%) and ‘Mv Ikva’ (9%) varieties.

The responses of the plants to the increase in carbon dioxide level were consistent only in the case of the ‘Mv Hópehely’ winter oat variety with regard to the harvest index. Compared to the atmospheric CO_2 level the 1000 ppm concentration, all treatments led to a significant decrease in HI values, and at a 700 ppm CO_2 level, compared to the current atmospheric concentration, we also determined significantly lower values in the stress treatments.

The effects of CO_2 concentration and simulated water deficit on water uptake

Early drought stress did not cause a significant change in water uptake at current atmospheric carbon dioxide levels, but drought at the heading-stage significantly reduced the water uptake of ‘Mv Ikva’ (24%) and ‘Mv Nemere’ (12%) wheat varieties. By ‘Mv Nemere’, there were also significant differences between the two stress treatments, the simulated water shortage at the heading-stage reduced the WU values to a greater extent. At 700 ppm CO_2 level, the water withdrawal at the tillering resulted in a significant change only in the case of the ‘Mv Ikva’ wheat variety, but the late stress reduced the WU of all the tested varieties, to the greatest extent by ‘Mv Ikva’ (20%). Significant differences were observed between the two stress treatments by the ‘Mv Kolompos’ wheat variety. At 1000 ppm CO_2 concentration, both applied drought stress treatments significantly reduced the water uptake of the ‘Mv Ikva’ variety (by 15% at early and by 12% at late-stage stress). WU was significantly affected by CO_2 fertilization only at 1000 ppm CO_2 level. Compared to the current atmospheric level, at 1000 ppm CO_2 concentration, we observed a significant decrease in the water uptake of all tested varieties, as a result of all treatments; the only exception to this was the ‘Mv Hópehely’ oat variety, which received optimal irrigation. With optimal irrigation, the plants' water demand was reduced by an average of 24%, and in the case of water withdrawal at tillering or heading stage, the WU was reduced by 23% and 20% as a result of the stress treatments at 1000 ppm CO_2

level compared to the control (current atmospheric carbon dioxide level) conditions.

The effects of CO_2 concentration and simulated water deficit on water-use efficiency

At the current CO_2 concentration, drought stress during the tillering stage did not modify the water-use efficiency of the tested varieties, on the other hand, the stress during the heading significantly reduced the WUE of the tested oat variety. At elevated CO_2 concentration (700 ppm), the simulated drought at BBCH 21 stage significantly reduced the WUE values of Mv ‘Hóhely’ and ‘Mv Nádor’ varieties by 48% and 6%, while there was no significant change in the case of the other tested varieties. The late-stage drought had significant consequences for the ‘Mv Hópehely’ oat variety; the WUE decreased by 76% compared to the optimal irrigation level. We also observed a significant decrease (25%, 15%, 10%) in terms of WUE by the ‘Mv Nádor’, ‘Mv Kolompos’ and ‘Mv Nemere’ wheat varieties as a result of the simulated drought during the heading-stage. Significant differences were also observed between the two stress treatments in the case of the ‘Mv Hópehely’, ‘Mv Nádor’, ‘Mv Nemere’ and ‘Mv Kolompos’ varieties, the water withdrawal during the late developmental stage reduced the plants' WUE values to a greater extent than the early-stage drought. At 1000 ppm CO_2 concentration, early-stage water withdrawal did not induce significant changes in the water-use efficiency of the tested varieties, which indicates that carbon dioxide fertilization can offset the negative effects of a water-deficient environment. The drought treatment during the heading only reduced the WUE values of ‘Mv Hópehely’ (by 60%) and ‘Mv Nádor’ (by 17%) varieties, indicating that the other tested varieties are less sensitive to drought.

Carbon dioxide fertilization had a positive effect on the grain yield and reduced the water uptake of the investigated barley variety (‘Mv Initium’), as a result of which the water-use efficiency of the variety improved in all applied treatments (by 39% in the in optimal irrigation treatment, by 34% in the early-stage and 48% in the late-stage drought treatment). By the tested oat variety (‘Mv Hópehely’) with optimal water supply or as a result of the tillering-stage drought treatment, we observed a reduced yield production at elevated carbon dioxide levels, which was offset by moderate water uptake, so the increase in CO_2 levels did not cause a significant difference in the plants' WUE as a result of the applied treatments. The drought stress during the heading significantly reduced the yield of the Mv ‘Hópehely’ oat genotype, as a result of which we can observe a significant decrease in the WUE values at both elevated carbon dioxide levels. At 1000 ppm CO_2 concentration, better WUE values were calculated by all tested wheat varieties in all applied treatments (compared to the current atmospheric CO_2 level). The largest increase was observed by 'Mv Kolompos' (63%, 38% and 56% by the control and the two stress treatments).

The discussions of the results of the greenhouse experiment

In our experiment, the drought stress treatment applied in the vegetative (BBCH 21) and generative (BBCH 55) developmental stage reduced the biomass of five out of the six tested varieties, when the plants were grown at current atmospheric carbon dioxide level. A similar trend was observed in case of the winter oat and wheat varieties 'Mv Hópehely', 'Mv Ikva', 'Mv Nemere' and 'Mv Nádor' respectively, when the level of carbon dioxide was raised to 700 ppm. Furthermore, in the case of 'Mv Ikva' and 'Mv Nádor' varieties, we found a decrease in biomass due to both applied stress treatments at 1000 ppm CO_2 level. The biomass of the tested barley variety ('Mv Initium') increased due to the increased carbon dioxide levels (700 ppm, 1000 ppm) and the applied drought treatment. Our results are similar to Dong et al. (2017), Ding et al. (2018), and Zhao et al. (2021) studies; according to which the biomass of winter wheat and oat varieties decreases as a result of limited water supply in when the plants were grown at current atmospheric carbon dioxide level. Manderscheid and Weigel (2007) and Li et al. (2017) observed that the water deficit after elongation at elevated carbon dioxide concentrations (~700 ppm and 800 ppm) reduces the biomass of spring wheat, which tendency was confirmed by our experiments in the case of winter wheat as well. According to studies, at elevated carbon dioxide concentrations (700 ppm), the water deficit in the vegetative growth phase reduces the biomass in durum wheat (Garmendia et al. 2017) and barley (Bista et al. 2020). However, based on our results, the biomass production of the examined barley variety was higher compared to the control, which could be explained by the different reaction to the CO_2 alterations. Shokat et al. (2021) claimed reduced biomass production as a result of late drought treatment compared to the control, when plants were grown at 800 ppm carbon dioxide level. Contrary to our results, Varga et al. (2017) did not find a significant difference in plant biomass production at elevated carbon dioxide level (1000 ppm) between optimally irrigated and drought-stressed plants, which can confirm the assumption that plant responses to changed carbon dioxide level differently, depending on the variety. In our experiment higher biomass production was observed at both elevated CO_2 levels (700 ppm, 1000 ppm) by the tested barley variety and the induced drought treatment at different stages of development (tillering, heading) increased the biomass of 'Mv Nádor' and 'Mv Kolompos' wheat varieties at elevated carbon dioxide level (700 ppm) compared to plants grown at current carbon dioxide level.

We also observed a higher biomass production by the optimally irrigated ‘Mv Hópehely’, ‘Mv Nemere’ and ‘Mv Kolompos’ varieties at 700 ppm CO_2 level, and in the case of the ‘Mv Kolompos’ variety at 1000 ppm CO_2 level, compared to the current atmospheric level. According to Ulfat et al. (2021), if drought occurs during the flowering period of winter wheat even at normal atmospheric or elevated (800 ppm) carbon dioxide concentration, the highest biomass production was observed in optimally irrigated plants grown at atmospheric CO_2 level, while this parameter will be lower at elevated CO_2 levels, with optimal water supply. In contrast, in our experiments, we determined higher biomass values at elevated carbon dioxide level (700 ppm) compared to the atmospheric level in the case of optimally irrigated and drought-stressed ‘Mv Nádor’, ‘Mv Nemere’ and ‘Mv Kolompos’ winter wheat varieties. Shokat et al. (2021) claimed, that the biomass of plants grown at elevated carbon dioxide level (800 ppm) was higher compared to the values of plants grown at atmospheric CO_2 concentration, but only in the case of optimal irrigation, while the opposite result was found due to late water withdrawal.

We observed that the lack of water at the beginning of tillering increased the number of ears in the case of the ‘Mv Nemere’ wheat variety and the ‘Mv Initium’ barley variety at the current atmospheric carbon dioxide level, but drought during heading reduce this parameter for the barley variety and one of the investigated wheat varieties (‘Mv Ikva’). Our results agree with Samarah et al. (2009), that late drought reduces the number of ears of barley. Khakwani et al. (2012) found that the lack of water reduces the number of ears, in the reproductive state of winter wheat. Early or late drought stress reduced spring wheat’s ear number according to Ding et al. (2018) and Rollins et al. (2013) and this were also confirmed by our results. A significant decrease in the number of ears was observed in the case of the tested barley variety when the plants received drought treatment during their generative phase. In our experiment, at 700 ppm CO_2 level, the early drought increased the number of ears in the tested barley variety and one of the wheat varieties (‘Mv Nemere’), furthermore, decreased it by the Mv ‘Ikva’ winter wheat variety. The lack of water by heading increased the number of ears of ‘Mv Nádor’ but decreased it in the case of ‘Mv Ikva’. According to Garmendia et al. (2017), in durum wheat the number of ears shows a slight increase due to the combined effect of late drought and elevated carbon dioxide concentration (700 ppm). We obtained similar results in the case of the tested variety. Shokat et al. (2021), on the other hand, observed the opposite, in their experiment, the number of ears in wheat decreased because of the late drought, where the plants were examined at 800 ppm CO_2 concentration. In plants grown at 1000 ppm carbon dioxide level, water withdrawal at tillering or heading developmental stage increased the number of ears of ‘Mv Ikva’ variety. Shokat et al. (2021) also observed a decrease in this parameter in wheat due to a late drought, but only at 800 ppm CO_2 concentration. According to our results, neither the drought stress treatment nor the difference between the carbon dioxide levels caused significant changes in this parameter in the case of the examined oat variety (‘Mv Hópehely’). In ‘Mv Nádor’ wheat variety, compared to plants grown at current atmospheric carbon dioxide level, higher ear number values were observed for all treatments when the plants were grown at 700 ppm CO_2 concentration. This is in agreement with Thilakarathne et al. (2013) observations, who found a higher number of ears at 700 ppm CO_2 than in control conditions, in spring wheat grown at the current atmospheric concentration.

Based on our results, early drought stress significantly reduced the thousand kernel weight (TKW) of two tested wheat varieties (‘Mv Ikva’ and ‘Mv Nádor’), and late drought had this effect on the ‘Mv Initium’, ‘Mv Hópehely’, ‘Mv Nádor’ and ‘Mv Nemere’ varieties. Other authors also observed a decrease in TKW due to drought during grain filling stage in barley (Samarah et al. 2009) or due to drought during heading in oat (Zhao et al. 2021) and wheat (Shokat et al. 2021). Both of the applied stress treatments reduced the thousand kernel weight of the plants grown at 700 ppm carbon dioxide level by the ‘Mv Hópehely’, ‘Mv Nádor’ and ‘Mv Kolompos’ varieties and at the 1000 ppm level by the ‘Mv Ikva’. We could also observe a decrease due to the drought at the tillering stage in the case of the ‘Mv Initium’ barley variety at 700 ppm CO_2 level and in the ‘Mv Hópehely’ and ‘Mv Nemere’ varieties at 1000 ppm CO_2 level. Drought stress during heading reduced the TKW of the ‘Mv Ikva’ wheat variety at 700 ppm CO_2 level and of the ‘Mv Nemere’ at 1000 ppm CO_2 concentration. A positive carbon dioxide reaction was observed in the TKW of the optimally irrigated ‘Mv Ikva’ and ‘Mv Nemere’ wheat varieties, which was detectable at both elevated carbon dioxide levels (700 ppm and 1000 ppm). In the case of the tested winter oats, we could only verify this tendency at the 700 ppm CO_2 concentration. The increasing carbon dioxide level (700 ppm, 1000 ppm) had a negative effect on the TKW of the optimally irrigated barley (‘Mv Initium’) and the tested oat variety at the 1000 ppm CO_2 level. As a result of the two applied stress treatments, we could observe higher values at 700 ppm carbon dioxide level than current atmospheric concentration by the ‘Mv Initium’ and ‘Mv Kolompos’ varieties. Raising the CO_2 level (1000 ppm) also had a positive effect on the tested wheat varieties, if the stress was applied in the generative developmental stage. The examined oat variety was negatively affected by the drought during heading and the increase in carbon dioxide levels (700 ppm and 1000 ppm).

Contrary to our results, Högy et al. (2009) found that the increased carbon dioxide level (~550 ppm) did not change in the thousand kernel weight of spring wheat, although in their experiment the used CO_2 concentration was significantly lower than the levels in our study. Fangmeier et al. (2000) claimed that the TKW of spring barley decreased slightly as a result of the increased carbon dioxide level (650 ppm), we experienced a significant decrease in this parameter by the tested barley variety at both investigated CO_2 levels. Wu et al. (2004), similarly to our results, found higher thousand kernel weight values at elevated carbon dioxide level (700 ppm) than at current atmospheric level, in the case of wheat with an optimal water supply and drought treatment. Ulfat et al. (2021) found that winter wheat also showed a higher TKW in optimally watered plants grown at elevated carbon dioxide level (800 ppm), and with regard to the parameter, the adverse effects of the late drought were also moderated by the effect of carbon dioxide increase. According to Shokat et al. (2021) results, the late drought significantly reduced the thousand kernel weight of the examined wheat at 800 ppm carbon dioxide concentration, and even the artificial increase of the gas concentration had a negative effect on this parameter; compared to those grown at atmospheric level, a lower TKW was found in both optimally watered and stressed plants (Shokat et al. 2021).

In our experiment, water deficit in the BBCH 21 development stage and BBCH 55 stage (compared to optimal irrigation) reduced the grain yield of the 'Mv Ikva' wheat variety at all investigated carbon dioxide levels (~400 ppm, 700 ppm, 1000 ppm). Both applied stress treatments reduced the GY of 'Mv Hópehely', 'Mv Nádor' and 'Mv Nemere' varieties at current atmospheric and elevated (700 ppm) carbon dioxide levels, and at ~400 ppm level by the 'Mv Initium' barley variety. At 1000 ppm CO_2 concentration, the late-stage water withdrawal reduced the grain yield of all tested varieties, except for the 'Mv Kolompos' wheat variety. Zhao et al. (2021) also found lower grain yield values for oat in response to drought stress applied at different stages of development. Quaseem et al. (2019) described similar results in the case of wheat as a result of water deficit treatment applied before flowering. Our results agree with Manderscheid and Weigel (2007); Varga et al. (2017); Shokat et al. (2021) and Ulfat et al. (2021) results; the authors observed a decrease in grain yield of wheat cultivars at elevated carbon dioxide concentrations (700 ppm, 800 ppm or 1000 ppm) as a consequence of early or late drought treatment. We observed a positive carbon dioxide reaction for the tested barley variety and a negative one for the oat variety in terms of grain yield at both elevated CO_2 levels (700 ppm and 1000 ppm) for all applied irrigation levels (optimal, drought at tillering or heading). A high level of grain yield was demonstrated in the optimally irrigated and early drought-stressed ‘Mv Nemere’ and ‘Mv Kolompos’ cultivars at elevated carbon dioxide level (700 ppm). Thilakarathne et al. (2013) also measured higher grain yield in spring wheat at elevated CO_2 level (700 ppm) with optimal irrigation. Shokat et al. (2021), on the other hand, described an opposite trend; reported higher values for the atmospheric concentration, both in the case of optimally irrigated wheat and as a result of the late drought treatment, at 800 ppm carbon dioxide level.

According to our results, the lack of water at tillering stage increased the Harvest index by the ‘Mv Kolompos’ wheat variety at current atmospheric CO_2 level and by the ‘Mv Ikva’, ‘Mv Nádor’, ‘Mv Nemere’ wheat varieties and reduced it by the ‘Mv Hópehely’ oat variety at atmospheric and elevated CO_2 level (700 ppm) and by the ‘Mv Initium’ barley at 700 ppm CO_2 level. The lack of water during heading reduced the Harvest index of the examined oat variety at both of the elevated CO_2 levels (700 ppm, 1000 ppm). The late drought reduced the HI values of all tested varieties at 700 ppm CO_2 level, and in ‘Mv Hópehely’ and ‘Mv Nádor’ varieties we also experienced a significant decrease in this parameter at 1000 ppm CO_2 concentration. Compared to the current atmospheric level, the increased level of carbon dioxide (700 ppm or 1000 ppm) had a negative effect on the Harvest index of the tested oat variety. Contrary to our results, Zhao et al. (2021) observed that the applied drought treatment had a positive effect on the HI of the examined oat variety at current atmospheric carbon dioxide level. According to Samarah et al (2009), the HI value of the examined barley decreased due to the late drought, in our experiment we experienced the opposite tendency. Ding et al. (2018) found that the drought stress during tillering improves the Harvest index of winter wheat at normal atmospheric CO_2 concentration, our results supported this only in the case of the ‘Mv Kolompos’ variety. Wu et al. (2004) published higher Harvest index values compared to the control at elevated carbon dioxide level (~700 ppm) in spring wheat as a result of the drought treatment. Compared to the control, Ulfat et al. (2021) claimed a reduced Harvest index value as a result of the drought treatment applied at 800 ppm CO_2 concentration. In our experiment, we also experienced a decrease in HI at elevated CO_2 level (700 ppm) as a result of water withdrawal during heading. Varga et al. (2017) also observed a decrease in the Harvest index caused by drought at 700 ppm and 1000 ppm CO_2 levels.

At the current atmospheric carbon dioxide level, drought stress during tillering developmental stage did not cause a significant change in water uptake, but drought during heading reduced this parameter in the case of the ‘Mv Ikva’ and ‘Mv Nemere’ wheat varieties. At 700 ppm carbon dioxide level, we observed a reduced water uptake in the case of tested wheat varieties as a result of late drought stress. Also, in the case of the ‘Mv Ikva’, the applied drought stress (early or late drought) reduced the water uptake of this variety at 700 ppm and 1000 ppm carbon dioxide concentration. Compared to the current atmospheric level, the artificial increase of the carbon dioxide concentration to the level of 700 ppm did not cause a significant change in WU, but at the 1000 ppm level it already had a positive effect. Compared to the current atmospheric level, at 1000 ppm carbon dioxide concentration, the water uptake of the tested varieties decreased significantly at all applied irrigation levels (optimal, water withdrawal at tillering or heading). According to Varga et al. (2017) results, optimal irrigation and late drought reduce the water uptake at elevated carbon dioxide levels (1000 ppm).

Our results show that early drought stress (applied at BBCH 21 development level) reduced the water-use efficiency of the ‘Mv Hópehely’ and ‘Mv Nádor’ varieties, but only at elevated carbon dioxide level (700 ppm). The late drought (BBCH 55 development stage) significantly reduced the WUE of the ‘Mv Hópehely’ oat variety at all investigated carbon dioxide levels, in ‘Mv Nádor’ wheat variety reduced this parameter at elevated CO_2 levels (700 ppm and 1000 ppm), and by the ‘Mv Nemere’ and ‘Mv Kolompos’ wheat varieties only at 700 ppm CO_2 concentration. We observed a positive effect of carbon dioxide in terms of WUE in the case of the examined barley variety and all the tested wheat varieties at 1000 ppm CO_2 in all the applied treatments. Positive effects were also observed at 700 ppm carbon dioxide level in the case of the ‘Mv Kolompos’ and ‘Mv Nemere’ wheat varieties, when the plants were irrigated optimally or treated with early drought stress. Liu et al. (2016) found a more favourable WUE value for oat at elevated carbon dioxide level (700 ppm) with optimal irrigation, however, based on our research, there was no significant difference in the WUE of optimally irrigated plants at different carbon dioxide levels. According to Li et al. (2017), the water-use efficiency of winter wheat slightly increased at elevated CO_2 concentration (800 ppm) as a result of late drought. Based on our results, at elevated carbon dioxide level (700 ppm), the WUE of the tested wheat varieties decreased when stress treatment was applied. Robredo et al. (2007) found that the highest WUE values were observed for winter and spring wheat and barley by drought at elevated CO_2 concentration (700 ppm). Medeiros and Ward (2013) found the most efficient WUE at elevated carbon dioxide level (700 ppm) by drought treatment.

Investigation of the production and water uptake of cereals in the field experiment

We observed remarkable differences in the rainfall of the two studied growing seasons (2019/2020 and 2020/2021); in Martonvásár and Pusztaegres, the first year was rainy, while in Nyíregyháza more precipitation fell in the second season. Based on the data on the monthly distribution of precipitation, we determined that a remarkable amount of precipitation fell in Martonvásár and Pusztaegres in November and December of the first growing season, and in June in Martonvásár and Nyíregyháza. In the second growing season, an outstanding amount of precipitation fell in May, compared to the other months, in all three growing areas.

The yield production of the tested varieties in the investigated production areas

In the first year of our experiment (2019/2020 growing season), among the three production areas, we observed the lowest yield in Nyíregyháza. Compared to the Pusztaegres, we measured a significantly lower yield on the sandy soil (Nyíregyháza) for all examined varieties, the largest difference (39%) can be observed in the case of the 'Mv Ikva' wheat variety. In Martonvásár, with the exception of the 'Mv Kolompos' wheat variety, the yield was significantly higher than in Nyíregyháza. The biggest difference (44%) between the two production sites was observed in the oat variety ('Mv Hópehely'). There were also significant differences between the yield values in Pusztaegres and Martonvásár. In the case of the examined barley variety ('Mv Initium') and three wheat varieties ('Mv Nádor', 'Mv Nemere' and 'Mv Kolompos'), the yield was higher at Pusztaegres, while the yield was higher for the examined oat variety ('Mv Hópehely') at Martonvásár. In the second year (2020/2021 growing season), there was no significant difference in the yield of the varieties between the three growing areas in the case of the 'Mv Initium' and 'Mv Hópehely' varieties. By the investigated wheat varieties, we observed significant differences in productivity between Pusztaegres and the other two production sites. The productivity of 'Mv Ikva' was higher in Pusztaegres, but in the case of the other three wheat varieties ('Mv Kolompos', 'Mv Nádor' and 'Mv Nemere'), we obtained significantly lowest values in Pusztaegres. In the two investigated growing seasons in Martonvásár, among the investigated plants, the grain yield of 'Mv Hópehely' and 'Mv Ikva' was significantly different between years, in both cases the yield was higher in the first, wetter year. The studied oat variety produced 19% less, while 'Mv Ikva' produced 17% less yield in the second studied year. With the exception of the investigated oats variety, the yield of the plants differed significantly between the two examined years, with higher values measured in the first, wet year. The biggest difference (34%) was observed in the case of the 'Mv Nádor' wheat variety, but there was also a difference of more than 30% in the case of 'Mv Nemere' (33%) and 'Mv Kolompos' (31%) between the two examined years, the on the production areas. The plants also produced a higher yield in the wetter year (2020/2021 growing season) on sandy soil, this difference was significant for all tested investigated except for the 'Mv Initium' barley variety. In the case of 'Mv Nemere' and 'Mv Ikva' wheat varieties, the difference between the two years was 50%, and in the case of 'Mv Hópehely' and 'Mv Nádor', there was a difference of 43% and 33%.

The precipitation-use efficiency of the tested varieties in the investigated production areas

In the first year of our experiment (the growing season of 2019/2020), the highest precipitation-use efficiency was calculated on sandy soil (Nyíregyháza) but in the case of 'Mv Hópehely' and 'Mv Ikva' varieties, there were no significant differences in the PUE values on the three different growing areas. In the case of 'Mv Initium', 'Mv Kolompos', 'Mv Nádor' and 'Mv Nemere' varieties, the PUE values differed significantly between the production locations. The lowest WUE values were obtained in Martonvásár. In the case of 'Mv Initium' and 'Mv Kolompos' we observed in Pusztaegres the plants had a better PUE compared to Nyíregyháza. We did not observe any significant differences in the PUE values of the investigated oat variety at the three studied production areas in the 2020/2021 growing season. In the second year (2020/2021 growing season), the PUE values of the tested barley variety were significantly lower at Nyíregyháza than at the other two production areas, but the difference was not significant between Pusztaegres and Martonvásár. In the case of the 'Mv Ikva' and 'Mv Kolompos' wheat varieties in Martonvásár had the highest PUE of the plants, but these values did not differ significantly from the values of the plants developed on sandy soil. We did not find any significant difference between Nyíregyháza and Pusztaegres in the PUE values of the two wheat varieties ('Mv Ikva' and 'Mv Kolompos'). The PUE values of 'Mv Nádor' in Martonvásár were higher compared to the other two production sites, and the values in Nyíregyháza and Pusztaegres are not significantly different. In the case of 'Mv Nemere', we also determined the highest PUE values in Martonvásár, but this difference was only significant compared to the PUE value of plants grown in Pusztaegres. The precipitation-use efficiency of all examined varieties was significantly higher in the second growing season. The PUE values in Pusztaegres also differ significantly between the two investigated seasons, but in the case of the 'Mv Ikva' and 'Mv Nemere' wheat cultivars in this growing area, higher values can be observed in the first growing season, while in the case of the other examined cultivars, this parameter was higher in the second investigated season. On the sandy soil, the two years differed significantly only in the case of the 'Mv Initium' barley variety, and 'Mv Nádor' and 'Mv Kolompos' wheat varieties, in all cases the 2019/2020 growing season resulted in higher PUE values.

The discussions of the results of the field experiment

Drought can reduce the yield of cereals (Sadras et al. 2017; Schmidthoffer et al. 2018; Chowdhury et al. 2021), but the drought stress in different growth phases affects in different ways (Mehraban et al. 2019), as well as the temporal exposure of the drought and its strength is also an important factor (Zhang et al. 2017). During our work, although we did not grow plants with optimal water supply, there was a significant difference in the amount of precipitation between the two investigated growing seasons, and in April of the first investigated growing season, a negligible amount of precipitation fell in all three production areas (Martonvásár, Pusztaegres, Nyíregyháza), which can be interpreted as an early drought. According to Mehraban et al. (2019), stress at an early developmental stage reduces the yield of wheat more than drought in later stages. We could only observe this effect grown in production site of Nyíregyháza; in the second, wetter year, the yield of all wheat varieties was higher. In Pusztaegres, we experienced the exact opposite, the effects of drought stress at a young age were later offset by rainfall during the growing season. Not only the amount of precipitation can affect the yield of our crops, but also the type of soil (Lipiec and Usowicz, 2018). The results of our experiment support the findings of Lipiec and Usowicz (2018), in the case of our barley and oat variety grown in nutrient-rich soil, we measured a higher yield.

Xue et al. (2019) determined a lower precipitation-use efficiency in the wettest years when the plants were grown in poorer quality soil in the case of winter wheat. On the other hand, higher PUE values were realized in soil with a better nutrient supply when significantly less precipitation fell. In the case of the plants growing on sandy soil, we found a significant difference between the two investigated years in PUE values only of the 'Mv Initium', 'Mv Nádor' and 'Mv Nemere' varieties. In the case of all three varieties, higher values were determined in the less rainy year, contrary to Xue et al. (2019) results. In the case of the Martonvásár production site, our results are consistent with Xue et al. (2019), we measured higher PUE values in the less rainy year. Peng et al. (2020) also found decreased precipitation-use efficiency in the case of wheat varieties in the less rainy year.

Investigation of the production and water uptake of cereals in the lysimeters

The biomass production of the investigated cereal varieties

Higher above-ground biomass production was observed in the second growing season (2020/2021) for all tested varieties. In the 2019/2020 growing season, the biomass of the ‘Mv Nemere’ wheat genotype was the highest (2618 $g{\cdot}m^{-2}$), and we observed the smallest difference between the two studied growing seasons (94 $g{\cdot}m^{-2}$) by this variety. In the first growing season, the lowest biomass was measured for the ‘Mv Ikva’ wheat variety (1674 $g{\cdot}m^{-2}$). In the second studied growing season, the highest biomass (2798 $g{\cdot}m^{-2}$) was observed in the case of the ‘Mv Ikva’ wheat variety, and the lowest (2144 $g{\cdot}m^{-2}$) by the ‘Mv Kolompos’ wheat variety. The average of the biomass values of our examined varieties in the first examined period was 1998 $g{\cdot}m^{-2}$, compared to this, the biggest difference was observed by the ‘Mv Ikva’ wheat variety. In the second period, the average value was 2473 $g{\cdot}m^{-2}$, and the biggest difference was observed in the case of the ‘Mv Nemere’ wheat variety.

The yield production of the investigated cereal varieties

We determined that in the second growing season (2020/2021) the investigated varieties produced more crops, except for the ‘Mv Nemere’ wheat variety. In the 2019/2020 growing season ‘Mv Nemere’ variety had the highest (816 $g{\cdot}m^{-2}$) yield, and we observed the smallest difference between the two studied growing seasons (12 $g{\cdot}m^{-2}$) by this variety. In the second growing season, the ‘Mv Ikva’ wheat variety produced the least grain yield (462 $g{\cdot}m^{-2}$), furthermore by the ‘Mv Hópehely’ and ‘Mv Kolompos’ varieties observed we almost the same yield values (610 and 614 $g\ m^{-2}$). There were similarly small differences between these two varieties in the second growing season (652 and 644 $g{\cdot}m^{-2}$), and the grain yield of the ‘Mv Nádor’ and ‘Mv Nemere’ wheat varieties also barely differed from each other (808 and 804 $g{\cdot}m^{-2}$). In the year of 2021, we observed the highest yield (1000 and 808 $g{\cdot}m^{-2}$) for the ‘Mv Initium’ and ‘Mv Ikva’ varieties, and the biggest difference in the yield (342 $g{\cdot}\ m^{-2}$ and 426 $g{\cdot}m^{-2}$) were also observed in the two examined years.

The harvest index of the investigated cereal varieties

A higher harvest index was determined in the first growing season in the case of the ‘Mv Hópehely’ oat and ‘Mv Nemere’ and ‘Kolompos’ wheat varieties and in the second season in the case of the ‘Mv Initium’ barley, and ‘Mv Ikva’ and ‘Mv Nádor’ wheat. In the two investigated seasons the highest (36 and 39 %) HI was observed by the examined barley cultivar, furthermore the biggest difference from the average HI value also showed by the barley genotype. The smallest difference (<1%) between the two investigated seasons was seen by the ‘Mv Kolompos’ wheat variety and the biggest (4%) was by the ‘Mv Ikva’ cultivar.

The evapotranspiration of the investigated cereal varieties

Higher evapotranspiration values were observed in the second examined period (2020/2021 growing season). In the 2019/2020 season, the highest ET (369 mm) was measured by the ‘Mv Nemere’ wheat variety and the lowest (275 mm) by the ‘Mv Ikva’ weak variety. In the second examined period, the highest value (386 mm) occurred for the ‘Mv Kolompos’ wheat variety, while the lowest (344 mm) was found by the examined oat variety. The largest difference in the evapotranspiration values (76 mm) between the two growing seasons was observed by the ‘Mv Ikva’ wheat variety, while the smallest difference (3 mm) occurred by the ‘Mv Nemere’ wheat variety. In the case of the examined oats variety (‘Mv Hópehely’), the difference between the two years was also not considerable (13 mm). In the first examined period, the average of the ET values was 326 mm, ET of the ‘Mv Ikva’ and ‘Mv Nemere’ wheat varieties deviated from the average the most. In the second examined growing season, the average ET was 363 mm, in this period we could observe the largest deviations from the average values in the case of the ‘Mv Kolompos’ and ‘Mv Hópehely’ genotypes. Based on the monthly sums of ET, in the first examined year we observed that, the highest monthly amount of ET was in April and in the second year in May, and that the plants evaporated more in the first growing season in March and April, and in May and June in the second growing season. The exceptions to this are the varieties the ‘Mv Ikva’ wheat and ‘Mv Initium’ varieties, in the case of the wheat variety we could measure a higher value in May 2021, while for the barley variety in June 2020.

The agronomical constant of the investigated cereal varieties

The lowest agronomic constant values were seen in the second examined period (2020/2021 growing season), except for the ‘Mv Ikva’ wheat variety. In the first examined period (2019/2020 growing season), the highest value (3.24) was determined for the ‘Mv Nemere’ wheat genotype, while the lowest (2.41) was determined for the ‘Mv Ikva’ wheat variety. In the second examined period, the highest value (2.76) was calculated for the ‘Mv Kolompos’ wheat, while the lowest value (2.45) was found by the examined oat variety (‘Mv Hópehely’). The average K_a of the examined varieties was 2.86 in the first year and 2.60 in the second. The largest deviation from the average was observed in the case of the 'Mv Ikva' and 'Mv Nemere' in the first examined period, and in the case of the 'Mv Kolompos' and the oat variety in the second period. The agronomic constant of the tested varieties was also determined monthly. We observed that its K_a values increased from March to May of the first year examined, and then this parameter decreased significantly in June; which indicates a decrease in the water consumption of the plants in parallel with the ripening. Similar trends can also be seen in the second examined year, but in the case of the Mv Hópehely autumn oat variety, we see a difference. The agronomic constant of the variety increased from March to May and this value decreased significantly by June, but still remained higher than the March and April values. We observed a decrease in the Ka value of the spring barley species (Mv Initium) and the wheat varieties (Mv Ikva, Mv Nádor, Mv Nemere and Mv Kolompos) in April 2021, compared to the value calculated for the previous month, which can be explained by the low moisture content of the soil.

The water-use efficiency of the investigated cereal

In the second examined growing season (2020/2021), we determined higher WUE values calculated based on the biomass for all investigated varieties, except for the 'Mv Kolompos' wheat variety. In the first examined period (2019/2020 season), the highest value (7.088 $g \cdot mm^{-1}$) was determined for the 'Mv Nemere' wheat variety while the lowest (5.614 $g \cdot mm^{-1}$) was determined for the oat variety ('Mv Hópehely'). In the second period, the highest WUE_{BM} value (7.972 $g \cdot mm^{-1}$) was calculated for the 'Mv Ikva' wheat variety, and the lowest (5.548 $g \cdot mm^{-1}$) for the 'Mv Kolompos' wheat cultivar. The WUE_{BM} value of the two examined periods differed the least for the 'Mv Kolompos' variety and the largest for the 'Mv Ikva' variety. In the first examined period, the WUE_{BM} value was on average 6.111 $g \cdot mm^{-1}$, the most significant deviation from the average was observed by the 'Mv Nemere' variety, while in the second year, the average was 6.828 $g \cdot mm^{-1}$ and the largest deviation was shown by 'Mv Kolompos' genotype. The water-use efficiency related to grain yield (WUE_y) was higher in the second examined period, with the exception of the 'Mv Nemere' and 'Mv Kolompos' wheat varieties. In the first examined period, the highest value of WUE (2.21 $g \cdot mm^{-1}$) was observed by the 'Mv Nemere' wheat variety and the lowest (1.68 g·mm-1) by the 'Mv Ikva' wheat variety. In the second period, the highest WUE_y value was determined for the investigated barley variety (2.87 $g \cdot mm^{-1}$) and the lowest for the 'Mv Kolompos' cultivar (1.67 $g \cdot mm^{-1}$). Between the two examined years, the smallest differences occurred in the examined oat variety ('Mv Hópehely') and ‘Mv Nemere’ (0.06 and 0.05 g·mm^{-1}) variety; the biggest differences were observed for the barley variety and ‘Mv Ikva’ wheat variety (0.73 and 0.85 g·mm^{-1}). The average WUE_y value of the examined varieties was 1.93 g·mm^{-1} in the first period and 2.21 g·mm^{-1} in the second. The largest deviation from the average was observed in the case of the ‘Mv Nemere’ and ‘Mv Ikva’ wheat varieties in the first examined period and in the case of the examined barley and ‘Mv Kolompos’ cultivar in the second period.

The precipitation-use efficiency of the investigated cereal varieties

In the second of the two investigated periods (2020/2021), we could observe higher precipitation-use efficiency values. In the first investigated growing season (2019/2020), the highest value (2.46 g·mm^{-1}) was observed by the ‘Mv Nemere’ wheat variety, while the lowest (1.39 g·mm^{-1}) was determined by the ‘Mv Ikva’ wheat variety. In the second examined period, the highest PUE value (4.62 g·mm^{-1}) was observed by the investigated barley variety (‘Mv Initium’), and the lowest (2.97 g·mm^{-1}) by the ‘Mv Kolompos’ wheat variety. The average PUE value of the examined varieties was 1.91 g·mm^{-1} in the first examined period and 3.69 g·mm^{-1} in the second. The largest deviation from the average was observed in the case of the ‘Mv Kolompos’ in the first growing season and the case of the examined barley variety in the second period.

The discussions of the results of the lysimeter experiment

Groh et al. (2020) in their lysimeter experiments, found the biomass values of the examined varieties of oat and wheat showed almost the same value in the area with different rainfall, but the biomass of the variety of the tested barley was higher in the drier area. Based on our results, the biomass of the varieties grown in the lysimeter was higher in the drier growing season, especially the tested barley variety and the early-maturing wheat variety showed the greatest difference. The biggest difference between the two investigated periods was found by the ‘Mv Initium’ and ‘Mv Ikva’ varieties; we measured higher values in the year when more precipitation fell in April and May. According to Umair et al. (2019) despite the significant (more than one and a half times) difference in rainfall between seasons, only negligible differences were measured in terms of biomass by the investigated wheat genotypes. We also observed these trends in the results of the ‘Mv Initium’ and ‘Mv Ikva’ varieties. Groh et al. (2020) results were similar; the value of the grain yield was higher in the drier area for winter barley, oat and wheat. The yield of the late-ripening varieties (‘Mv Hópehely’ oat variety and ‘Mv Kolompos’ wheat variety) differed only slightly between the two years, the grain yield of the ‘Mv Nemere’ wheat variety was higher in the wetter growing season. Umair et al. (2019) measured significantly higher grain yield values for wheat as a result of significant rainfall excess. A higher Harvest index could be determined by the 'Mv Hópehely' oat variety, 'Mv Nemere' and 'Mv Kolompos' wheat varieties in the wetter growing season, while for the barley variety 'Mv Initium' and 'Mv Ikva' and 'Mv Nádor' wheat varieties in the drier period. The results of the early ripening varieties are similar to the findings of Groh et al. (2020), according to which higher HI values can be determined in a drier area. In agreement with the findings of Groh et al. (2020) and Umair et al. (2019), in our experiment, we could determine higher evapotranspiration in the growing season when more significant precipitation was observed in April and May. Examining the monthly evapotranspiration values, we observed an increasing trend in the wetter year until the end of April, which after significantly decreased it in the following months. Groh et al. (2020) and Tezera et al. (2019) also found similar trends for barley, wheat and oat. When the water-use efficiency values were calculated on the basis of grain yield the WUE were higher in the drier year, except for the 'Mv Nemere' and 'Mv Kolompos' wheat varieties, similar to the results of Groh et al. (2020). In their experiment, the WUE values of the studied varieties were higher in the drier area, and if the WUE was calculated based on biomass, higher values were also determined in the drier area. In the case of spring wheat and naked oat, Zhang et al. (2015) found that the maximum WUE coincided with warm and dry weather conditions, and the minimum values were calculated under warm and wet climatic conditions. We found higher WUE values for all studied varieties except for the late-maturing wheat variety, when we calculated it based on biomass, in agreement with Groh et al. (2020) results.

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Conclusions

In our greenhouse experiments, we examined six Martonvásár-bred winter cereal varieties at current atmospheric and elevated (700 ppm and 1000 ppm) carbon dioxide concentrations, at three irrigation levels (optimal water supply and water withdrawal treatment applied at tillering or heading developmental stage). Under controlled climatic conditions, we investigated the effect of two factors on the biological production and water circulation parameters of our selected varieties. Among these, the simulated water deficit is a stress factor, and the elevated carbon dioxide concentration is a factor, in connection with which much research have pointed out that species and varieties react very differently to the level of carbon dioxide. Thus, this factor can be a stressor, but it can also increase production. Based on several parameters, it was shown that the 'Mv Initium' barley variety reacted positively to the increase in CO_2 concentration, and this factor was not present as a stressor but as a stimulator for this variety. In the case of the barley variety, we observed that the elevated carbon dioxide concentration not only alleviated the negative effects of the applied drought treatments but also significantly improved the yield parameters. In the case of the tested oat variety ('Mv Hópehely'), the increase in carbon dioxide concentration acted as a stressor, and a negative carbon dioxide reaction was observed. The 'Mv Hópehely' variety showed considerable sensitivity to both applied stress treatments, although to a greater extent to the drought stress at heading, in addition, an increase in the carbon dioxide level did not alleviate the effects of the drought treatment, but aggravated them, in the case of several parameters. In regard to the four wheat varieties, we found a correlation between the effects of drought stress applied at different stages of development, the CO_2 reactions and the ripening groups. According to our investigations, the early-ripening variety ('Mv Ikva') was most severely affected by the applied drought treatment, which was not alleviated even by increasing the carbon dioxide level. In the case of early-ripening varieties, increasing the CO_2 level acted as a stressor. In the medium-ripening varieties ('Mv Nádor' and 'Mv Nemere'), the drought reduced the tested parameters less, and a positive CO_2 reaction was observed in these varieties, especially in the case of the 'Mv Nemere'. The best drought tolerance was observed in the late-maturing wheat variety ('Mv Kolompos'), this variety also showed the most favourable CO_2 reactions at 700 ppm and 1000 ppm levels. The 700 ppm carbon dioxide concentration did not cause any significant differences in the water uptake of any of the studied species or varieties, regardless of the level of water supply, compared to that observed at the current atmospheric level. On the other hand, the 1000 ppm level of the gas significantly reduced the water uptake compared to the current atmospheric level, and the time of application of water withdrawal did not influence this trend either. The positive effect of the carbon dioxide level on the water-use efficiency of the tested plants was already demonstrated at a level of 700 ppm, but this effect was even more pronounced at a level of 1000 ppm

Due to climate change, extreme events are occurring more frequently in our country - including intense and long-lasting droughts - which threaten the crop safety of our cultivated plants. An important indicator of drought tolerance is water-use efficiency. Examining carbon and water circulation is important in the breeding of drought-tolerant varieties, so in the course of our work, we tried to set up experiments and experimental systems in which we can determine this parameter as precisely as possible. We determined the water-use efficiency of various Martonvásár-breed cereal in a greenhouse model experiment, in the field, and in a lysimeter experiment system. Among the examined varieties, the oat variety (‘Mv Hópehely’) had the lowest values in all three experimental systems. The late-maturing wheat variety (‘Mv Kolompos’) showed low WUE and PUE values in the greenhouse and lysimeter experimental systems, similar to the oat variety, lower compared to the other tested wheat varieties, but in the field system, the PUE values of the ‘Mv Kolompos’ variety were also high. The water- and precipitation-use efficiency of the early- (‘Mv Ikva’) and mid-ripening wheat varieties (‘Mv Nádor’, ‘Mv Nemere’) show a very similar trend in all three experimental systems. The tested barley variety (‘Mv Initium’) had similarly high PUE values as the other tested early ripening variety (‘Mv Ikva’), but in the greenhouse system the WUE value of the tested barley variety was lower than that of the ‘Mv Ikva’, but in the lysimeter system it exceeded it. Based on our results, we determined that the variability of the varieties in terms of the water-use efficiency of the varieties grown in the lysimeters and the precipitation-use efficiency of those developed in the field was the same, and the results of the greenhouse system also follow the trends determined in the other systems.

We have observed that the water- or precipitation-use efficiency of plants grown in different systems if they are not the same in absolute terms, show similar trends. The lowest values were determined for the plants grown in the greenhouse experimental system, whereas higher WUE values were obtained for the plants grown in the lysimeters. The PUE values determined in the lysimeter system were higher than the WUE values determined in the lysimeter system. The highest values were determined in the field experimental system. The lysimeter experimental system allows for the most accurate determination of evapotranspiration, but due to the large investment requirements and the complicated operation, it cannot represent a perspective for testing the water circulation of a wide range of genotypes for breeding purposes. The greenhouse model experimental system developed by us can also be used effectively for testing a wide range of varieties.

In the early stage of the development of winter cereal the tillering in the autumn and in the period of vegetative development in spring, lack of water is typically not the main limiting environmental factor, even though more and more often precipitation-lacking periods may occur at the end of winter and beginning of spring. Water uptake is primarily influenced by, if it occurs, in which phase of the generative development the water shortage occurs and whether it affects the yield. Based on these, if water is available in the soil, during vegetative development the plants take up the necessary amount of water regardless of the amount of yield, which in turn accounts for a significant part of the total water demand during the growing season. However, the water-use efficiency is typically affected by the last month and a half of development, when the water circulation is already reduced in intensity, but it is during this period that it is decided how the previously used amount of groundwater is utilized from the production area. The water-use efficiency cannot be separated from drought tolerance, since species and varieties that can take up the soil's water resources in a wider range, with appropriate root structure and plant physiological mechanisms can maintain their assimilating surface for longer, translocation can be more efficient and produce a higher yield level, so their water-use efficiency can also be more efficient.

New results (theses)

1. We have developed a model experimental system suitable for determining the water-use efficiency of winter wheat, winter barley, and winter oat varieties, validated with lysimeter data, high throughput, and enabling the testing of a wide range of cereal varieties. The new experimental methodology can be used for the comparative investigation of the water-use efficiency of strains developed in breeding, and also for the selection of varieties that can be tested in the lysimeter system from a wider range of varieties in basic research.
2. The parallel application of several different experimental systems can provide the most accurate method to determine water circulation and water-use efficiency. Controlled climatic conditions are necessary to examine the correlations between stress responses and water turnover, however, the obtained water-use efficiency values can only be used for genotype comparison. The results of the lysimeter and field systems provide data that can be used in agronomic practice, however, due to the complex interactions of the environmental conditions, the water circulation effects of the individual factors can be estimated using a model.
3. Drought tolerance and water-use efficiency are inseparable indicators, water-use efficiency alone as an indicator is not suitable for characterizing drought tolerance. The variability in productivity is significantly greater than the variability in evapotranspiration of the varieties.
4. Under greenhouse conditions, the most sensitive varieties to the applied drought stress treatments were the ‘Mv Hópehely’ oat variety and the ‘Mv Ikva’ wheat variety, and in these varieties, the negative effects of drought stress could not be offset by the elevated carbon dioxide concentration. The most favourable drought tolerance was observed in the late-ripening wheat variety (‘Mv Kolompos’) and the barley variety (‘Mv Initium’) under greenhouse conditions. The CO_2 reaction of these varieties was the most favourable, the increased carbon dioxide concentration alleviated the negative effects of the drought treatments.
5. Compared to the current atmospheric level, the artificial increase of the carbon dioxide concentration had a positive effect only at the 1000 ppm CO_2 level, among the examined carbon dioxide concentrations; with regard to the water requirements of the winter wheat varieties, the water uptake of the tested species and varieties was significantly reduced even in the case of optimal water supply and simulated drought.

Publications related to the present study

Research papers

Farkas, Z., Anda, A., Vida, G., Veisz, O., Varga, B. (2021): CO_2 responses of winter wheat, barley and oat cultivars under optimum and limited irrigation. In: *Sustainability,* 13 9931.

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