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Some physiological responses of agricultural crops to global warming

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Abstract—Food production is largely affected by weather variables; the year-to-year yield variations are due to changes in air temperatures, precipitation, and other meteorological elements. The crop-weather relationship is interaction, therefore, the agriculture is also responsible for greenhouse gas emissions (land clearing, fossil fuel use, rice cultivation, livestock production, N fertilization). The advantage of agricultural models is that they could simulate the above relations quantitatively. However, there are a variety of dynamic models dealing with crop-environment interactions in different levels from local to global one. The start of the studies used to be the cognition of crop growth and development by description of governing physiological and physical processes. The economic models close the range of investigations through impact estimation of climate change on the whole agricultural sector.

The first part of this study is devoted to some selected basic crop-environment relations from the literature. The second half of the work is dealing with on-site case study for maize, whereby different scenarios were established to project the crop response (stomatal resistance, photosynthesis) to various aspects of global climate change. The results of the crop microclimate simulation model were treated with restraint, because the majority of weather influences might have additive or synergistic impacts causing more severe damages than simulation models ever estimate. A simple example may be a stressed crop that become more sensitive to damaging pests and diseases excluding fully from most of the dynamic models. Despite known weaknesses of crop-environment models, the end-users (farmers, politicians) can respond more specifically to climate change besides such widely applied interventions as using warmth- or drought tolerant species, altering dates of planting and harvesting, irrigation, modification of cultivation systems, etc.

Key-words: climate change, agriculture, physiological processes, simulation model, maize

1. Introduction –brief selection from the related literature

Increasing demand for food is caused by the world's population growth and higher per capita income of well-developed countries. In addition to the amount of food, its distribution between different regions is also uneven; abundance and shortage of food are present at the same time. The most important task of the agriculture is to meet the higher demands, and to overcome the increasing risks with better management regarding agricultural food production. After FAO 2009's origin report, the number of people suffering from hunger is over a billion. Not encouraging for the future, that we have to nourish nine billion people by 2050 (*Godfray et al.,* 2010). The reasons of hunger are manifold from low agricultural productivity, lack of knowledge about cultivation facilities, poorness, overpopulation, poverty, etc. Luckily, majority of the above mentioned difficulties are not characteristic for Hungary, although there is also a contingency to improve the Hungarian agricultural production. The Carpathian Basin occupying a transition region of the precipitation pattern in Europe is probably one of the most sensitive places regarding impacts of global warming (*Torma et al*. 2010, *Giorgi* and *Coppola,* 2007). Whilst the climatic projections for different regions of Hungary may vary temporally (they are getting better and better), the sensitivity remains the same, which is caused by the special pool-type geographical position of the country.

Not to mention of all social causes of uneven food distribution, only one of the possible reasons will be discussed, namely the weather. The most vulnerable farmers are the rainfed crop growers due to extremely high rainfall variability (within a season and between seasons), and the intentions that force them to avoid risks, the meteorological hazards. The global climate change concerns both sides. *Easterling et al*. (2007) found that even a 2 °C warming in global air temperatures by 2100 (IPCC low emissions; SRES: B1) may destabilize the current farming systems reconfiguring the contemporary food distribution. The size of land for cultivation is strictly limited. One of the most important tasks in mitigating the negative impacts of global warming may be to produce more production from less land (*Vermeulen et al*., 2012).

Consequences of global climate modification include warming, variation in precipitation events, and shifting of seasonal (phenological) cycles. Among these three terms, the precipitation projections are the most uncertain. Phenology (length and timing of the various phenological stages) comprises periodic life cycle of crops largely depending on weather conditions. The phenological phases are governed by the interaction of genetic characteristics and weather conditions (in temperate climate mostly temperatures and day length), that are modified by land cultivation to gain the highest yield (*van Bussel et al*., 2011, *Kirby et al*., 1987). In phenological observations, the impact of temperature has of primary importance. Air temperature directly determines the ratio of the biochemical processes (enzyme activity, cell die). Temperature has no less significant impact on the sequence of development stages. Phenological shifts modify the distribution of the species ranges, e.g., migrations toward higher elevation and latitude (*Vitassea et al.* 2011, *Bertin*, 2008). The extension of the photosynthetically active period may effect crop growth positively on the mid- and high latitudes (*Menzel* and *Fabian,* 1999) due to enhancing the carbon-uptake period, which stems from earlier leaf emergence and later leaf senescence. At the same place, shorter season for field crops could have rather negative impacts through blocking the formation of the yield components (*Chmielewski et al*., 2004). Surprisingly, in Germany, despite of warming of the last two decades, no strong effect on fruit (apple) yield formation was observed so far (*Chmielewski et al*., 2004). However, a question may arise: till what time?

During the past few decades, most of the studies were focusing on the changes of the natural vegetation only, and limited number of papers were dealing with the trends of agricultural crops (*Schelling,* 2000), despite their significance in reducing negative influences of climate change. Direction and magnitudes of observed phenology trends showed a different picture over Europe between the time period of 1986 and 2006 using satellite images (*Ivits et al*., 2012). The authors reported that until north-eastern Europe deployed a trend to an earlier and longer vegetation period, in central Europe the length of the season exhibited rather stable indicating a shift towards an earlier start of the entire growing season. At the same time, the Mediterranean areas displayed a phenological shift towards later dates with both earlier and shorter growing seasons, depending on the actual place of observation. On the basis of a twenty six years analysis *Brown et al*. (2012) found, that one third of the cereal's growing area has experienced changes in the length of the growing seasons on global level; on most areas the length of the growing seasons was with 2.3 days/year longer on average, since 1981. The above authors reported both negative and positive trends in the start of the vegetation period depending on the country and region studied. Considerable variability among crop species and observation ways has to take into account to get well-appreciated future phenological estimations. In the past three decades, variation in weather (temperature, precipitation, solar radiation) jointly increased the wheat yield in northern China by 0.9–12.9%, however, they reduced wheat yield in southern China by 1.2–10.2%, with a large spatial difference (*Tao et al*., 2014). The above authors reported that the wheat growth period before anthesis and the whole growing season were shortened, however, the length of reproductive growth period was significantly prolonged. In Europe, Hungary included, an earlier beginning of the growing season and a longer growing period may be waited. In Hungary, *Gaál* (2008) reported 12-17 days longer vegetative period for 2050, favorable for the warm season plants. Non-standard results were also born in the literature such as from *Brown et al*. (2012). The authors concluded that due to variations in weather effects on crop production, in the northern hemisphere the humidity based, while in the southern hemisphere, the accumulated growing degree days concept fitted better, when phenological models were applied. This concern likely may be expanded on larger scale only. It is well known by many investigators that significant differences are expected on country level.

Perennial crops as fruit trees and grapes are the most vulnerable classes considering the negative effects of global warming. For European temperate tree species, an average increase of the growing period of 11 days has been reported from the 1960s to the end of the 20th century by *Menzel* and *Fabian* (1999). *Richardson et al*. (2013) chronicled phenological advances of approximately 3–8 days for each 1 °C growth in air temperature for the same group of trees. *Taylor et al*. (2008) assumed that one of the reasons of the extended vegetation period may be the elevated CO_2 that delayed the autumn coloration and senescence in trees. The warming trend in our present climate is expected to continue, so in case of grapes, the ripening period will be characterized by higher temperatures worsening the berry quality (*Fila et al*., 2014). This means that the Italian traditional grape growing areas will be in serious risk. *Jones* (2012) in Quebec suggested to explore new cultivation areas, previously cool regions, where the climate change towards for more favorable environmental conditions for grapes. The current Hungarian grape growing regions may shift into another maturity group due to more rapid phenological development (*Ladányi,* 2008).

At the very beginning of climate change impact studies, the most controversial part was the possible effect of elevated CO_2 on crop physiological processes. Studies in phenological shifts are important, because physiological processes related to the carbon cycle, plant-water relation, or nutrient uptake are directly mediated by phenology (*Noormets et al*., 2009). *Richardson et al*. (2013) reported spring onset of photosynthesis by about 3 days at +1°C anomaly in spring air temperature that grew the photosynthetic activity and respiration by 35±5 and 20±3 $gCm^{-2}/°C^{1}$, respectively in a deciduous forest. Finally, the photosynthetic gains were positive, +9±2 $gCm^{-2}/°C^{1}$ on the study site. It is important to mention that in dry conditions, the influence of precipitation may exceed the effect of higher temperature on the intensity of carbon-assimilation. *Ma et al*. (2007) gave a good example for a grassland at California, in which 1 mm increment in springtime precipitation gave 2 gCm^{-2} growth in daily productivity of the ecosystem.

Doubling of the current ambient CO_2 raised the growth with 10–20 and 40–45% in C_4 and C_3 crops, respectively (*Ghannoum et al*., 2000). Increasing atmospheric CO_2 concentration has long been known to stimulate C_3 photosynthesis better than photosynthesis of C_4 crops. The C_4 crop's photosynthesis regarded an improved version of the C_3 pathway that raises the level of the photosynthetic efficiency in addition to lower evapotranspiration rate. The advantage of C_4 crops is the lower photorespiration in comparison to C_3 ones. The C_3 crops will benefit net photosynthetic rate, stomatal resistance, and transpiration water loss. The photosynthetic way of C_4 crops was implemented due to the less favorable environmental conditions of their native places (dry and hot environments). The C_4 crops have higher production rates than that of the C_3 ones because of the gains in the used water and CO_2 values. On ecosystem level, the type of the photosynthetic pathway impacts the carbon fixation, on the one hand influencing the size of food resources for animal feeding purposes, and on the other hand effecting the amount of CO_2 released back to the atmosphere.

One of the possible impacts of increasing CO_2 levels may be the increase in stomatal resistance, causing less transpiration intensity (*Ainsworth et al.*, 2002), lowering the latent heat loss that increases canopy surface temperatures (*Bernacchi et al.*, 2007). This process will likely increase in heat and drought stress, declining the crop productivity (*Cias et al.*, 2005). *Leaky et al.* (2009) noted that in addition to higher photosynthetic activity of C_4 crops at elevated CO_2 level, the concomitant reduced water use and lower stress levels could play a more important role than the increased photosynthesis.

Although the crop response patterns could not be generalized (*Richardson et al.,* 2013), each one-day increase in the length of the growing season rose the yearly evapotranspiration water loss by 1.6 mm on a Mediterranean grassland (*Ryu et al*., 2010). Contrary to the results of *Rye et al*. (2010), *Richardson et al*. (2013) found weak correlation between length of the growing season and yearly evapotranspiration total in both deciduous (9 species) and evergreen (12 species) forests (*Richardson et al*., 2010).

However, it is obvious that phenology effects canopy microclimate, less information is available about the multitude ways in which phenology influenced canopy feedbacks to regional-scale weather patterns (*Penuelas et al*., 2009). More observations are necessary to get reliable results for levels excessing microclimate.

The water budget–crop canopy relationship is a less known process in spite of its everyday practical use in irrigation, in which water inputs such as precipitation and irrigation, and outputs as evapotranspiration and outflows have to be considered. Precise estimation of water balance terms is almost impossible, because they use a lot of variables and parameters that are inferring and roughly measured from the sides of soil (water storage, infiltration rate, hydraulic conductivity, etc.), plant (phenology, root depth, volume, hydraulic properties, hydraulic conductivity, different types of leaf resistances, crop level characteristics, etc.), agronomic practices (cultivation, canopy level characteristics, etc.), actual weather conditions impacting the crops (interception), and climate change (changing meteorological elements excluding precipitation and temperatures) (*Savé et al*., 2012, *IPCC* 2007). A model prediction for maize in Portugal showed an increase in actual evapotranspiration of maize in spring, when soil water content was still enough to cover the increased water demand of crop. Oppositely to observations for spring, in summer, a decline in maize evapotranspiration was observed due to soil moisture reduction, in total providing an increase in irrigation necessity of the studied area (*Savé et al*., 2012). The general tendency of climate modification suggests that in temperate climate, a moderate increment in the irrigation necessity can be waited until 2050, while by the end of the 21th century, an extension of the irrigation period should be waited, irrespective to investigated crop species. The higher water use of vegetation may interact with the environment providing a feedback that currently seems to be difficult to quantify accurately. Due to the complexity of maize physiological responses to variation in environmental conditions, and to early initiation of the season, the shortening of 33% in the growing period (10 days) may be waited using B1 SRES scenario (*Warrington et al*., 1999). This number was registered much higher in apple trees up to 20–25 days by the above authors for the Mediterranean area. Summing the earlier comments, we assume increasing irrigation water amounts during this century ranging from 40 to 250% depending on the crop species and growing area of the agricultural crops (*Savé et al*., 2012).

2. Simulation of maize photosynthesis and stomatal resistance: an on-site case study

2.1. The purpose of the on-site simulation

The likely effect of increased evapotranspiration and modification in plant growth as a result of global warming are less known, however large amount of investigations was devoted to this topic (*Graaff et al*., 2006). Due to the foregoing special behaviour of C_4 crops, it seems to be evident, that their response to elevated CO_2 received less attention than the more sensitive C_3 crops. In this study use of maize was motivated because C_4 stomata are as responsive, and in some cases more so, than C_3 stomata (*Anda* and *Dióssy,* 2010, *Triggs et al*., 2004). We aimed to project the impacts of climate change on some maize microclimate and crop properties applying the Crop Microclimate Simulation Model (CMSM) of *Goudriaan* (1977) driven by scenario output from regional climate model. Drivers of climate change (meteorological elements and crops) interact with each other under field conditions. As the systematic synthesis regarding the impact of different meteorological and crop feature combinations is not very common, we wanted to investigate the variations in microclimatic elements and maize physiological properties resulted from climate modification side by side. Though conclusion of *Ehleringer* and *Thure* (2002) seems notable as they assume that at rising CO_2 levels the ambient gas concentration will once again cross a threshold value, where C_4 plants loose their competitive advantage over C_3 plants from the standpoint of reduced photorespiration and enhanced light-use efficiency. Maybe results of this case study should contribute to preparations in mitigating negative impacts of future climate modifications.

In order to develop proper long-term adaptation and mitigation strategies, detailed observations about on-site weather-crop responses concerning influence of climate modification are also necessary. In this study the modelling tool was applied to estimate the possible impacts of climate change on physiological characteristics of maize grown at Keszthely (Hungary). To achieve this goal, thirty-year crop and climate observations served as an archive of inputs for the CMSM model (*Goudriaan,* 1977). The principle of analogy was applied when choosing the proper crop and weather inputs for a specified scenario.

2.2. The modelling outline of crop features and inputs

Oppositely to other simulated microclimate and crop characteristics, the CMSM calculates the net photosynthesis (F) empirically on canopy level (*Goudriaan,* 1977; *Goudriaan* and *van Laar,* 1994):

$$F = \left(F_m - F_d\right)\left[1/\exp\left(R_v \varepsilon / F_m\right)\right] + F_d , \qquad (1)$$

where F_m is the top of 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 light use efficiency ($17.2 \cdot 10^{-9}$ $\mathrm{kgJ^{-1}}$ for maize). The size of respiration was assumed to be –0.1 of the F_m (*Goudriaan,* 1989).

The Eq. (1) was the basis in simulation of leaf stomatal resistance (r_{leaf}) as follows:

$$F = \frac{1.83 \cdot 10^{-6}\left(C_e - C_r\right)}{1.66 r_{leaf} + 1.32 r_{b,h}} , \qquad (2)$$

$$r_{leaf} = \frac{1.83 \cdot 10^{-6}\left(C_e - C_r\right)}{1.66 F} - 0.795 \quad [\mathrm{sm^{-1}}], \qquad (3)$$

where $r_{b,h}$ is the boundary layer resistance, 1.66 is the ratio between diffusivities for CO_2 and water vapor, $1.83 \cdot 10^{-6}$ converts CO_2 concentration into $\mathrm{kgCO_2\ m^{-2}}$ at 20°C, C_e is the external CO_2 concentration, C_r is assumed regulatory CO_2 concentration, 1.32 is coming from conversion of r_{bh} for CO_2.

The sensible heat flux (Q_{Hi}) in the i layer is as follows:

$$Q_{Hi} = \rho c_p \frac{\left(T_{ci} - T_{ai}\right)}{r_{aHi}} , \qquad (4)$$

where T_{ai} is air temperature in the i layer [K], T_{ci} is canopy temperature in the i layer [K], r_{aHi} is aerodynamic resistance for sensible heat transfer in the i layer [$\mathrm{sm^{-1}}$], ρ is air density [$\mathrm{kgm^{-3}}$], c_p is specific heat of air [$\mathrm{Jkg^{-1}/K^{1}}$].

The latent heat flux (λE_i) in the i layer is:

$$\lambda E_i = \rho c_p \{e_s(T_{ci}) - e_s\} / [\gamma(r_{awi} + r_{ci})] \quad (5)$$

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

More details about model structure, functioning and on-site validation of simulated variables were published earlier by *Anda* and *Dióssy* (2010), *Anda* and *Kocsis* (2008) and *Dióssy* and *Anda* (2009).

A short growing season maize acted as test crop in the model. The inputs were site and plant specific parameters and variables (geographical position of the study place, plant height, maize leaf density in three different crop layers), soil properties (actual soil moisture, physical soil characteristics) and locally collected meteorological data (on hourly basis). The meteorological elements were observed at Agrometeorological Research Station of Keszthely by using standard QLC-50 type automatic climate station. In the reference scenario (1961-90) monthly average soil moisture of -7 bar water potential was applied as an average soil moisture in July (*Table 1*). The crop characteristics such as plant height, LAI and leaf density were measured at the station between 1981 and 2010. In selection of crop characteristics for different scenarios, analogy was looking from the on-site historical measurements during the past three decades. The reference run and the present (past decade: 2004–2013) had 340 and 380 ppm (*Haszpra et al.*, 2012) atmospheric CO_2 concentrations in July, respectively. In addition five scenarios were created, in which the projections had doubled CO_2 level (760 ppm) that corresponded with the RCP6 scenario (*Moss et al.*, 2010). As the highest value, a medium range forecast for atmospheric CO_2 composition by the RCP6 scenario was applied with smooth transition towards concentration stabilization level after 2100 achieved by linear adjustment of emissions around 2100 (*vanVuuren et al.*, 2014). The RCP6, among other Representative Concentration Pathways, was adopted by the IPCC fifth Assessment Report (AR5) in 2014 (IPCC, 2014). Number 6 (Wm^{-2}) means the range of radiative forcing for 2100, relative to pre-industrial values. Associated temperature rise projection is 3.2 degrees. The intercellular CO_2 level was kept in one third of the open air one (*Anda* and *Kocsis,* 2008).

Model runs were exemplified for an "average" day in July (warmest and driest months at Keszthely).

From the model outputs, crop properties were presented for the middle (cob) layer of fully grown maize. The layer of cob formation is assumed to be the most intensive regarding the crop physiological processes.

Table 1. Summary of the used scenarios

Scenario	Air temp.	Soil moisture	CO_2 conc. Ambient air	LAI	Abbrev.
	Means for month July				
Reference	**20.3 °C**	**–7 bar**	**340 ppm**	**2.8**	**Ref***
Actual	20.8 °C	–7.7 bar	380 ppm	2.8	Act
2 × CO_2	20.3 °C	–7 bar	760 ppm	2.8	2 × CO_2
Scenario 1.	+2 ºC*	–25%*	760 ppm	2.5	Scen1
Scenario 2.	+4 ºC*	–40%*	760 ppm	1.5	Scen2
Scenario 3.	+6 ºC*	–55%*	760 ppm	1.5	Scen3

Assuming normal distribution of both samples, paired *t*-test was used to evaluate differences between model runs performed by SPSS 17.0 Program Package. In accordance to the null hypothesis, if the mean value of differences is equal to 0, then the two samples are statistically the same. The significance level was fixed at 5%.

2.3. *Discussion of the simulation results*

Presently, new scenarios are applied describing the recent and future atmospheric composition including CO_2 level. These new scenarios allow a smooth transition to the future projections harmonizing with historical data (*Moss et al.*, 2008). In the projected global average air temperatures, four multi-gas emission scenarios were adapted from literature and updated for release as Representative Concentration Pathways (RCPs), with the range from 1.5 to 4.5 °C for the lowest RCP3-PD and for the highest RCP8.5 scenarios, respectively (*Moss et al.*, 2010). The range of radiative forcing are 3 and 8.5 Wm^{-2} in the scenarios RCP3-PD and RCP8.5, respectively. The assumption complemented and actualized the previous scenario-based estimations of atmospheric composition known as SRES scenarios (SRES: Special Report on Emissions Scenarios, *Nakicenovic et al.*, 2000). Scenarios in this study was about in the middle of RCP ones.

The opening of the pores that can be expressed by the stomatal resistance values has of primary importance in crop photosythetic activity due to regulation of admitted CO_2 and released water vapor. The balance between these two decisive factors may be the promise of high crop productions.

The CMSM assumes the closed pores as 2000 sm^{-1} that happens when the wilting point (–14 bar soil water potential) or sunset is reached. The midday minimum r_s of 379 sm^{-1} was calculated by the model for cob level that is about three times higher than that of the on-site measured absolute minimum r_s value for July.

In our model estimation, the lowest daily mean r_s of 577 sm^{-1} was observed in the Ref scenario (*Fig. 1*). In each scenario the daily mean r_s values significantly increased compared to the index of the period of 1961–90. A moderate but highly significant increment of 13.7% ($P<=0.001$) in daily average r_s of present days was simulated, probably due to warmer July temperatures (+0.5°C) and reduced monthly rainfall sums (–22%) during the past decade. Result of this simulation was in accordance to findings of *Erdélyi* (2008), who observed shortened phenological phases in maize due to temperature rises in Hungary. The only doubled CO_2 had the highest impact on maize r_s; the growth of 59.1% was highly significant ($P<=0.001$) with respect to Ref. The elevated CO_2 level itself narrowed the pore openings more than a half that reduced the daily mean water loss about 0.5 mm on an average day in July. On a monthly basis it is equivalent to 15 mm water decline for the whole month. This reduction in transpired water amount may be the on-site positive impact of global warming. Regarding the three scenarios with gradually intensified warming and drying, the daily average r_s increases were 54.2% ($P<=0.001$), 41.6% ($P<=0.014$) and 45.4% ($P<=0.006$) in Scen1, 2 and 3, respectively comparing to the r_s values of the reference period. There is an apparent contradiction between the increases of r_s in Scen1 being higher than in Scen2 and 3, but only until biological variables are taken into account by involving the size of LAI. The possible reason might had been the way of crop – and weather – input selection, the used analogies from the past. On the basis of local measurements, drastic LAI decline from LAI=2.5 to LAI=1.5 was performed in the last two scenarios (Scen1, 2), where the lower transpiring surface size and r_s might regulate the rate of transpiration together. Results of this study suggested that simulation of Scen1 kept the r_s values close to the resistance curve of only raised CO_2 scenario, implying that the negative consequences resulted from variable modifications included to Scen1 avoided strong variation in the r_s.

Tendency in daily change of r_s values was similar in model runs with the particularity that the simulated r_s values were similar to each other at high solar radiation, just about solar noon. In the case of high solar angles, the stomatal resistance values of the different scenarios were closer to each other and to the Ref run as well.

Besides daily mean r_s values, the opening time of the pores was also shifted in some of the model scenarios. Earlier on-site studies showed that the opening of pores in July used to be at 6 a.m. under clear-sky weather conditions (*Anda* and *Lőke,* 2003, *Anda et al*., 1997). In reality, the stomatal resistance measurements of the early morning hours may be hampered by cloudiness or dewfall. The 6 a.m. pore opening was simulated only in the first three scenarios (Ref, Act, Scen1); opening time of all the other scenarios were shifted to 7 a.m. The stomatal closure time of the last three scenarios was delayed one hour either; it was 8 p.m. instead of 7 p.m. Duration of "active" pores remained the same in each scenario.

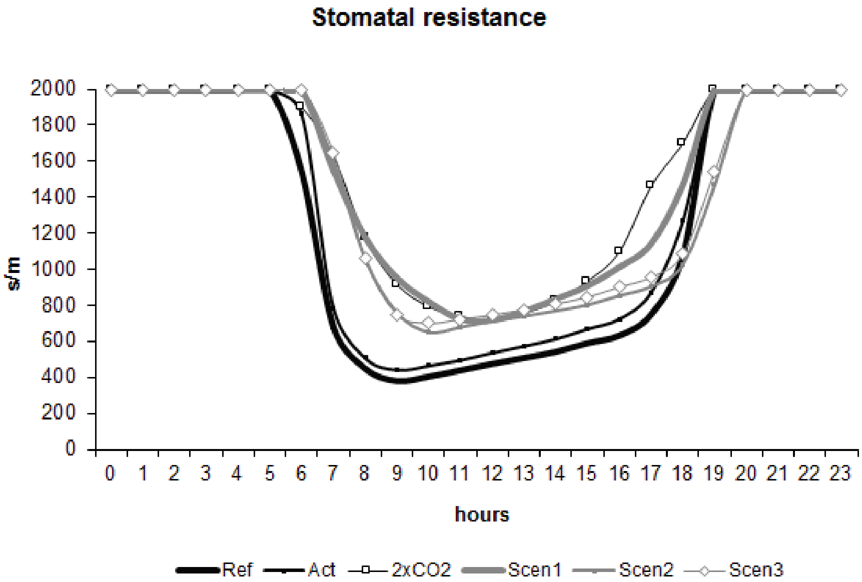

Fig. 1. Diurnal variation of simulated stomatal resistance ($r_s sm^{-1}$) in maize for Keszthely, during an average sample day in July. Results are presented for the cob level. Inputs of different scenarios and their abbreviation are in the text. Closure of stomata was assumed as 2000 sm^{-1}.

The CO_2 is one of the basic materials in photosynthesis; the higher the CO_2 concentration is, the more intense the biological process will be. The favorable effect of increased CO_2 level is widely applied long ago as CO_2-fertilization under closed growing conditions (greenhouses). The gain in carbon assimilation depends on the other physiological process, on the rate of respiration as well. At nighttime, there was no difference in respiration intensity of used scenarios (*Fig. 2*); see negative data of the *Fig. 1* by night.

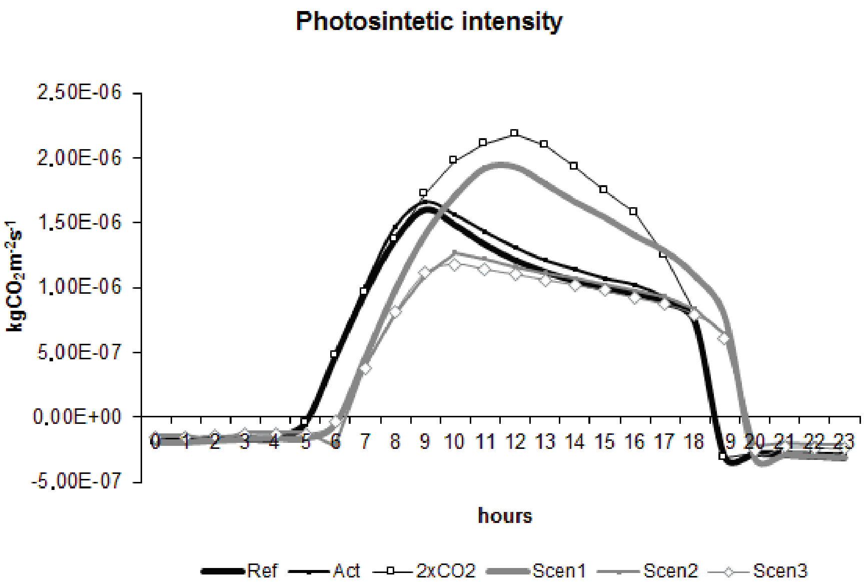

Fig. 2. Daily change in maize photosynthetic intensity ($kgCO_2m^{-2}/s^1$) during daytime hours and respiration rate ($kgCO_2m^{-2}/s^1$) by night in different scenarios for Keszthely.

Ref run was the lowest photosynthetic activity treatment in this study. Higher photosynthetic rates were simulated in all other scenarios in spite of increased r_s values, likely due to elevated CO_2 concentrations. During the past decade, the Ref photosynthesis value increased to 6.2% ($P<=0.001$) indicating an on-site positive direction of present climate modifications. Summary of the statistical analysis of different scenarios was placed in *Table 2*. Supposing otherwise unchanged weather, the Scen with doubled CO_2 level produced the highest increase of 36.1% ($P<=0.003$) in daily mean photosynthetic rate. This favorable influence could not be entirely realized with significant weather changes. As it was presented earlier in data for r_s, temperature increase of +2 °C increased with 22.7% ($P<=0.065$) rather than decreased the intensity of photosynthesis. A moderate decline was present in Scen1 with respect to doubled CO_2 scenario. We assume that this temperature rise of 2 °C together with moderate soil moisture decline does not provide a strong threat for growing maize at the surroundings of Keszthely. Photosynthesis dropped only in cases with warming exceeding +4°C and stronger soil moisture cuts. In spite of doubled CO_2, like a tendency, the daily mean photosynthesis rates were reduced by 14.1% ($P<=0.493$) and 18.6% ($P<=0.273$) in the Scen2 and 3, respectively. In these two latter scenarios, not only the expected warming but strong reduction in precipitation was also taken into account.

The energy retained by plant stands is distributed among the energy-users. The largest of all the users is the energy spent for evapotranspiration (about 70%) as latent heat flux that protects the crops from overheating. About one-third part of net radiation dissipates from the canopy as sensible heat, forming the microclimate of crops. Only a few percent of energy is utilized in the process of photosynthesis. There was a real surprise, that significant changes in both energy fluxes were only observed at doubled external CO_2 concentrations (*Figs. 3* and *4*). Elevated carbon-dioxide closing stomata gap decreased the transpiration of maize. Decline of 15.6% ($P<=0.001$) in the latent heat flux of Scen $2xCO_2$ was simulated when comparing to Ref run. The other scenarios of latent heat fluxes did not differ statistically either from each other or Ref (see also *Table 2*). The opposite modification occurred for sensible heat fluxes. Elevated CO_2 ($2xCO_2$) increased the sensible heat flux with 21.9% ($P<=0.001$) in comparison to Ref. Similarly to latent heat fluxes, in addition to Scen of $2xCO_2$, there was no significant modification in the sensible heat fluxes in any scenarios when compared to Ref one.

Table 2. Paired Samples Test of the outputs of the scenarios (Significant results are in bold)

	Paired Differences					**t**	**df**	**Sig. (2-tailed)**
				95% Confidence Int. of the Differences				
	Mean	**Std. Dev.**	**SE**	**Lower**	**Upper**			
Stomatal resistance								
Ref - Act	–55.542	75.277	15.366	–87.328	–23.755	–3.615	23	**.001***
Ref – 2×CO_2	–257.042	289.505	59.095	–379.289	–134.794	–4.350	23	**.000***
Ref - Scen1	–233.458	258.245	52.714	–342.506	–124.411	–4.429	23	**.000***
Ref - Scen2	–148.208	273.335	55.794	–263.628	–32.789	–2.656	23	**.014***
Ref - Scen3	–169.500	274.221	55.975	–285.293	–53.707	–3.028	23	**.006***
Photosynthetic intensity								
Ref - Act	–3.67E-8	4.3E–8	8.77E-9	–5.48E-8	–1.85E-8	–4.179	23	**.000***
Ref – 2×CO_2	–2.51E-7	3.67E–7	7.49E–8	–4.06E-7	–9.65E-8	–3.357	23	**.003***
Ref - Scen1	–1.61E-7	4.07E-7	8.31E-8	–3.33E-7	1.09E–8	–1.938	23	.065
Ref - Scen2	4.53E-8	3.19E-7	6.51E-8	–8.93E-8	1.8E-7	.697	23	.493
Ref - Scen3	6.85E-8	2.99E-7	6.1E-8	–5.78E-8	1.95E-7	1.122	23	.273
Sensible heat flux								
Ref - Act	–1.202E0	5.334E0	1.088E0	–3.454E0	1.050E0	–1.104	23	.281
Ref - 2×CO_2	–1.116E1	1.347E1	2.750E0	–1.685E1	–5.477E0	–4.060	23	**.000***
Ref - Scen1	–5.53E0	2.37E1	4.84E0	–1.56E1	4.49E0	–1.142	23	.265
Ref - Scen2	–1.36E0	2.15E1	4.39E0	–1.04E1	7.71E0	–.311	23	.759
Ref - Scen3	1.42E0	2.14E1	4.38E0	–7.63E0	1.05E1	.325	23	.748
Latent heat flux								
Ref – Act	–4.208E-1	4.336E0	8.851E-1	–2.251E0	1.410E0	–.475	23	.639
Ref - 2×CO_2	1.370E1	1.516E1	3.0964E0	7.298E0	2.011E1	4.426	23	**.000***
Ref - Scen1	6.272E0	3.311E1	6.760E0	–7.713E0	2.025E1	.928	23	.363
Ref - Scen2	1.580E0	3.703E1	7.560E0	–1.405E1	1.722E1	.209	23	.836
Ref - Scen3	–3.529E-1	3.793E1	7.743E0	–1.637E1	1.566E1	–.046	23	.964

* Significant difference

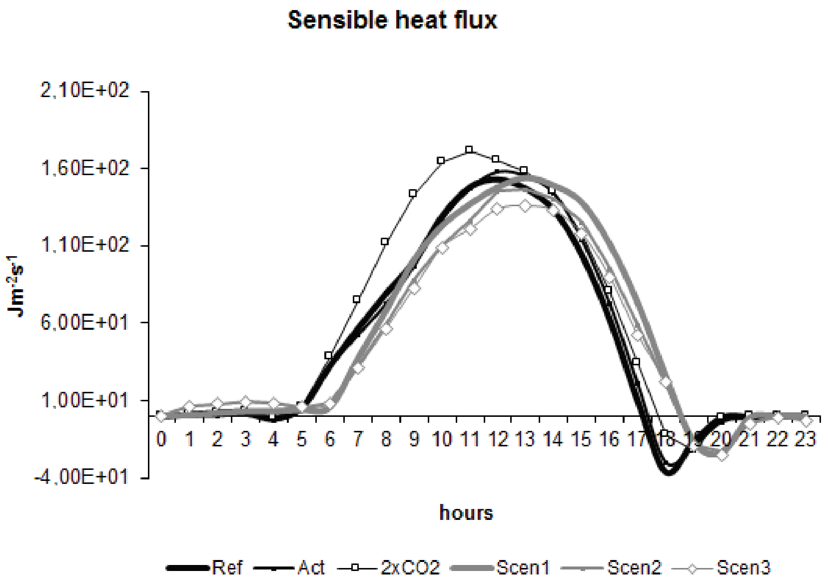

Fig. 3. Daily change in maize sensible heat flux (Jm^{-2}/s^{1}) in different scenarios for Keszthely.

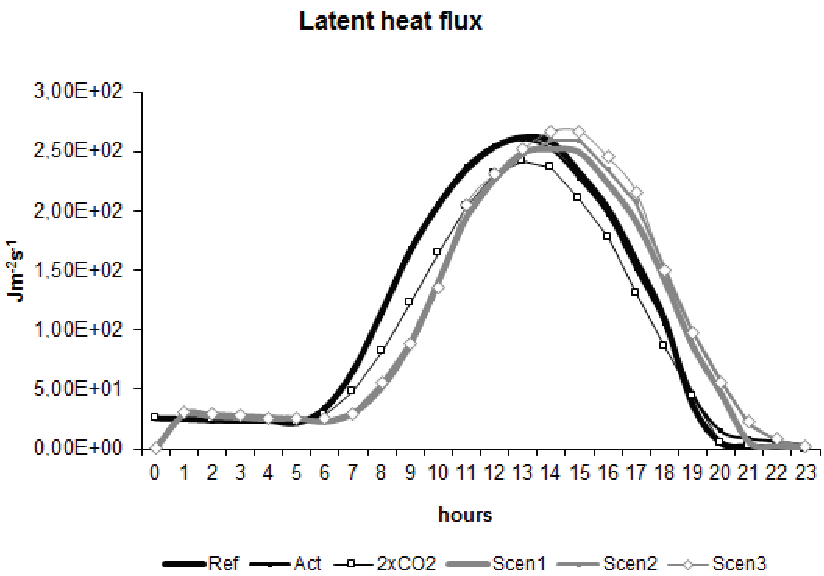

Fig. 4. Diurnal variation of latent heat flux (Jm^{-2}/s^{1}) in maize for Keszthely, during an average sample day in July.

3. Conclusion

In accordance to projected future weather scenarios, our region is expected to have more frequent and longer drought periods than at present. On the basis of scenarios, an increased importance of irrigation is expected when mitigating the on-site negative impacts of future climate change.

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