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Consequences of climate change on some maize characteristics in Hungary

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Abstract—The influences of global climate change on sensible and latent heat fluxes of maize were studied by using the simulation model of *Goudriaan* (1977). Eight scenarios were made, an increase of CO_2 content until doubling the recent content was included in the scenarios. Some of the scenarios were developed by downscaling the *IPCC* (2007) report (A2 and B2) to Hungary, and the others by taking into account more serious weather changes. Surprisingly, the distribution of intercepted radiation among sensible and latent heat fluxes in the individual scenarios was not significantly modified. A given increase in ambient air temperature caused a lesser rise in crop temperature at cob level, demonstrating the compensation role of the canopy. The moderate rise in crop temperature indicated that the plants did not suffer significantly from lack of water in any of the scenarios. However, there was a variation during the diurnal cycle. The doubled CO_2 concentration alone increased the net carbon assimilation rate of maize by 40%. Photosynthesis decreased only in cases with warmings higher than 6 °C. Decreased precipitation counteracted the positive influence of elevated CO_2 on carbon assimilation.

In other scenarios the latent heat flux increased in comparison to control run. This justifies the existence of reserve soil water at Keszthely, even in on extra hot day during July.

Key-words: micro-meteorological model, simulation, maize canopy, global warming

1. Introduction

The plant canopy architecture determines the energy and mass exchange creating the canopy microclimate, which affects the plant physiological processes. Thus, there is a long series of impacts from changes in environmental factors to plant responses. To investigate such complex relationships, simulation

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models are the most suitable tools, because they draw attention to those fields where there is a lack of knowledge. The early works of *de Wit* (1965), *Monteith* (1973), *Shawcroft et al.* (1974), *Norman* (1979), *de Vries* (1975), and *Waggoner* (1975) can be considered as the beginning of crop growth simulation modeling. The first reflections on modeling were provided by *Passioura* at a relatively early date, in 1973. *Bouman et al.* (1996) has summarized the 30-year experience of the "Dutch school" dealing with the simulation modeling founded by *de Wit,* and outlined the way of further development.

The simulation models offer advantages in quantitative assumption of crop growth. Although the shortcomings of model application are well known, including limited accuracy of local climate change projections, the crop microclimate simulation model (CMSM) of *Goudriaan* (1977) provides complexity in crop-environment studies. The effect of increased atmospheric carbon dioxide concentration may be hypothesized by its direct effect as well as its effect on plant canopy temperature via evaporative cooling. The paramount importance of crop temperature is provided by the fact that it determines the intensity of physiological processes including photosynthesis through influencing intensity of biochemical processes. The aim of this examination was to present the expected changes based on various scenarios in crop temperature and intensity of photosynthesis to the area of Keszthely. The model results are illustrated by plants at fulfilled tasseling, a stage of phenological development that is certainly achieved in Keszthely in the month of July. Out of the three model layers regarding the energy distribution, we have chosen the middle one: the cob stratum in which physiological processes are the most intensive.

Topicality was grounded by the appearance of the latest climate scenarios published in *IPCC* 2007 Report, and its scenarios downscaled to Hungary (*Bartholy et al.,* 2007). At a certain part of the scenarios we used average changes (*Bartholy et al.,* 2007), while – due to the growing frequency of extreme weather phenomena – we have also drafted several notions regarding extreme hot days. However, due to the uncertain precipitation scenarios we have not widened this to the precipitation.

2. *Material and methods*

2.1. Source of model inputs

The model inputs are site- and plant-specific values (plant height, leaf density in different layers), soil characteristics (soil moisture content, physical soil properties), and hourly meteorological data (air temperature, global radiation, relative humidity, soil temperatures). The hourly meteorological elements were the driving variables of the model, which were transformed from the standard measurement level (Agrometeorological Research Station at Keszthely, 46°44’N; 17°14’E; 114.2 m above sea level) to the reference level required by the model. The automatic weather station equipped by Eppley pyranometer is a part of the observation network of the Hungarian Meteorological Service. Data from the preceding station back to 1961 are also included. The meteorological data measured under standard conditions were correlated to the reference level required by the model on the basis of former investigations by *Anda et al.* (2003). The leaf area and its density were measured in the field on 10 sample plants weekly, using a LI-3000A type leaf area meter. The soil moisture content in the upper 1 m was also measured in the field with thermo-gravimetric method at 10 cm intervals every 10 days.

Our test plant was a maize hybrid for which we have more than 30-year data with weekly observations of plant height, leaf area index, leaf breadth, density, etc. These values and relative water content of crop were parameters of the model. The observed soil water content also covers more than 30 years with weekly soil sampling and gravimetric determination of soil water down to a depth of 1 m for every 10 cm layer. Precipitation projections were converted into local soil water content expressed in terms of soil water potential, which in turn is the model input regarding crop water supply. The water, as a basis material of photosynthesis and a cooling substance for transpiration, determines crop energy balance together with the intensity of photosynthesis. Physical properties of the soil (heat capacity, heat conductivity, soil surface resistance, starting value of soil heat flux, diameter of soil particles) were the parameters of the model. The former and current atmospheric CO_2 concentrations as parameters were taken into account on the basis of the local measurements by *Dunkel* (1982) and the national measurements of *Haszpra* (2007). More details on plant and other data samplings are found in an earlier publication of *Anda* (2006).

A one-day detailed study by canopy simulation will only be presented for an “average day” in July. Weather, crop, and soil data for July between1961 and 1990 served as a reference in our simulation. We chose the month July for demonstration because the intensity of maize physiological processes is the highest during July. The one day resolution attributes to model construction. In some scenarios the influence of extreme hot days is also included in the study.

2.2. The applied scenarios

The **first scenario,** called the control scenario, is the same as presented in the *IPCC* (2007) Report. Mean values of July during 1961–1990 and a CO_2 concentration published by *Haszpra* (2007) at 340 ppmv were applied. Soil water potential was –7 bar.

The **second scenario,** called 1997–2006, represents the changes of recent years by data from 1997–2006. According to the last climate normal of Keszthely, the summer air temperature has been significantly higher by 0.6 °C as compared with the monthly mean of July of the period 1901–2000. Accumulated precipitation of the same month has decreased by about 10–15% in Keszthely, though it is not statistically significant. The soil water potential was equal to –7.7 bar. We estimated the atmosperic CO_2 concentration to be 380 ppmv on the basis of the background measurements.

The **third scenario**, called 2×CO_2, represents the impacts of the rising ambient air CO_2 concentration alone. We doubled the present CO_2 gas concentration (760 ppmv), and the meteorological inputs remained the same as in the control scenario. With this we estimated the expected change due to increased CO_2 concentration to the time period 2071–2100.

In scenarios four to eight – beside doubling the current CO_2 level (760 ppmv) – we gradually increased the air temperature and decreased the precipitation values compared to the basic run (1961–1990). The **fourth scenario**, called 3.8 °C/–15%, is based on the B2 scenario (*IPCC*, 2007). Mean summer temperature in Keszthely is estimated to rise by 3.8 °C and precipitation to decrease by about 15% (soil water potential: –9 bar).

The **fifth scenario**, called 4.8 °C/–25%, used the summer data of the A2 *IPCC* (2007) scenario for 2071–2100, downscaled to Hungary by the above mentioned method. It has estimated a stronger warming of +4.8 °C and a 25% decrease in precipitation. We have noted that standard deviation is rather high in both scenarios (±15%), which implies strong uncertainty. The soil water potential was settled to –10 bar.

In the **sixth scenario**, called 6.0 °C/–25%, we increased the average air temperature by 6.0 °C together with a 25% decrease in precipitation. This 6 °C rise is close to the value of the upper limit value (6.4 °C, annual average) in the *IPCC* Fourth Assessment Report (2007). The soil water potential was –9 bar.

Keeping that in mind we performed a further increase in the degree of warming up by involving the 1.4 times product of the upper temperature rise (6.4 °C) pertaining to Hungary (9 °C) in the last two scenarios. To evaluate the effects of the uncertainty of precipitation projects, we assumed a weak decrease in precipitation (–10%) in the **seventh scenario** (9 °C/–10%), and then a more significant drying (30% precipitation decrease) in the **eight scenario** (9 °C/–30%). Their soil water potentials were –7.7 and –11 bar. The comparison of these latter two scenarios provided opportunity to quantify the impacts on plant growth of the different amounts of precipitation.

2.3. Model description

2.3.1. Energy balance of canopy layers

The advantage of present study, the use of *Goudriaan*'s (1977) simulation model is that it could keep its high scientific level together with its relative simplicity. In 1989 the author himself published the critical evaluation and application problems of the model (*Goudriaan*, 1989). The modified versions of the model (*Chen*, 1984; *Goudriaan* and v*an Laar*, 1994) are also user-friendly and suitable for the better knowledge of the relationship between plant and environment and for providing the consequences of scenarios like global warming (*Dióssy*, 2008). The time step in the model is one hour.

The CMSM of Goudriaan simulates the canopy microclimate as a function of plant, soil, and weather characteristics. Plant stand plays important role in the model feedback as partly influenced by earlier weather. One of the advantages of the model is that short-term and long-term influences are also incorporated in its structure.

The amount of intercepted radiation was determined after *Monsi* and *Saeki* (1953). Partioning of the intercepted radiation into sensible and latent heat fluxes was calculated on the basis of energy balance equations (*Goudriaan*, 1977):

$$0 = Rn - M - Q_H - \lambda E, \tag{1}$$

where Rn is the canopy net radiation [W m^{-2}], M is the metabolic storage [W m^{-2}], Q_H is the sensible heat flux [W m^{-2}], λE is the latent heat flux [W m^{-2}], and λ is the evaporation heat [kJ kg^{-1}].

The metabolic storage was neglected in the model. The sensible heat flux (Q_{Hi}) in the *i*th layer in the canopy is:

$$Q_{Hi} = \rho c_p \frac{T_{ci} - T_{ai}}{r_{aHi}}, \tag{2}$$

where T_{ai} is the air temperature in the *i*th layer [K], T_{ci} is the canopy temperature in the *i*th layer [K], r_{aHi} is the aerodynamic (boundary layer) resistance for sensible heat transfer in the *i*th layer [s m^{-1}], ρ is the air density [kg m^{-3}], and c_p is the specific heat of air [J kg^{-1} K^{-1}].

The latent heat flux (λE_i) in the *i*th layer can be calculated as follows:

$$\lambda E_i = \rho c_p \{e_s(T_{ci}) - e_s\} / [\gamma(r_{awi} + r_{ci})], \tag{3}$$

where $e_s\,(T_{ci}) - e_i$ is the difference between saturation vapor concentration at plant temperature and actual vapor concentration [m^3 m^{-3}], r_{awi} is the aerodynamic resistance for water vapor transfer in the *i*th layer [s m^{-1}], r_{ci} is the crop resistance in the *i*th layer [s m^{-1}], and γ is the psychrometric constant [0.5 g m^{-3} K^{-1}].

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

$$T_{ai} = T_{ai-1} + Q_{Hi} r_i / \rho c_p, \tag{4}$$

where r_i is the characteristic value of resistance against heat in the *i*th layer [s m^{-1}] when $i = 1$ (when canopy is considered as one layer) and (T_{ai-1}) is the air temperature for the reference level. When canopy is divided into more than one layer, the $i-1$th layer means the bordering one. The crop temperature (T_{ci}) was calculated similarly to the air temperature:

$$T_{ci} = T_{ai} + (Q_{Hi} - Q_{Hi-1}) r_{H,i} / \rho c_p. \tag{5}$$

2.3.2. Photosynthesis of the whole canopy

Rate of net CO_2 assimilation (F) was considered empirically as follows:

$$F_n = (F_m - F_d)[1 - \exp(-R_v \varepsilon / F_m)] + F_d, \tag{6}$$

where F_m is the maximum rate of net assimilation, F_d is the dark respiration, R_v is the absorbed short wave radiation (per LAI), ε is the slope of the curve of F–R_v at low light intensities, or efficiency ($17.2 \cdot 10^{-9}$ kg J^{-1} light in maize). Contrary to crop temperature and sensible and latent heat fluxes, the photosynthesis is calculated independently of energy balance and for the whole canopy only (*Goudriaan*, 1977).

The validation of the CMSM pertaining to the location of model building was performed by several authors (*Stigter et al.*, 1977; *Singh* and *Jacobs* 1995). The publication of *Hiramatsu* and *Maitani* (1984) firstly drew attention to the problems for simulation during the night hours. The Hungarian verification of the model regarding both the microclimate and several plant characteristics was performed by *Anda* and *Lőke* (2003, 2005) and *Anda et al.* (2001, 2002).

2.3.3. Assumption of crop water status

The water status of the canopy influences both the transpiration and photosynthesis by setting a lower limit to stomatal resistance. The relation between this lower limit and relative water content is given by *Goudriaan* (1977). The relative water content is calculated as the ratio of actual and maximum water contents. The value of maximum water content is based on leaf thickness ($2.5\ 10^{-3}$ kg m^{-2} times the leaf area index). The actual water content is an integral of water uptake minus transpiration rate (*Penman*, 1948*)*. The first feedback is created by the relationship between transpiration and stomatal resistance. Another feedback functions through the water uptake, since lower water content of plants forces more water to flow from the soil. The soil water stress was supposedly set at -0.1 bar water potential, root resistance is a function of soil temperature, and plant stress is a function of the relative water content.

2.3.4. *Statistical evaluation*

We evaluated the significanct differences between model runs by using paired t-test that was performed by the free version of *STATA 5.0* (1996) program package. The process reduces the two-sample t-test to one-sample test since there is no possibility of repetition (thus, of calculation of standard deviation) of the model runs. The test compares the mean value of the sample to an expected mean value. According to the null hypothesis, if the mean value of differences is 0 then the two samples are statistically the same. If the mean value of differences is not 0 then the control and the given scenarios are significantly different. The significance level was fixed at 5% in the course of the process.

3. *Results and discussion*

3.1. *Energy use in the cob layer*

The energy distribution for sensible and latent heat fluxes of the individual scenarios were not significantly modified in comparison to the control scenario, the difference to the control did not exceed 10% in any treatments (*Table 1*) which is in the range of error of the models as evaluated by *Singh* and *Jacobs* (1996), who diagnosed overestimations of 9 and 10% regarding the amount of simulated latent and sensible heat, respectively. It is worth noting that soil moisture reserves in Keszthely, even during the extremely hot days of July, were it is big enough to allow the latent heat to increase as compared with the control run. However, in case of more serious precipitation decrease they will supposedly be reduced and cause drastic fallback in latent heat (evapotranspiration depression).

Table 1. Ratio of the sensible and latent heat fluxes in maize on an average day in July at Keszthely

Scenario/ fluxes	**1961–1990**	**1997–2006**	**2×CO_2**	**3.8 °C/ –15%**	**4.8 °C/ –25%**	**6.0 °C –25%**	**9.0 °C/ –10%**	**9.0 °C/ –30%**
Sensible heat (%)	32.3	32.2	35.4	32.1	32.4	31.4	26.0	29.3
Latent heat (%)	67.7	67.8	64.6	67.9	67.6	68.6	74.0	70.7

Though, the hardly changing energy ratios do not mean that the amounts of the sensible and latent heat were not modified by the different model runs as compared with the control runs. The changes produced by the individual scenarios are illustrated through the example of the latent heat. The narrowing of the stomata opening due to the doubled CO_2 concentration significantly decreased the latent heat by 14.2%. A further significant difference could be found on extremely hot days (at the temperature change of + 9 °C), when the degree of modification depended also on water supply. In the scenario with a modest decrease in precipitation (only 10%) the energy spent on evaporation significantly increased, by 30.2%. If the average precipitation was reduced by 30%, the amount of latent heat increased only by 13.9% due to a reduced amount of available water. A comparison of the daily water loss of the individual scenarios with that of the control run also credibly reflected the differences determined in latent heat (*Fig. 1*). Change in soil moisture influences the movements of stomata. Interaction in soil water and transpiration is taken into account by calculation of stomatal resistance.

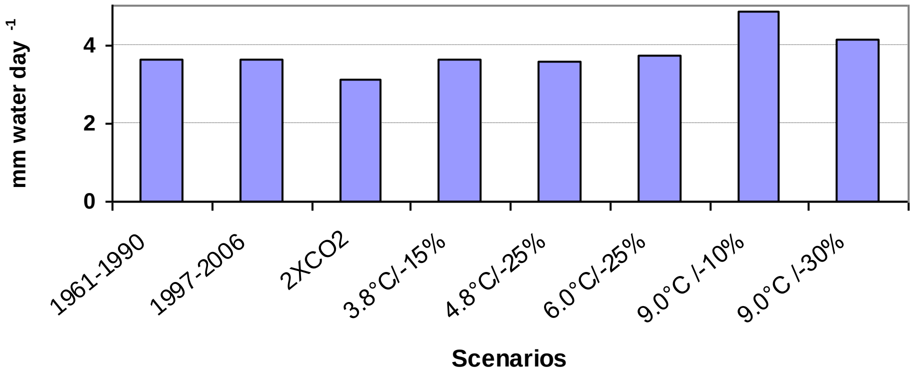

Fig. 1. Daily amounts of maize water losses (mm) in different scenarios at Keszthely during July.

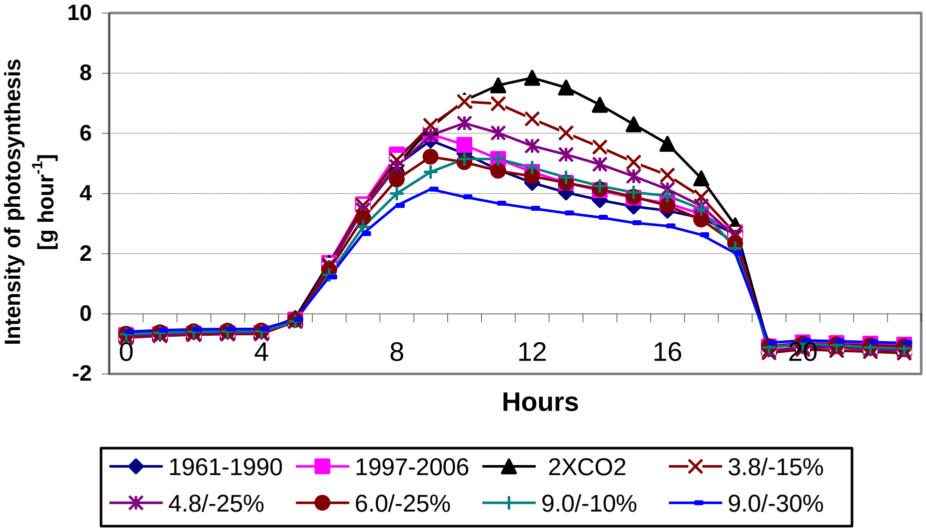

Fig. 2. Daily variation in the intensity of carbon assimilation in maize during July. Changes refer to 1961–1990.

Under the same weather conditions, the doubled CO_2 content significantly increased the net carbon assimilation rate of maize by 40% (*Fig. 2*). The balance of the photosynthetic rate of the past decade was positive (+7.1%), and increasing carbon assimilation are predicted by the fourth and fifth scenarios (14 and 24%). Photosynthesis decreased only in cases with warmings higher than 6 °C. A loss in photosynthesis will result from reduced amount of available soil water (precipitation); a good example of this relationship is the comparison of the two model runs with the same warming up of 9 °C but with different precipitation. At a decrease of 10% the daily carbon assimilation rate was reduced by 13%, while with a 30% less rainfall the rate was reduced by more than 30%. The model application suggests that in Hungary the future limiting factor of outdoor maize production without irrigation might be the precipitation.

3.2. *Crop temperature inside the canopy*

The simulated plant and air temperatures of the scenarios showed similar diurnal pattern but at different temperature in levels (*Fig. 3*) given by *Dióssy* (2008). Air temperature was in all cases higher than leaf temperature as found also by *Singh* and *Jacobs* (1996), but the difference remained under 1 °C. This indicates that the plants did not suffer significantly from lack of water in any of the scenarios.

In the past decade the crop temperature at cob level, similarly to that of the air temperature, rose significantly by 0.6 °C. However, there was a variation during the diurnal cycle. From the second half of the night to the solar noon, the hourly rise in crop temperature was significantly higher for the past decade (1–1.5 °C per hour) (*Fig. 3*). The difference between the temperatures of the control and second scenarios decreased during early afternoon, and in the late afternoon it stabilized between – 0.2 and – 0.7 °C. Such a variation during the diurnal cycle was not found when comapring other scenarios with the values of the basic run of 1960 –1990.

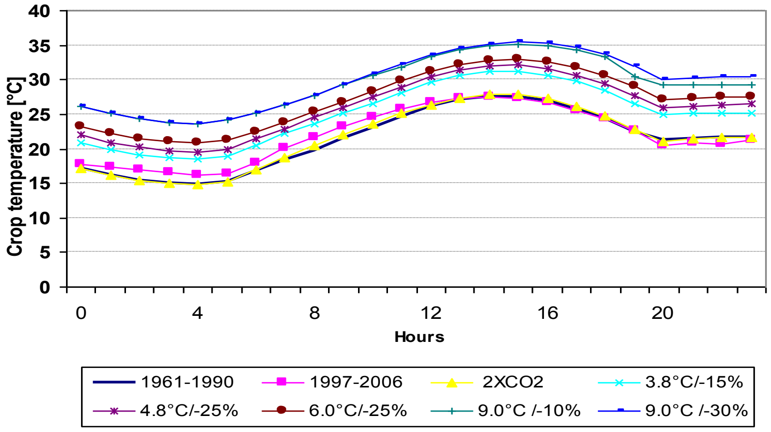

Fig. 3. Daily variations in maize crop temperature in the middle of the canopy (cob level).

The rise in plant temperature determined for the downscalings of the A2 and B2 scenarios to Hungary did not reach the rise of the ambient air temperature. This means that the cooling effect of the canopy transpiration on plant temperature was significant. In the scenarios with a smaller warming up, the degree of cooling was lower, only a couple of tenths of a degree. With simulating a greater warming up (above 6 °C), the canopy compensating effect on plant temperature still worked, but it was significantly reduced. The cooling effect of the canopy that mitigates the increase in plant temperature as compared with that of the ambient air emerged even in the last two scenarios (seventh and eighth). The cooling effect was 0.9 °C in the seventh scenario with low precipitation reduction, and only about the half of that, namely 0.5 °C in the eighth secenario with greater reduction in rainfall.

The optimum crop temperature range for maize in July is somewhere between 22–24 °C on average under Hungarian climatic conditions. At present, in most of the seasons there is enough precipitation for plant cooling to not override this optimum temperature. During global warming, the air temperature rise may increase the leaf temperature above this optimum level. Reduced precipitation may disturb the present balance, and farmers have to adapt to the changes for example by choosing more suitable crops for the given environment. One of the best tools in the hands of the Hungarian farmers to mitigate future impacts of climate change seems to be the use of irrigation to a greater extent.

4. *Conclusions*

The ratio of sensible to latent heat flux remained almost the same of all different scenarios. At a magnitude of less than 10% this was comparable to the overestimations by the crop microclimate simulation model in earlier simulations. It does not have the meaning that the absolute values of future projections were the same as the latent heat flux of control run. The doubled CO_2 level narrows the pore opening by about 14%. This may be a positive effect of global warming on the water loss of plants at Keszthely, where the water is the limiting factor of non irrigated maize growing. The latent heat flux of additional scenarios increased in comparison to control run. This justifies the existence of the reserve soil water at Keszthely even in an extra hot day during July.

Reduced transpiration and thus plant cooling at elevated CO_2 produced a moderate rise in plant temperature of 0.2 °C (in the third scenario). A given increase in ambient air temperature caused a lesser rise in crop temperature at cob level (place of yield formation in maize), demonstrating the cooling role of the canopy transpiration. This effect was detected even in extreme hot days.

Photosynthesis decreased only in cases with warmings higher than 6 °C. The photosynthesis was reduced by one third on an extremely hot day with 30% reduction in rainfall. This decline in photosynthesis may result in serious yield depression.

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