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Evaluation of the Influence of Climatic Changes on Maize Energy Consumption in Hungary

Angela Anda* **• Tímea Kocsis**

University of Pannonia, Georgikon Faculty of Agriculture, Keszthely, Hungary

***Corresponding author*: * anda-a@georgikon.hu**

ABSTRACT

The effect of possible climate change on the traits of maize plants was evaluated using the simulation model of Goudriaan, based on local climatic conditions and locally measured plant characteristics. The scenarios included not only doubled CO_2 concentration, but also moderate air warming (+1.3, 2 or 3°C) and varying extents of rainfall reduction (–25%, –35% and –50%). The ratio of sensible and latent heat fluxes in plant energy consumption exhibited very little change. The probable reason for this is the equalising influence of elevated CO_2 and changes in other climatic factors. Stomatal resistance increased in all the scenarios. Stomatal closure was only observed in the case of a drastic (–50%) reduction in soil water. The intensity of photosynthesis was governed by the actual soil moisture level. Severe water deficiency led to a sharp decline in photosynthetic efficiency. Based on the local scenarios determined for Hungary, at about 20% reduction in rainfall can be expected in 2050, leading to a decline in the intensity of photosynthesis, so the role of irrigation will probably be enhanced.

Keywords: simulation model, heat fluxes, photosynthesis, stomatal resistance

INTRODUCTION

The prediction of how climate change will affect the Carpathian Basin (Hungary) will require regional climate scenarios with adequate temporal and spatial resolution, capable of translating global phenomena to a local scale. Bartholy *et al*. (2004) developed a stochastic-dynamic downscaling model to estimate the regional effects of climate change in the Lake Balaton–Sió Canal catchment area, using ECHAM/GCM outputs. This catchment area, which also includes Keszthely, is one of the most vulnerable regions in Hungary in terms of climate change. The latest regional model runs for Carpathian basin (RCMs) using the A2 and B2 global emission scenarios of the IPCC 2007, expect more than 2.5 and less than 4.8°C for all seasons and both scenarios (Bartholy *et al*. 2007). A 20-33% decrease in precipitation is predicted for the summer half-year and there is high uncertainty for the rainfall for the winter half-year.

If atmospheric, hydrological or ecological models are to provide an accurate description of surface energy and water fluxes, they must also include soil and plant parameters in order to ensure a realistic simulation of how the available energy is partitioned into sensible and latent heat fluxes and of how carbon is cycled through various organic and inorganic phases (Mihailovic *et al*. 2002).

The aim of the present work was to investigate how locally grown maize (*Zea mays*) plants react to predicted climate change in terms of energy use and physiological processes at the plant stand level. Despite indisputable progress in our understanding of the processes involved in climate change, there is still considerable uncertainty in local climate projections, which must be considered in any impact study (Calanca *et al*. 2006). Climate change scenarios have thus been developed on the basis of local data taken from the literature. The Crop Micrometeorological Simulation Model (CMSM) constructed and reworked by Goudriaan and van Laar (1994) was used in this study.

MATERIALS AND METHODS

Study location of data collection

The meteorological and plant data used in the simulation were collected at the Agrometeorological Research Station in Keszthely (N 46°44′, E 17°14′, altitude: 114.2 m). Although daily meteorological data are available from 1973 onwards, the data set of the last eight years was used (1999-2006), since a QLC-50 automatic climate station was established in the end of the 1990s. Over the last eight years the sampling frequency of the automatic station (every six seconds) has allowed hourly means to be calculated for use as model inputs. These were not available previously, as observations were only made every six hours. The sample day was an average day in July, when the plants were fully developed.

The reference level for the model inputs were obtained by calculating aerodynamic depths for each stage of plant development. The roughness length and zero-plane displacement for maize were adapted from Monteith (1973). The reference value of wind speed was estimated using a combination of the friction velocity and the logarithmic wind speed profile above the canopy. Measurements of wind speed were made 10 metres above the ground.

Ever since the 1970s, the test plant, the mid-season maize hybrid Norma (FAO 450), has been sown during the last ten days of April at a plant density of 7 plants m^{-2} on plots measuring 0.7 ha. The crop, grown using the technology normal in the Keszthely region, as recommended by experts from the local Agricultural University, was harvested in the second half of September.

The inputs of the model are site- and plant-specific values (plant height, leaf density in various leaf zones), soil characteristics and hourly meteorological data (air temperature, global radiation, relative humidity, soil temperatures at various depths at 00.00 hours), and the standard measurements were transformed to the reference level required by the model (see above). Leaf area and leaf density were measured in the field on the same ten sample plants weekly using a LI-3000A leaf area meter. In the present case, the data recorded for the cob layer in the fully developed stand in July were applied. The soil moisture value was taken as the monthly average for July over the past decade (–7 bar soil

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water potential). The soil moisture content in the upper 1 m was also measured gravimetrically in the field at 10 cm intervals every ten days. The actual soil water content was expressed in terms of soil water potential.

The results of each simulation where compared statistically with the control run applying paired T-test (STATA 5.0). The chosen significance level (α) was 5%.

Description of the Crop Micrometeorological Simulation Model (CMSM)

The model is based on the calculation of radiation distribution between various environmental processes. The sensible heat flux (H_i) [J m^{-2}] in the i^{th} layer is:

$$H_i = \frac{(T_{L,i} - T_{a,i})\rho c_p}{r_{H,i}} \tag{1}$$

where ρc_p is the volumetric heat capacity of the air [J m^{-3} K^{-1}]
$T_{L,i}$ and $T_{a,i}$ are the temperatures of the plant and the air [°C]
$r_{H,i}$ is the resistance against heat transmission [s m^{-1}].

The latent heat flux (λE_i) [J m^{-2}] in the i^{th} layer can be calculated as follows:

$$\lambda E_i = \frac{(e_{s,T_{L,i}} - e_{a,i})\rho c_p}{r_{V,i}\gamma} \tag{2}$$

where γ is the psychrometric constant [mbar K^{-1}]

$e_{s,T_{L,i}}$ is the saturation water vapor pressure at actual plant temperature [mbar]
$e_{a,i}$ pressure of the air [mbar]
$r_{V,i}$ is the resistance to the entrance of moisture into the layer [s m^{-1}].

Simulation of photosynthesis and leaf resistance

The intensity of photosynthesis *(F_n)* was evaluated using the following equation:

$$F_n = (F_m - F_d)[1 - \exp(-R_v\varepsilon / F_m)] + F_d \tag{3}$$

where F_m is the maximum rate of net CO_2 assimilation [kg CO_2 m^{-2} s^{-1}],
F_d is the net CO_2 assimilation in the dark respiration [kg CO_2 m^{-2} s^{-1}],
R_v is the absorbed visible radiation (per leaf area) [J m^{-2} s^{-1}],
ε is the slope of the curve of F_n-R_v at low light intensities [kg CO_2 J^{-1}],
or efficiency ($17.2 \cdot 10^{-9}$ kg CO_2 J^{-1} light in maize).

At calculation of F_m the influence of leaf age and ambient CO_2 concentration were simplified and their average values were applied. Dark respiration made up approximately a tenth of the net assimilation, Fm. The leaf resistance was calculated from this net CO_2 assimilation value as:

$$F_n = \frac{1.83 \cdot 10^{-6}(C_e - C_r)}{1.66 r_{leaf} + 1.32 r_H} \tag{4}$$

where r_H is resistance to heat transmission [s m^{-1}],
1.66 ratio between the diffusivities of CO_2 and H_2O
$1.83 \cdot 10^{-6}$ converts CO_2 concentration into kg CO_2 m^{-3} from ppmv at 20°C,
C_e is the external CO_2 concentration [ppmv],
C_r is taken as the 'regulatory' CO_2 concentration [ppmv],
1.32 is derived from a calculation of the boundary layer resistance for CO_2
or

$$r_{leaf} = \frac{1.83 \cdot 10^{-6}(C_e - C_r)}{1.66 F_n} - 0.783 r_H \quad [\text{s m}^{-1}] \tag{5}$$

where *0.783* is an empirical constant given by the author of the model.

From the outputs regarding the maize stand the sensible and latent heat fluxes, the leaf stomatal resistance and intensity of photosynthesis were presented. This is the place of cob formation, where the intensity of physiological processes is the highest.

The model outputs were validated under local conditions by Anda and Lőke (2002, 2005) using RMSD (Willmott 1982).

Scenarios applied

In order to simulate the impact of climate change on maize, scenarios representing moderate climatic variations for Hungary were created. Over the last two decades the amount of rainfall in Keszthely has tended to decrease by 10–15%. Most publications on local climate changes suggest that this tendency will continue in 2050 (Bartholy *et al.* 2004, 2007), together with increases in air temperature of 2-3°C in the summer half-year. Model inputs for plant architecture, and for the size and density of the assimilatory surface were chosen from local measurements taken over the last three decades on the principle of analogy. Plant data were used for vegetation periods when the air temperature and soil water content were similar in July to those of the scenarios. Except in the control treatment, the locally measured ambient air CO_2 concentration was doubled (to 760 ppmv).

The following scenarios were applied:

- Control: present climatic conditions (average July day), with average soil moisture content and 380 ppmv ambient CO_2 concentration. The value of LAI was taken as 3.0, the characteristic mean for maize grown in Keszthely.
- Scenario 1: Soil water content was reduced by 25% and LAI was taken as 2.6.
- Scenario 2: Soil water content was reduced by 35% and LAI was taken as 2.1.
- Scenario 3: Soil water content was reduced by 25%, air temperature was increased by 1.3°C and LAI was taken as 2.3.
- Scenario 4: Soil water content was reduced by 35%, air temperature was increased by 2°C and LAI was taken as 2.0.
- Scenario 5: Soil water content was reduced by 50%, air temperature was increased by 3°C and LAI was taken as 1.8.

As it was proved by Jackson *et al.* (1994) that the ratio of intercellular to ambient air CO_2 concentrations is constant, the intercellular gas concentration was maintained at one third of the ambient value (van de Geijn and Goudriaan 1996).

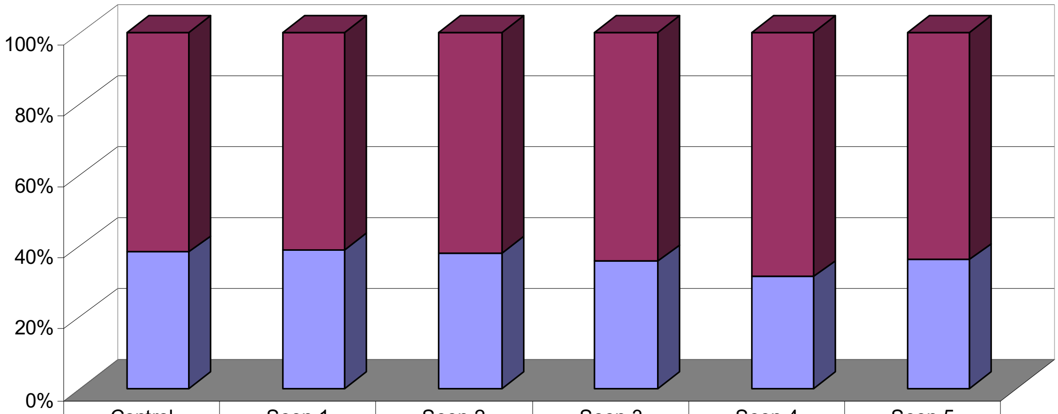
RESULTS

The theoretical background of the Crop Micrometeorological Simulation Model (CMSM) is based on the physics of energy transformation and transport processes. The model evaluates micro-environmental and plant parameters using the principles of soil/atmosphere physics and plant physiology. The model traces the path of incident solar radiation in different layers of the canopy. Part of the incident radiation is reflected from the canopy, part is transmitted to the soil and part is absorbed by the plants.

The sensible and latent heat fluxes in maize stand

The incoming radiation remaining after reflection from the stand and transmission to the soil provides a source of energy for heating processes (sensible heat flux) and evapotranspiration (latent heat flux). If there is no water limitation, the main user of energy is evapotranspiration from the plant stand. Only a third of the energy remaining in the plant canopy is used for heating purposes. In Hungary the average ratio of sensible to latent heat consumption is 70:30. Only a relatively low amount of energy (1-2%) is utilised for metabolic storage in the form of photosynthesis.

In the present simulation no variation in the external environment (temperature, CO_2, water level) was found to have significant influence on 5% probability level on the energy consumption of the stand, except for the intensity of photosynthesis (**Fig. 1**). At elevated CO_2 a moderate decrease in soil moisture (Scenarios 1 and 2) had no influence on the ratio of sensible to latent heat fluxes. This suggests that the higher CO_2 level balanced out the decrease in avail-



	Control	Scen.1	Scen.2	Scen.3	Scen.4	Scen.5
▨ latent heat [diurnal mean, %]	61.63	61.14	61.91	64.35	68.57	63.87
▨ sensible heat [diurnal mean, %]	38.37	38.86	38.09	35.65	31.43	36.13

Fig. 1 Ratio of sensible to latent heat fluxes in different climate scenarios as follows. -25% and -35% soil moisture reductions in Scenarios 1 and 2, respectively. In the next two model runs decrease in available soil water was accompanied with 1.3 and 2°C air temperature warming. In the 5th Scenario the soil moisture depletion fall half with 3°C increase in air temperature. Except of control run the outside air CO_2 content (760 ppmv) was doubled in each Scenario.

able soil water by decreasing the opening of the stomata. At doubled CO_2 it was observed that the higher the air temperature the lower the sensible heat. Due to the warmer surrounding air, intensive plant cooling was required, but in the model run in Keszthely there was sufficient water in the soil for cooling purposes. Even the greatest modification in energy partitioning was not statistically proved, it was observed in Scenario 4, where the reduction in sensible heat was about 7% compared with the results of the control run. Kimball (1995) reported that elevated CO_2 alone caused considerable changes in the energy use of maize, with a 9% decrease in the latent heat flux at doubled CO_2 level.

When analysing the results of the different scenarios it was assumed that the moderate climate change associated with increased ambient CO_2 level had no radical influence on the distribution of energy within the maize stand. Surprisingly, there was less change in energy partitioning in Scenario 5 than in Scenario 4. This may have been due to the drastic reduction in the size of the transpiration surface (LAI) and in its specific density in Scenario 5. In arid weather the maize leaves on the upper third of the plant tend to thicken, while the lower leaves may wither. The plant traits used in the simulation have been recorded over the past 30 years (from 1977 to 2006) under field conditions. The values measured in years when the weather was similar to that predicted in the scenarios were used as input data.

Physiological processes in maize

Among the parameters influencing yield formation, variations in leaf resistance and photosynthetic intensity were studied in the present work.

The photosynthetic intensity and transpiration are influenced by the CO_2 concentration due to its modifying effect on stomatal resistance. Photosynthesis is the only process capable of utilising the energy of sunlight to produce organic matter from inorganic elements. Atmospheric carbon dioxide, the basic material of photosynthesis, reaches the site of the biochemical process through the stomata. For this reason stomatal resistance is a limiting factor for the penetration of CO_2 into the leaf, but also regulates the emission of water vapour in the process of transpiration. If high yields are to be obtained, a balance must be achieved in stomatal opening, so that sufficient CO_2 is available for photosynthesis, while water loss is kept at a moderate level.

Variation in stomatal resistance

The stomata of the maize plants were considered to be closed when the resistance exceeded 2000 s m^{-1} (**Fig. 2**). Values in this range were recorded during the night (from 8 pm to 7 am). The daily mean resistance significantly differed from the control run and increased by 61.1, 67.9, 61.6, 69.1 and 140.9% in Scenarios 1 to 5, compared with the control run (**Table 1**), the increment depending on the severity of the climate change. The increase in stomatal resistance was greatest in the morning hours (8-10 am). When the level of incoming radiation is low, pore movement appears to be more sensitive to variation in ambient air properties such as elevated CO_2 and air warming.

As expected, increased CO_2 concentration and reduced soil water content caused a rise in the daily mean stomatal resistance, while stomatal closure was even more intense if the air temperature was also increased.

In Scenario 5, when the available soil water was reduced to half the mean value, the stomata closed between 2 and 4 pm in response to the high air temperature and the drastic reduction in soil water. Despite the severe climate changes in Scenario 5, the increase in stomatal resistance during the morning (8-10 am) was statistically less in per cent than in Scenarios 1 and 2. This may have been due to the greater increase in the air temperature (3°C) in this scenario.

Intensity of photosynthesis

The process of photosynthesis uses CO_2 from the ambient air and the water supplies stored in the soil to produce organic matter of plants. The final gain from the process is the difference between assimilation and the use of assimilates for respiration (“negative photosynthesis” by night) (**Fig. 3**). The respiration intensity (between 8 pm and 6 am) was not found to be sensitive to climate change: there were no statistically proved differences between the various scenarios for the night hours. The net gain from the process of photosynthesis (assimilation – respiration) decreased with the severity of the climate changes. In Scenarios 1 and 3 (doubled air CO_2 content with a slight reduction in soil moisture, with or without a moderate increase in air temperature) the net result of the process was positive, and statistically different from the control (**Table 2**), but in the other scenarios probably respiration used more assimilates than could be produced by photosynthesis during the daylight hours. A temperature increase of 2°C, combined with a middle level reduction in soil moisture, caused a non significant decline in the intensity of photosynthesis in spite of the elevated CO_2 level (**Table 3**). Growth in ambient air temperature above 3 °C together with 50% reduction in soil moisture content has significant influence on the intensity of photosynthesis. This is in accordance to latest findings of

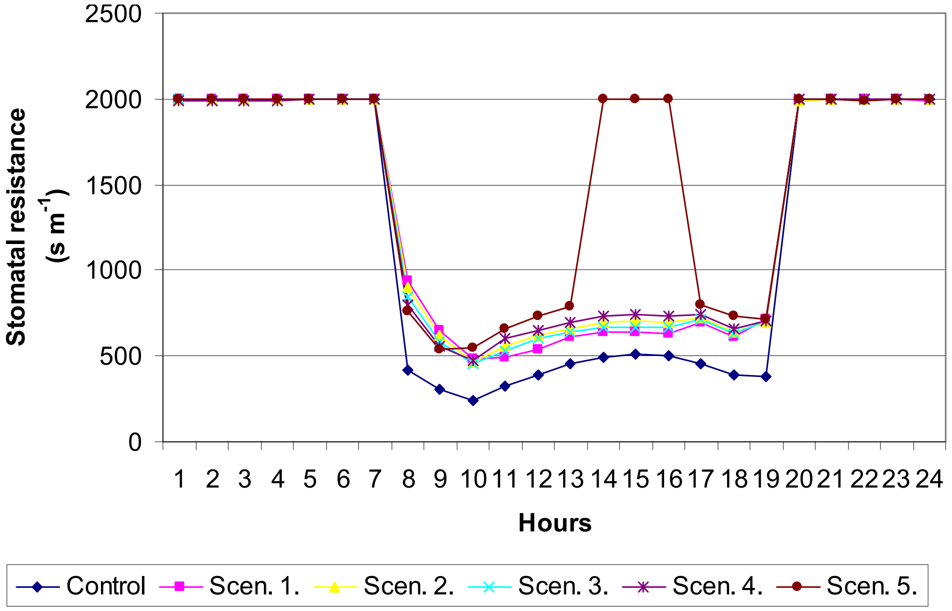


Fig. 2 Simulated stomatal resistance of maize under varying climatic conditions. Resistance above 2000 s/m means closure of stomata.

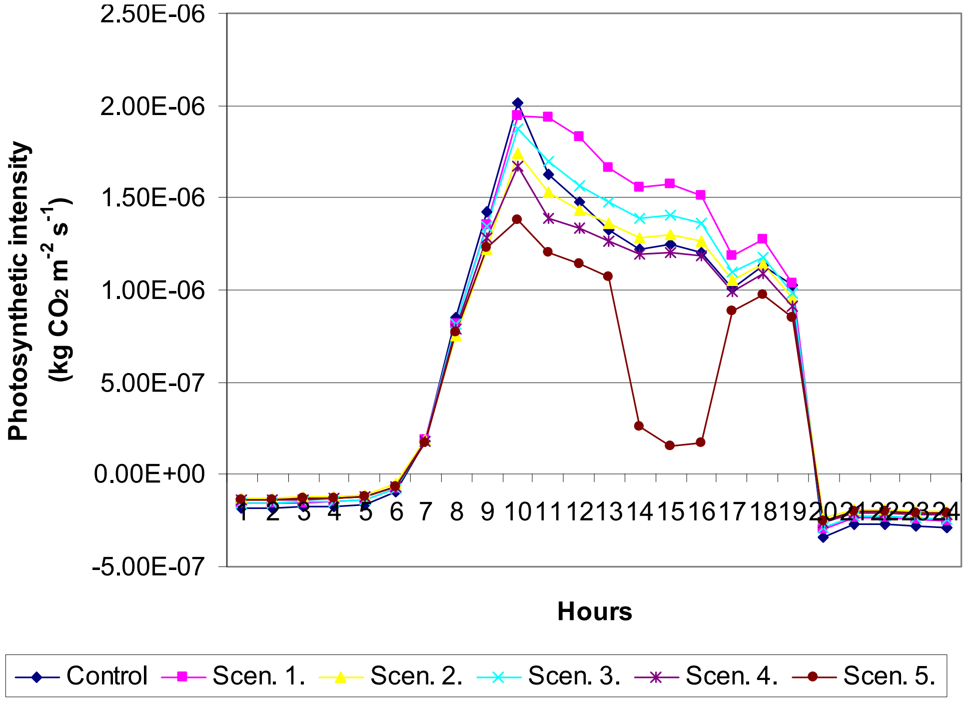


Fig. 3 Simulated photosynthetic intensity of maize under varying climatic conditions. Negative values represent respiration intensity by night.

Table 1 Results in statistics for the simulation of stomatal resistance.

Stomatal resistance	Mean (1-24 hours) (s m^{-1})	Paired T-test p value
Control	1.20E+03	-
Scenario 1.	1.32E+03	0.0008
Scenario 2.	1.33E+03	0.0002
Scenario 3.	1.32E+03	0.0003
Scenario 4.	1.34E+03	0.0001
Scenario 5.	1.51E+03	0.0049

Significant when $p < 0.05$

Table 2 Results in statistics for the simulation of photosynthetic intensity.

Photosynthetic intensity	Mean (1-24 hours) (kg CO$_2$ m^{-2} s^{-1})	Paired T-test p value
Control	5.55E-07	-
Scenario 1.	6.57E-07	0.0018
Scenario 2.	5.64E-07	0.6301
Scenario 3.	5.98E-07	0.0093
Scenario 4.	5.26E-07	0.1954
Scenario 5.	3.53E-07	0.0134

Significant when $p < 0.05$

Long *et al*. (2006), who found that elevated open air CO_2 enhanced yield by about 50% less than in inside trials. This casts serious doubt on projections that rising CO_2 will fully offset losses due to climate change.

DISCUSSION

Scenarios of the IPCC for 21st century combine a variety of assumptions about demographic, economic and technological driving forces likely to influence greenhouse gas emissions and global climate. Investigation of the result, the global warming and its influences need many-sided assumption in time and space as well. Olesen and Bindi (2002) reviewed the knowledge on effects of climate change on agricultural productivity in Europe. In their paper the authors concluded that in northern Europe climate change may pro-

Table 3 Difference in photosynthetic intensity between the control and the five scenarios. The control run contains the value of an average day in July, at Keszthely. Scenario 1 and 2: Soil water content reduced by 25 and 35%, respectively. In the last three Scenario the soil moisture decreases were accompanied with 1.3, 2 and 3°C air temperature rise.

Scenarios	**Mean daytime difference in % (8 am to 7 pm)**
Scenario 1	13.8%
Scenario 2	-2.8%
Scenario 3	4.5%
Scenario 4	-7.3%
Scenario 5	-34.9%

duce positive effects on agriculture through introduction of new crop species, higher production and expansion of suitable areas for crop cultivation. In southern areas disadvantages will predominate, the possible increase in water shortage and extreme weather events.

One of the confusing factors in studies regarding climate variation is the influence of increased CO_2 level on photosynthesis and transpiration of crops through affecting the stomata opening. The lack of information on maize physiological responses to climate variations in Hungary turned our attention to the above mentioned area. The number of publications in abroad is also limited. As soon as maize belonging to less sensitive C_4 plant group has any modification in its physiological processes considering the climate change, the other C_3 crops must have more serious response under Hungarian climatic conditions. In Mediterranean part of Australia negative effects of 15% reduced rainfall can be compensated for by a 2°C increase in temperature and 50% higher CO_2 concentrations in wheat (Fulco and Asseng 2006). However due to the non-linearity of climate change effects a 30% reduction in rainfall cannot be compensated for by higher temperatures and elevated CO_2 in the same place. Effects of higher temperatures, elevated CO_2 and changed rainfall were in general not linear and differed significantly between soil types and location (Fulco and Asseng 2006). Mera *et al.* (2006) considered that as a result of climate change the C_3 crops are more sensitive than C_4; however, the temperature–radiation related changes shown also effected significant changes in maize.

Simulated maize yield and biomass with CERES and EPIC increased when only effects due to doubled CO_2 were considered (Dhakhwa *et al.* 1997). When the effects of CO_2 fertilization and the climate change were combined, 8 and 13% depressions in aboveground biomass and yield were simulated in North-Carolina. In south-eastern Australia Anwar *et al.* (2007) found that the effect of elevated CO_2 reduces the severity of the warmer air temperatures and lower rainfall but the effect was only 4%.

Prasad *et al.* (2006) called the attention of the adverse effects of elevated temperature on reproductive processes and yield of C_4 sorghum were more severe at elevated CO_2 than at ambient CO_2. The beneficial effects of elevated CO_2 decreased with increasing temperature.

Results show the global warming will be harmful for most of the countries, and an efficient adaptation to alternative climates tends to reduce the damages. For wheat, maize and barley, there is a clearly negative response of global yields to increased temperatures (Lobell and Field 2007).

Surprisingly, with the exception of photosynthesis, the energy utilisation of the maize stand did not cause statistical change in any of the five scenarios, the greatest difference being only 7%. This could probably be attributed to the fact that the increase in CO_2 concentration and the changes in other environmental factors cancelled each other out. It was similar to the finding of Prasad *et al.* (2006) where the adverse temperature sensitivity of reproductive processes and yield at elevated CO_2 was attributed to higher canopy foliage and seed temperatures. The other reason might has been the majority of previous studies only considered modifications in environmental factors, while in the present simulation consideration was also given to the effect of previous climatic events on plant architecture (LAI, leaf density), based on local observations over several decades.

The stomatal resistance significantly increased in all the scenarios, suggesting that the plants were attempting to reduce water loss. We found that in the morning hours, when the level of incoming radiation is low, pore movement appears to be more sensitive to variation in ambient air properties such as elevated CO_2 and air warming. Although the rise in stomatal resistance could be expected to reduce the quantity of CO_2 penetrating into the leaf, the higher concentration of the gas led to significantly more intensive photosynthesis (between 8 am and 7 pm) when soil moisture reduction was moderate (Scenario 1), even when this was combined with a moderate rise in temperature (Scenario 3). When the rise in air temperature was combined with more severe water deficiency, the positive effect of elevated CO_2 was unable to counteract the negative impact of these factors. The most drastic and statistically proved decline in photosynthesis, by about a third, was observed when a 50% reduction in soil moisture and a 3°C rise in temperature were simulated. This extent of climate change would make it very dubious whether maize could be grown economically at the experimental location without irrigation. Most climate scientists agree that global climate change is likely to lead to a 20% reduction in rainfall in Hungary in 2050. This suggests that the irrigation of field crops, which has been carried out very rarely up to now, may be essential in the future. In Hungary one way of reducing the negative effects of climate change could be to increase the ratio of irrigated areas.

The modeling technique that can estimate local weather patterns 50 years from now could help stakeholders to prepare for shifts in crop productivity. Keeping in mind the uncertainties of the modelling assumption we can get to the point where and which crops are most suitable for climatic conditions of 2050. Findings call for monitoring of climate change and dissemination of information to end-users to encourage adaptations to local climate. In Hungary seems to be true that the advances in technology and plant breeding must boost crop yields by around 20% over the coming decades, to keep in step with predicted climate modification (Anwar *et al.* 2007).

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