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REGURAL ARTICLE

Modeling maize response to climate modification in Hungary

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ABSTRACT

Modeling provides a tool for a better understanding of the modified plant behaviour that results from various climatic differences. The present study provides new information about the physiological processes in maize (*Zea mays* L.) in response to climatic changes. The aim was to help local farmers adapt to climate modifications in Hungary and mitigate the future consequences of these changes. A simulation model was applied to estimate the possible feedback on crop properties and elevated CO_2. Increased CO_2 and warming increased the ratio of energy converted into sensible heat. At canopy level, warming and elevated CO_2 strengthened the influence of an external rise in air temperature. It was cooler inside the stand, as the canopy was able to compensate for external warming. Doubled CO_2 concentration had a positive influence on photosynthesis when rainfall remained unchanged. Precipitation shortage decreased the positive effects of warming and elevated CO_2. Considering the sensitivity of the photosynthetic process to meteorological factors, a gain in maize production with climate modification is not probable in Hungary.

Key Words: *global warming; greenhouse gases; maize response; simulation.*

INTRODUCTION

According to the latest prognosis of Intergovernmental Panel on Climate Change (2001), the air temperature rise by the end of the 21st century is predicted to be between 1.4 to 5.8°C. The data refer to changes on a global scale, but meaningful alterations may occur at the local or country level. All predictions indicate that the Carpathian Basin will warm up. The extent of temperature increase predicted depends on the model type applied, the boundary conditions, and the initial values of the parameters used for the simulation. In literature, as a rule, the later the date of publication, the higher the temperature prognosticated. In Hungary, the temperature rise is very close to the global average, though possibly a little higher in summer (Mika et al., 2001). Much uncertainty exists about the amount of rainfall. In spite of the decreasing trend in annual precipitation in recent decades, the higher the extent of warming is, the greater the likelihood that the change in the yearly amount of rainfall will have a positive sign. On the basis of downscaling of global circulation models, Mika (2002) published a local climate prognosis for Hungary. Four scenarios were examined for the summer and winter half-years separately. The great uncertainty of rainfall predictions is clearly illustrated by the fact that rainfall changes, ranging from 40 mm deficiency to a 400 mm surplus, have been prognosticated for a temperature rise of 1 to 4°C in Hungary (Table 1, adapted from Mika (2002)). The author also draws attention to the fact that the sign and extent of the predicted change in precipitation also depend on the Global Circulation Model applied and on downscaling. Some investigators (e.g., Mika et al. 2001) assume a decline in rainfall of about 10% with a shift in its seasonal distribution (drier summers).

Table 1. Prognosis of air temperature and precipitation for 2100 in Hungary (after Mika, 2002).

Global changes	+ 0.5 °C	+ 1 °C	+ 2 °C	+ 4 °C
Air temperature (°C) Summer half year	+ 1.0	+ 1.3	+ 2	+ 4
Air temperature (°C) Winter half year	+ 0.8	+ 1.7	+ 3	+ 6
Precipitation (mm) Yearly sum	- 40	- 66	Uncertain	40–400 (Extremely uncertain)

Crops are extremely sensitive to climate modifications for the following reasons:

1. All bio-physical processes are governed by plant temperature. Even slight variations in the air temperature would affect physiological processes due to the direct relationship between air and plant temperatures. Because plants adapt to their environment across a long period of time, sudden modifications would probably affect them unfavorably.

2. In most temperate zones, the limiting factor in crop production is the available soil water that originates from precipitation. Not only the amount of seasonal rainfall, but also its distribution, is of primary importance for plant life.

3. An elevated level of CO_2, one of the greenhouse gases, may have a positive role in photosynthesis. However, the final consequences cannot be foreseen if changes also occur in meteorological conditions.

The weather has a significant impact on food production. Any change in climatic elements could modify the life cycle of food crops. Crop simulation models have great potential for predicting plant responses under changing climates. They could provide the basis for a better understanding of the modified plant behaviour resulting from various climatic differences. There are two ways to estimate the future consequences of global warming: search for analogies from the past or via the use of modeling. The present study was designed to provide new information about the physiological processes in maize under climatic changes via modeling.

MATERIAL AND METHODS

A simulation model was applied to forecast modifications in the energy consumption and physiological processes of plant stands as a result of climate variation. The inputs (meteorological and plant features) in the simulation applied were collected locally at the Keszthely Agrometeorological Research Station, Hungary. Data were available for the past 128 years, but meteorological data only for the last eight years were used, because a QLC-50 automatic climate station was established only in 1997. During these eight years, the sampling frequency of the automated station (every six seconds) allowed the meteorological data to be used as model inputs. Hourly averages were not available previously, as the observations were made every six hours.

A mid-season maize hybrid, "Norma" (FAO 450), had been planted in April for three decades since the 1980s at a plant density of 7 plants m^{-2} on plots fertilised with 100 kg ha^{-1} N, 80 kg ha^{-1} P and 120 kg ha^{-1} K in autumn. The hybrid was harvested in the second half of September. The crop was grown using the prevailing technology of this region, as recommended by experts from the local Agricultural University. The climate of Keszthely was highly favourable for maize production (Table 2).

Table 2. Monthly climatic norms in the growing season in Keszthely (1971-2000).

Month	Monthly mean temperatures (°C)	Rainfall (mm)
March	5	36
April	10.4	43
May	15.3	74
June	18.7	79
July	20.6	76
August	20.4	71
September	16.8	57
October	10.3	58

Plant-specific model inputs, such as plant height and leaf density in different layers of canopy, and site-specific model inputs, such as soil characteristics and hourly meteorological data (air temperature, global radiation, relative humidity, soil surface temperatures), were transformed into reference level values required by the model (Anda et al., 2002b). The leaf area and its density were measured weekly in the field on the same 10 sample plants, using a LI-COR 3000A type leaf area meter. The model divided the whole canopy into homogeneous layers. The number of layers depended on the actual structure of the plant stand. In the present case, three layers in the fully developed canopy were used (July). The height of the completely developed sample maize plant was 2.20 m, with a leaf area index of 3.0.

The soil moisture content in the upper 1 m was gravimetrically measured in the field every 10 days at 10-cm intervals. The actual soil water content was expressed as soil water potential. The physical properties of the Ramann type brown forest soil (heat capacity, heat conductivity, etc.) were determined at the beginning of the investigations. Among the available outputs, only the values for the cob layer (1.6 m above soil surface) were included in the study.

The basis of the model is the calculation of energy proportioning in the canopy after the reflection and transmission processes:

$$0 = Rn - M - Q_H - \lambda E$$

where Rn is the net radiation (W m^{-2}), M is the metabolic storage (W m^{-2}), Q_H is the sensible heat flux (W m^{-2}), and λE is the latent heat flux (W m^{-2})

The sensible heat flux (Q_{Hi}) in the ith layer is:

$$Q_{Hi} = \rho c_p \frac{T_{ci} - T_{ai}}{r_{aHi}}$$

where T_{ai} is the air temperature in the ith layer (K), T_{ci} is the canopy temperature in the ith layer (K), and ra_{Hi} is the aerodynamic resistance for sensible heat transfer in the ith layer (s m^{-1}).

The latent heat flux (λE_i) in the ith layer was calculated as follows:

$$\lambda E_i = \rho c_p (e_s(T_{ci} - e_s)) / (\gamma(r_{awi} + r_{ci}))$$

where e_s (T_{ci}) – e_i is the difference between the saturation vapour concentration at plant temperature and the actual vapour concentration (m^3 m^{-3}), r_{awi} is the aerodynamic resistance for water vapour transfer in the ith layer (s m^{-1}), and r_{ci} is the crop resistance in the ith layer (s m^{-1}).

After calculating the sensible and latent heat, the air temperature (T_{ai}) in the ith layer was estimated as:

$$T_{a,i} = T_{a,i-1} + H_i R_i / \rho c_p$$

where R_i is the value characteristic of resistance in the ith layer (s m^{-1}) when i =1 (Ta_{i-1}) is the air temperature for the reference level.

The intensity of photosynthesis was calculated empirically after Goudriaan (1977) as:

$$F = (F_m\text{-}F_d)\ (1/\exp\ (R_v/F_m)) + F_d$$

where F_m is the maximum net photosynthesis (g m^{-2} s^{-1}), F_d is the dark respiration (g m^{-2} s^{-1}), and R_v is the absorbed short wave radiation (W m^{-2}).

The stomatal resistance was estimated as follows:

$$r_s=(1.83{\cdot}10^{-6}(C_e-C_r)-0.783\ r_{H,a})/(1.66 + F)$$

where 1.66 is the ratio between diffusivities (CO_2 and water), $1.83{\cdot}10^{-6}$ is the conversion factor of CO_2 (kg CO_2 m^{-2} at 20°C), C_e is the CO_2 concentration in the ambient air, C_r is the CO_2 concentration inside the plant, and 0.783 is the empirical constant given in Goudriaan (1977).

Before applying the Goudriaan model in the present work, validation of physiological characteristics, such as stomatal resistance, canopy temperature and intensity of photosynthesis (Anda and Lőke, 2003), and microclimate elements, such as within-canopy air temperature and humidity (Anda et al. 2001; Anda and Lőke, 2005), was carried out locally. The air temperature and humidity inside the plant stand were recorded in the field with a combined temperature/humidity sensor connected to an LI-1000 DataLogger housed in a Stevenson screen. Stomatal resistance was measured hourly with a porometer of the Delta T4 type on the leaf segment where the resistance was closest to the mean resistance of the whole plant (Anda, 2004). The canopy temperature data were collected with a RANGER II RTL infrared thermometer. The intensity of photosynthesis was monitored via a LI-COR 6400 device every hour. All plant character data used in the validation of the model were collected locally in the field.

To validate the model, the root mean square deviation (RMSD) of a number of pairs (n) of simulated (S) and observed (O) elements was applied:

$$RMSD = ((\sum (O-S)^2)/n)^{0.5}$$

The RMSD is one of the best overall measures of model performance (Willmott, 1982).

In the linear regression between predicted (S) and observed (O) values, $S = a + bO$, the intercept a was not significantly different from zero at α = 5%. So a regression through the origin was applied (Sváb, 1981). The slopes of the curves were not significantly different from 1 (each 95% confidence interval included 1). The statistical analysis of data indicated that the model gave an appropriate estimation of both physiological values and microclimate elements. Further details can be found in the cited publications (Anda et al., 2002a).

Slight adjustments were made to facilitate model application without affecting the basic structure of the model (Anda et al., 2001). The reconstruction of the Goudriaan model was designed to make it easier to enter measured data and to display the results in a user-friendly manner. A further aim was to increase the maximum number of input data, which was previously limited to 20 values.

For the four scenarios, an “average day in July” served as the benchmark. In the additional treatments, the widely applied value of elevated CO_2 (760 ppm) and air temperature (4°C) were constant, while the water supply varied as follows:

- Mean soil water content representing Keszthely climatic conditions in July (–7 bar soil water potential) between 1971-2000.

– Mean soil water content reduced by 20% (dry treatment), equivalent to a 10% decrease in precipitation.

– Soil water content reduced to close to the wilting point (–14 bar water potential; extra-dry treatment), equivalent to the severe drought experienced in Keszthely approximately every 10 years.

The increase in air temperature was in accordance with the prognosis of Mika (2002) for Hungary. The basic CO_2 concentration was measured locally with an infrared gas-analyzer during each season.

RESULTS AND DISCUSSION

ENERGY CONSUMPTION OF PLANT STANDS

As a rule, the ratio of sensible and latent heat fluxes is about 30:70 for Hungary during the growing season. Together with photosynthesis, these fluxes are the main users of the energy remaining in the plant stand after reflection and transmission processes. The sensible heat flux, as its name indicates, provides the energy for heating processes. The source of energy for transpiration is the latent heat flux. The energy utilized in photosynthesis (metabolic storage) is relatively low (1–2%) as compared with the two main users (sensible and latent heat fluxes), which is why the proportion of energy bound in photosynthesis was neglected in some research on plant microclimate (Jones, 1983). In the present simulation, every change in the external environment (temperature, CO_2 and water levels) was found to influence the energy consumption of the plant stand (Table 3), even the intensity of photosynthesis (see below).

The elevated CO_2 level and warming increased the amount of energy utilized as sensible heat. A further increase in this heat flux was observed at reduced soil water content. The increase in energy use for “heating” processes was as much as 20% when the available soil water content was close to the wilting point. Parallel with intensified heating processes, the amount of energy in the latent heat category declined gradually. The reduction in latent heat flux in the case of the third and fourth scenarios could be attributed to the lack of water as a “cooling substance.” In a field study, Kimball (1995) reported a 9% decrease in latent heat flux due to elevated CO_2 concentration alone. It was concluded that at constant precipitation, during an “average” July day in Keszthely, higher air temperature and elevated CO_2 strengthened external warming by altering the proportion of sensible and latent heat fluxes.

PROCESSES INSIDE THE CANOPY

The cob layer is important in plant studies, since the assimilatory (or transpiration) surface is the most developed and the intensity of physiological processes is the highest at this level. The within-canopy air temperature is one of the users of sensible heat flux. The air temperature has a regulatory role and governs the plant temperature and the intensity of biochemical processes. By cooling the crop, transpiration helps adjust the plant temperature to that of the air. If there is no water limitation, the plant temperature is close to that of the air. Surprisingly, in the present simulation, the rise in the daily mean of the within-canopy air temperature was lower than the increase in the external air temperature (Figure 1).

Table 3. Influence of doubled CO_2 level on energy division at Keszthely on an average day in July.

	Sensible heat flux (%)	Latent heat flux (%)
Basis (control)	29	71
Air temperature rise, 4°C	65	35
4°C rise and reduced soil water (20%)	38	62
4°C rise and soil water close to wilting point	48	52

The change in daily average air temperatures at the cob level was always below 4°C in all four scenarios. The canopy itself behaved as a compensator, but only within the stand. This more moderate microclimate may favour physiological processes and may also compensate for the effect of global warming.

Some exceptions existed for the afternoon hours, when the soil water content was close to the wilting point. The moderate rise in plant temperature at elevated CO_2 at high radiation levels was in accordance with the findings of Van de Geijn and Goudriaan (1996).

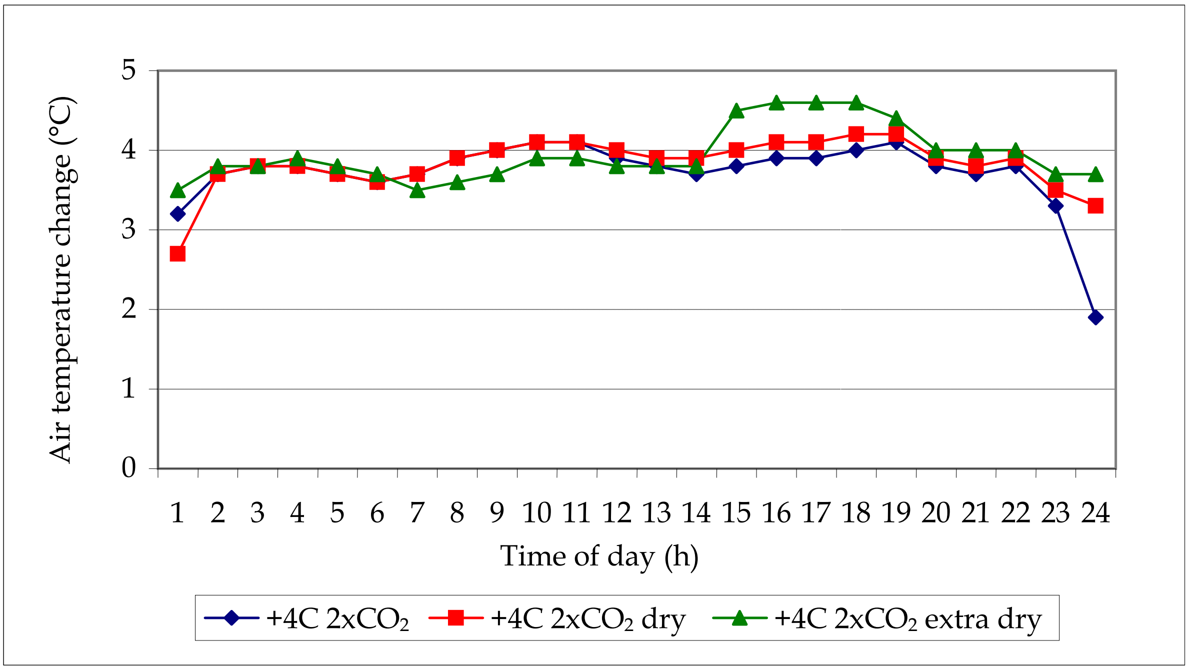

Figure 1. Air temperatures inside the maize canopy at 1.5 m above the soil surface (cob level). Level of global warming was 4°C. Elevated CO_2 was applied in each scenario. There were two water levels, one close to the wilting point and the other 20% below the average level in July.

PHOTOSYNTHESIS AND RESPIRATION IN PLANTS

Crop plants can be divided into two categories: the C_3 and C_4 crops, in which photosynthesis takes place in different ways with different levels of efficiency. The net photosynthesis of C_3 plants is very sensitive to elevated CO_2, so the positive effect of an increase in the greenhouse gases is extremely large. At elevated CO_2, the modification in the physiological processes of C_3 plants exceeds the variation in the net photosynthesis of C_4 plants (Goudriaan and Van Laar, 1994). For the present study, a member of the less sensitive C_4 group (maize) was chosen, assuming that if there were a moderate response in maize at elevated CO_2, the plants in the C_3 group would give an even greater response.

The changes in physiological processes as the result of the simulation are presented in Figure 2. The respiration intensity, shown as the negative part of the figure during the night-time hours, was not sensitive to modifications in climatic variables. There were no significant differences among the four scenarios in the respiration of maize. On the other hand, the reaction of net photosynthesis to increased CO_2 and temperature level was intense. In the case of constant watering during July, the rise in net production reached 21.8%. When the soil water level was reduced by 20% at increased CO_2, there was an increase in net photosynthesis compared with the control, but this increase was only half of that recorded at mean water supplies. The decrease in net photosynthesis was the highest in the extra-dry treatment, being only a third of that recorded for the benchmark scenario (average day in July at Keszthely, at 380 ppm CO_2 level).

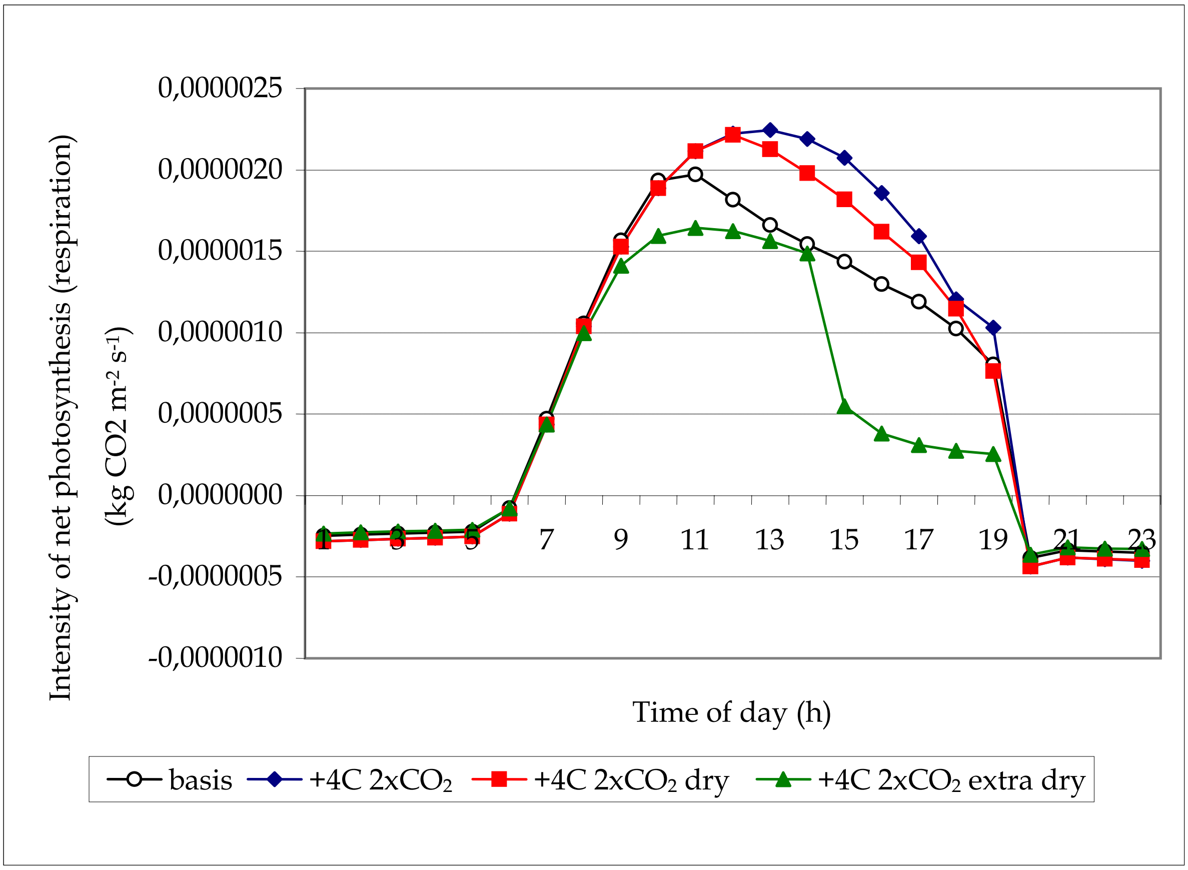

Figure 2. Intensity of photosynthesis and respiration at different CO_2, air temperature and water levels at Keszthely, in July. Photosynthesis takes place whenever there is solar radiation. At night, there is no photosynthesis, but respiration occurs, which uses photosynthates. Hence the negative sign. The dimensions of photosynthesis and respiration are the same.

Stomatal resistance

The study of stomata is of primary importance in plants, due to their role in connecting photosynthesis and transpiration. The basic material for photosynthesis, CO_2, enters the plant tissues through the stomata, from where water vapour leaves the leaf. The very sensitive balance between the resistances of these two gases determines the final plant production. The larger the diameter of the stomata, the more CO_2 can enter into the plant cells, but the higher the water loss. In a moderate climate, the plants partially close their stomata, especially in the afternoon hours, because of the limiting soil water availability.

Significant increases were recorded in the daily mean of stomatal resistance: 253.4, 284.7, and 1395.2 s m^{-1}, in the second, third and fourth scenarios, respectively (Figure 3). In the extra-dry treatment, relatively high values of stomatal resistance were simulated, particularly in the afternoon hours. These findings are in accordance with the changes in sensible and latent heat fluxes presented here.

The partial closure of the stomata in the extra-dry treatment caused a decrease not only in transpiration, but in the intensity of photosynthesis as well. The plant–environment response led to a decline in the positive effect of doubled CO_2 concentration on photosynthesis, which in turn led to lower yields.

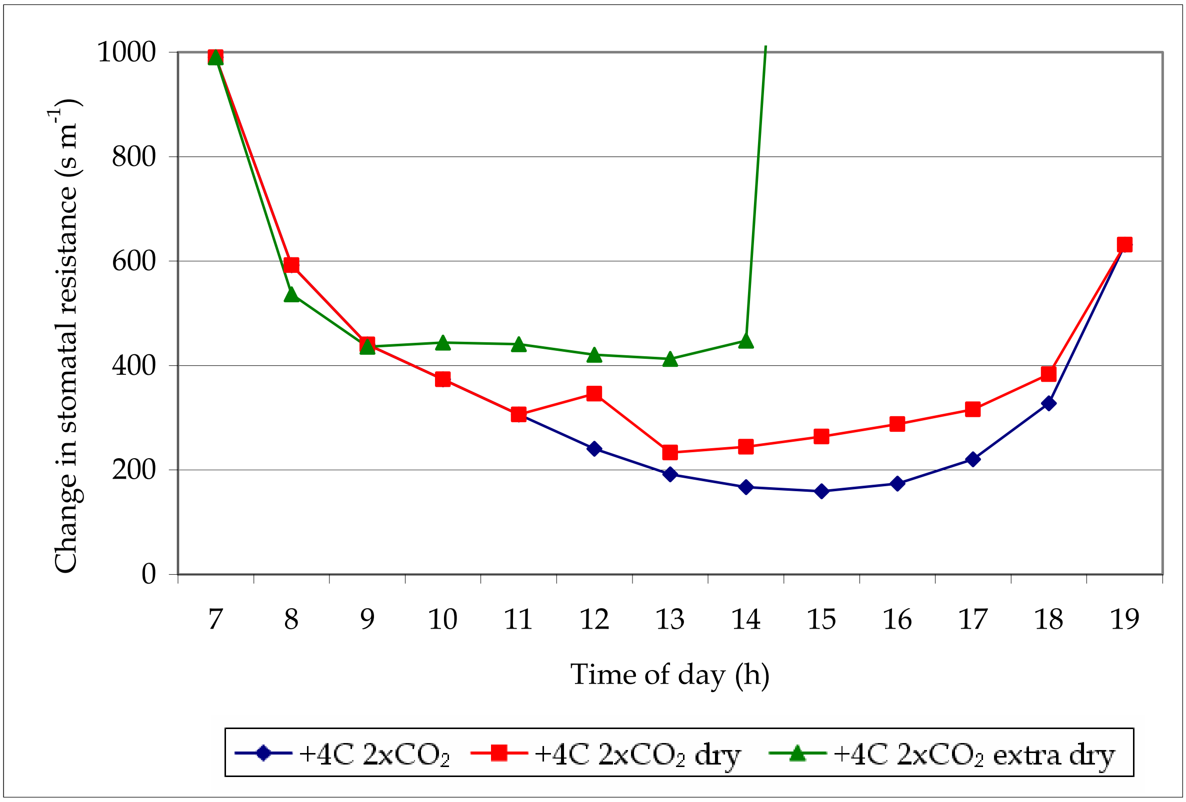

Figure 3. Daily deviation in the stomatal resistance of three scenarios compared with the control treatment (simulation for an average day in Keszthely, in July). The scenarios were as follows: elevated CO_2 in each treatment; air temperature warming (4°C); decreased soil moisture (20%); soil moisture level close to the wilting point (soil water potential –14 bar).

SUMMARY AND CONCLUSIONS

No significant differences were observed for air temperature and precipitation between the climatic norms (1971–2000) and the eigth-year sample data. The deviations in air temperature and precipitation were +0.2°C and –11 mm, respectively. An analysis of a long time series of the two meteorological elements observed in Keszthely indicated no sign of global warming from the beginning of observations (1871) until the present (Kocsis and Anda, 2006).

In the simulation, external air warming exceeded the increase in air temperature inside the plant stand. In the case of the physiologically most intensive layer, the cob level, the canopy was able to compensate for the influence of external warming.

Elevated CO_2 level and a rise in air temperature intensified the effects of the warming process by changing the ratio of the sensible and latent heat fluxes. In this case, the whole plant stand was considered as one layer. If the canopy is sufficiently extensive, the plants may have positive feedback on the process of global warming by enhancing the amount of energy transmitted to the surrounding air. It means that the local warming may be more intensive.

At constant precipitation, a rise of 4°C in the daily mean air temperature in July increased net photosynthesis by 22% under Keszthely growing conditions. This positive effect disappeared, however, as the available soil water was reduced by 20%. At a soil water potential of –14 bar, the intensity of photosynthesis dropped to one third of that in the benchmark treatment. Considering the sensitivity of photosynthesis to the environment, any gain from climate variations in Keszthely does not appear to be probable. The prognosis of decreasing amount of rainfall will probably affect maize production negatively in the surroundings of Keszthely.

REFERENCES

Anda, A. (2004). Determination of the site of the mean stomatal resistance characteristics for the whole plant. *Acta Physiol. Plant.* 26(3), 79–80.

Anda, A., Lőke, Z. (2003). Transpiration, stomatal resistance, canopy temperature and photosynthesis of maize: a simulation study. *Növénytermelés* 52(3–4), 351–363.

Anda, A., Lőke, Z. (2005). Microclimate simulation in maize with two watering levels. *Időjárás* 109(1), 21–39.

Anda, A., Lőke, Z., Burucs, Z. (2001). Microclimate of maize with different water levels. *Növénytermelés* 50(2–3), 249–260 (in Hungarian).

Anda, A., Lőke, Z., Varga, B. (2002a). Processing of standard meteorological data into inputs for micrometeorological models. *Légkör* 2, 28–33 (in Hungarian).

Anda, A., Lőke, Z., Kirkovits M. (2002b). Simulation of water balance components in maize. *J. Cent. Eur. Agr*. 3(2), 95–103 (in Hungarian).

Goudriaan, J. (1977). *Crop micrometeorology: A simulation study. Simulation monographs*. Pudoc, Wageningen.

Goudriaan, J., van Laar, H. (1994). *Modelling potential crop growth processes*. Kluwer Academic Publishers, Dordrecht-Boston-London.

Houghton, J.T. et al., (Eds.) (2001). *Climate Change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press, Cambridge, UK.

Jones, H. G. (1983). *Plants and microclimate.* Cambridge University Press. Cambridge London-New York-New Rochelle-Melbourne-Sydney.

Kimball, B.A. (1995). Productivity and water use of wheat under free-air CO_2 enrichment. *Glob. Change Biol.* 1, 429–442.

Kocsis, T., Anda, A. (2006). Statistical analysis of long-time series air temperature data of Keszthely (1871–2000). *Légkör* 1, 42–45 (in Hungarian).

Mika, J. (2002). On climate change: from the point of view of a meteorologist. *Fizikai Szemle* 52, 258–268 (in Hungarian).

Mika, J., Horváth, S., Makra, L. (2001). Impact of documented land use changes on the surface albedo and evapotranspiration in a plain watershed. *Phys. Chem. Earth* 26, 601–605.

Sváb, J. (1981). *Biometric methods in research*. Mezőgazda Kiadó, Budapest (in Hungarian).

Van de Geijn, S.C., Goudriaan, J. (1996). The effects of elevated CO_2 and temperature change on transpiration and crop water use. In: Bazzaz, F.; Somboek, W. (Eds.) *Global climate change and agricultural production*. FAO and John Wiley and Sons, New York.

Willmott, C.J. (1982). Some comments on the evaluation of model performance. *B. Am. Meteorol. Soc.* 63, 1309–1313.