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EFFECT OF INCREASED ATMOSPHERIC CO_2 CONCENTRATION AND OTHER ENVIRONMENTAL FACTORS ON WINTER WHEAT (*Triticum aestivum* L.)

Main points of the PhD Thesis

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Introduction

The atmospheric concentration of CO_2, which was approx. 280 ppm for centuries prior to the industrial revolution, has now increased to around 380 ppm. Even the most optimistic predictions suggest that it will reach 550 ppm by 2100, while it may even be as high as 1000 ppm. Over the course of the last century the mean temperature of the Earth rose by 0.6°C, the North Pole ice cap became 40% thinner and sea level rose by around 12 cm. The cost incurred each year due to increasingly frequent climate anomalies can now be measured in billions of dollars. Numerous factors involved in climate change have an influence on agriculture. Higher mean temperatures accelerate plant development, resulting in a shorter vegetation period and smaller yields. Although the increase in the atmospheric CO_2 concentration has an indirect negative influence due to the greenhouse effect, it also stimulates biomass accumulation, thus increasing yields. The increase in the number of heat days during maturation not only causes yield losses but also leads to a deterioration in quality. Rainfall deficiency, like high temperatures, has a negative effect on both the quantity and quality of yield, while excessive rain may delay ripening and lead to a high yield with poor quality.

Among the research projects on global climate change currently underway in the Agricultural Research Institute of the Hungarian Academy of Sciences, the thesis deals with the results of experiments on nutrient supplies, heat stress during ripening, and the consequences of changes in the atmospheric CO_2 concentration in winter wheat.

Aims

In the course of the experiments, answers were sought to the following questions:

1. What effect does high atmospheric CO_2 concentration have on winter wheats, most of them Hungarian, with different genetic backgrounds? What changes in morphology, phenology and the quantity and quality of yield are caused by doubled CO_2 level and how are these related to plant nutrient supplies?
2. What effect does extremely high temperature during ripening have on winter wheat varieties with different agronomic traits and genetic backgrounds? How do nitrogen supplies affect heat stress tolerance?
3. Is a high CO_2 level able to reduce or balance out the damaging effects of heat stress and how does yield quality change due to the interaction between these

two factors? How do nitrogen supplies influence the effects of increased atmospheric CO_2 concentration on the heat stress tolerance of wheat varieties?

Materials and methods

Growing conditions and nutrient treatments

The experiments were carried out on the winter wheat varieties Martonvásári 15 (Mv 15), Mv Martina, Mv Emma, Mv Mezőföld and the Polish variety Alba in growth chambers (Conviron PGV-36, Controlled Environments Ltd., Winnipeg, Canada) in the phytotron of the Agricultural Research Institute of the Hungarian Academy of Sciences in several steps between 1999 and 2004. The atmospheric CO_2 concentration in the chambers was ambient (375 μmol mol^{-1}) or doubled (750 μmol mol^{-1}).

For the analysis of early development, in addition to the nutrients present in the soil, 25 combinations of five levels each of nitrogen (0, 100, 200, 400 and 800 mg kg^{-1} soil dry weight) and phosphorus (0, 50, 100, 200 and 400 mg kg^{-1} soil dry weight) were mixed with the soil. In order to study the effect of nutrient supplies the plants received **0N+0P** (control), **400N+200P, 800N+200P** or **800N+0P** mg kg^{-1} dry soil, dissolved in tapwater, in ten instalments up to heading, in addition to the other macro- and micronutrients. In the heat stress experiment, the plants were supplied with 0 or 400 mg nitrogen (**0N, 400N**) kg^{-1} soil dry matter, dissolved in tapwater, as in the nutrient supply experiment.

Heat stress treatment

As the plants headed at different times in the various treatments, heat stress was commenced on the 12th day after the mean heading date of each group, to ensure that the plants were in the same phenophase during the treatment. For the period of the treatment the plants were transferred to two other chambers where the maximum temperature was 35°C for 8 hours, with a night minimum of 20°C and a daily mean temperature of 25.2°C. All the other plant growth conditions, including the CO_2 level, were the same as in the control. After the 15-day treatment the plants were returned to their original chambers.

Determination of morphological, phenological and yield data

In the early development experiment measurements were made on plant height, tiller number, leaf number, leaf area per plant (Automatic Area Meter AAM-7, Hayashi Denkoh, Tokyo, Japan), shoot dry weight and total root dry weight per pot. An analysis was made of shoot nitrogen content (Kjeltec Auto Sampler System 1035 Analyser, Tecator, Sweden) and the photosynthetic pigment composition was determined by measuring the absorbance at 644.8 and 661.6 nm in a pure acetone extract. Values of chlorophyll-a, chlorophyll-b, total chlorophyll and total carotenoids were calculated using the equations suggested by Lichtenthaler (1987).

The Zadock's scale was used to distinguish the plant development stages (Tottman and Makepeace 1979). A record was made of the appearance of the second tiller, the heading date for each tiller and the date of full maturity (stages 12, 59 and 92 on the Zadock's scale). After harvest, measurements were made of the total aboveground biomass (biomass), the spike number, the number of grains and the grain yield per plant. The thousand-grain weight was calculated from these data for each plant, and the harvest index was determined according to Donald (1962).

Chlorophyll fluorescence induction measurements

For the investigation of photosynthesis the chlorophyll fluorescence induction parameters were determined on the middle part of the fully developed leaves in the growth chambers in light using a PAM-2000 fluorometer (Walz, Effeltrich, Germany). The quantum yield of Photosystem II ($\Delta F/Fm'$) was calculated as suggested by Genty et al. (1989). The nomenclature described by Kooten and Snel (1990) was used for the chlorophyll fluorescence induction parameters.

Determination of yield quality

The protein content of the wholemeal was determined using a Kjeltec Auto Sampler System 1035 Analyser (Tecator, Sweden), converted to dry matter content and using a factor of 5.7 (ICC Standard 105/2). The wet gluten content was measured from the flour according to ICC Standard 137/1, while the gluten index was calculated from ICC Standard 155 (Perten method).

Statistical analysis

The data were evaluated using two- and three-way ANOVA and the two-sample Student t-test.

Results

The effects and interactions of increased atmospheric CO_2 level, nitrogen and phosphorus supplies, and high temperature during maturation were studied under controlled conditions on winter wheat varieties with different genetic backgrounds in phytotron experiments. It was found that the diverse responses of the individual genotypes and changes in environmental factors could explain the contradictory results previously published in the literature.

The main results can be summarised as follows:

Relationship between doubled CO_2 level and nutrient supplies

- A comparison between the responses of the Hungarian variety Mv 15 and the Polish variety Alba at the tillering stage revealed an increase in the tiller number in Mv 15 as a response to a higher atmospheric CO_2 level, while Alba plants grew taller, forming greater fresh mass.
- At the doubled atmospheric CO_2 level photosynthesis was more intensive and more biomass was accumulated. It was found that the soil nitrogen level optimum for plant development shifted to a higher value, while the increase in CO_2 had the greatest effect at N values close to the optimum (except in the case of root mass).
- At low N supply levels the aboveground biomass did not increase in response to higher atmospheric CO_2 level, but the root mass increased to a maximum as the result of greater nutrient requirements.
- It was proved that at above-optimum soil N levels the inhibitory effect of nitrogen could be mitigated by high CO_2 concentration. In Alba an increasing concentration of phosphorus also played a role in reducing the inhibition caused by the highest soil N content.
- The reduction in N content frequently observed in the shoots as the result of higher atmospheric CO_2 level was only significant at N levels above or below the optimum range, as the plants were best able to maintain a balanced nutrient composition, with an ideal C/N ratio, at around the optimum N level.
- The photosynthetic pigment content in the leaves was determined fundamentally by the genotype. In Alba no change was observed at higher atmospheric CO_2 level, while in Mv 15 the pigment content was stable at higher atmospheric CO_2 level over a wide

range of soil N treatments (at all but the highest, 800 mg/kg level). At ambient atmospheric CO_2 level, however, the quantity of chlorophylls and carotenoids was proportional to the nitrogen supplies in both varieties.

- The team was one of the first to prove changes in plant heading at enhanced atmospheric CO_2 level. With favourable nitrogen supplies heading was found to begin several days later in all three varieties tested, but the rate was faster for Mv Martina and Mv Emma, where there was also an increase in the number of spikes. At low nitrogen supply levels the spike number did not differ at the two CO_2 levels, but the spikes appeared at a faster rate at doubled atmospheric CO_2 level in Mv Martina and Mv Mezőföld, while there was no change in the heading parameters of Mv Emma.
- The team was the first to record the effect of higher atmospheric CO_2 level on ripening. Plants grown at the doubled atmospheric CO_2 level with favourable nitrogen supplies were found to begin ripening latest. At full maturity, however, there was only a significant difference for one variety, Mv Mezőföld, where the ripening process was shorter at high atmospheric CO_2 level.
- The role of phosphorus in certain developmental stages was also proved. The appearance of the second tiller was accelerated by the presence of phosphorus, but the ripening of the spikes was delayed by a few days. In the case of phosphorus deficiency the yield quality was found to be poorer despite the high nitrogen supply level.
- Doubled atmospheric CO_2 concentration was found to increase the grain number and the grain mass both separately and together. An explanation was found for the phenomenon occasionally described in the literature, when a reduction in thousand-grain mass was recorded in response to higher atmospheric CO_2 level. This could be a consequence of the interaction between high nutrient supplies and the enhanced atmospheric CO_2 level, since the quantity of organic matter per grain declined compared with the greatly increased grain number.
- The yield generally increased at doubled atmospheric CO_2 level, but in some cases, depending on the variety and the nutrient treatment, there was an increase in the biomass, but not in the yield.
- Higher atmospheric CO_2 level was found to influence the quality of the grain yield, depending on the genotype. At low nutrient supply levels there was a decrease in the grain protein content, for two genotypes also in the gluten quantity and gluten index, and the quality deteriorated, but all in all the quality of Mv Emma, a variety giving

excellent grain quality, did not decline. At higher nutrient levels, however, the grain quality only deteriorated at doubled atmospheric CO_2 level in one variety, Mv Mezőföld.

Effect of heat stress

- The experiments proved that in response to heat stress the plants matured earlier and exhibited a reduction in biomass and grain yield. Changes in grain quality, however, were also influenced by the genotype; unlike the other genotypes, in Mv Martina there was no reduction in grain quality as the result of heat stress.
- The investigations demonstrated that the reduction in grain yield in response to heat stress was smaller at low nitrogen levels than with normal nitrogen supplies, but the parameters examined (protein and gluten content, gluten index) indicated that the best grain quality was achieved in the 0N×heat stress or 400N×heat stress treatment, depending on the variety.

Changes in heat stress tolerance in response to nitrogen supplies and high CO_2 level

- Higher atmospheric CO_2 level was proved to reduce the damaging effect of heat stress on biomass and yield quantity.
- At normal nitrogen supply levels the protein and gluten contents of the yield in heat-stressed plants were either lower at doubled atmospheric CO_2 level than at ambient level, or were unchanged, while there was no substantial change in gluten quality in response to higher atmospheric CO_2 level.
- The quantitative and qualitative parameters of the grain yield were generally closest to those recorded at normal N level and temperature, at the ambient CO_2 concentration, when heat stress was applied at doubled CO_2 concentration with low nitrogen supplies.

Conclusions

The experiments proved that it is not sufficient to examine a single variety in order to understand the effects of climate change on cereals. Using an example from Hungary, it was illustrated that extremely diverse response types can be found even within a single species among cultivated varieties bred locally in a relatively small growing region. The differences demonstrated between genotypes raise the possibility of using conventional breeding methods to develop gene combinations providing better adaptability to changed environmental conditions, which can then be used to produce new varieties.

References

Scientific publications serving as a basis for the thesis

1. Papers in reviewed journals

2. Books, book chapters

3. Conference proceedings, abstracts