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SIMULATION OF THE IMPACTS OF GLOBAL CLIMATE CHANGE IN MAIZE

THESIS OF DOCTORAL (PHD) DISSERTATION

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TABLE OF CONTENTS

1. The Antecedents of Research

To date, global climate change is one of the most serious challenges for mankind. The fact of climate change – and the role of the anthropogenic factor within – is more and more justified by observation and research. Today, climate change embodies a double challenge.

On the one hand, its serious consequences can be prevented by reducing greenhouse gas emissions, and, on the other hand society should adapt to its effects. Hungary's mid-term climate policy, the VAHAVA (Hungarian acronym for Change – Effect – Response) has been elaborated on a scientific basis, as being one of the actors in its preparation. We laid significant stress on that the National Climate Strategy (NCS) should take into account the possibilities of adapting to the effects of climate change, even in the field of agriculture.

However, besides the determination of the mid-term tasks, scientific research has an enormous role in providing help for the farmers in offsetting the adverse effects of global warming as well as in the preparation of the necessary and possible adaptation, in a way that the adaptation procedures should be adjusted to the local conditions (*Láng* 2006).

With the help of the regional scenarios of global warming, the Well Applicable Simulation Model, the research using the available plant and meteorological data in Keszthely, conclusions can be reached even for the end of the century.

The aim of the examination

Our research goal was to present the changes expected in the conditions of maize production under changing climate conditions for the period of 2071-2100.

Micrometeorological simulation examination was used to determine the effects of changing CO_2 concentration as a consequence of climate change, warming up and the difference of precipitation supply to the plant vital processes of maize.

Our goal was to provide local level information in order to start the preparation for preventing the expected adverse effects in time.

2. The materials and methods

During the past decades research of special microclimate and canopy climate showed significant development. This resulted in theoretical models simulating physical processes and gained ground beside the former prevailing empirical approaches. Our model, a simplified version of an existing system (e.g. a plant or canopy), is able to emulate the behaviour of a more complex real system. The model also provides an opportunity to examine the elements of the system individually or as a whole, and to follow the selected characteristic(s) embedded in a real system, in a complex way. The model applied by us was the PC-executable version of the newer edition (*Goudriaan and van Laar* 1994) of the CMSM (Crop Microclimate Simulation Model) by *Goudriaan* (1977). This is a physical model, therefore its application required no adaptation.

Nowadays a lot of Hungarian and foreign studies have been elaborated on the impacts on the vegetal vital processes caused by global warming, as well as one of its source, the increasing level of the atmospheric CO_2 concentration (*Mihailovic and Eitzinger* 2007, *Mera et al.* 2006, *Anda and Kocsis 2007, etc.*). Scenarios with doubled CO_2 concentration try to give a picture on the expected (even positive) changes at different levels (from global to local) and try to outline an expected result for different plants, sometimes even positive changes. The technical literature interprets doubling of CO_2 concentration as two different values and therefore two different expected occurrences. According to the standard interpretation the double CO_2 concentration is 560 ppm, namely double of the 280 ppm, the value of the period before the industrial revolution. Its realisation is expected between 2050 and 2060 as a function of the international emission reduction agreements, the innovations in technology and energetics as well as the world economy's growth. Another interpretation considers 760 ppm, double the figure of the current atmospheric level (~380 ppm) as a target function; the different scenarios take its expected occurrence time to about 2100 or later (*IPCC*, 2007). In our scenario the latter concept was applied. With the scenario doubling only the CO_2 concentration we wanted to quantify the local positive effects of global warming.

The expected temperature due to its uncertainty is viewed in two different ways. Global warming is expected to increase between 1.1 and 6.4 °C to 2071-2100 in the latest IPCC report. According to *Mika* (2007) a multiplying factor of 1.4 should be applied for the Hungarian version; it refers to the higher weather sensitivity of the Carpathian basin. In our study the higher frequency of the extreme weather phenomena was also taken into account; by using the highest value of the IPCC forecast (6.4 °C) as well as the increased sensitivity of the

Carpathian basin (multiplying factor: 1.4), resulting in two local scenarios, respectively. We used the *IPCC* Fourth Assessment Report *(2007)* and the results of the Global Circulation Models relevant to Hungary, based on the works of *Bartholy et al. (2007).* In the case of precipitation forecasts the results of the individual GCM runs were very different, in some cases even the signs of the changes differed. Due to the uncertainty, exceeding the temperatures in the precipitation forecasts, we laid stress on analysing the changes in air temperature without ignoring the changes in precipitation. The applied scenarios contained the most probable precipitation forecasts for Hungary.

The aim of the thesis was to determine the effect of the change(s) in plant characteristics on the basis of the values of global warming relevant to Hungary. The model is based on energetics providing a new approach in the analysis of the plant vital processes. If the energy consumption of the canopy changes, it will affect all plant vital processes (*Mera et al.* 2006). Early maturing Norma SC maize hybrid was used as a test plant. Based on eight scenarios, our analysis ranged over canopy inside air temperature, plant temperature, stomatal resistance-evaporation, carbon assimilation as well as development of the energy consumption of the canopy.

Input data and parameters derived from the Agrometeorological Research Station of Keszthely (46°44'N; 17°14'E; 114.2 m above sea level). Input meteorological elements were provided by the QLC-50 type local automatic climate station equipped by Eppley pyranometer. Similarly to the meteorological inputs, we used the principle of analogy in the case of the input plant data of the given scenario. At the input plant data we chose a month – an average July – being analogous with the weather to be simulated, where the data on maize and soil moisture were the same or almost the same as the values of the year to be simulated. For this we had about a 30-year data series for medium early maturing maize. Out of the eight scenarios one showed the control basic run of the period between 1961 and 1990, one examined the changes of the recent past, and another one analysed the impacts of the double CO_2 concentration. The remaining five scenarios contained different degrees of warming up beside the double CO_2 concentration as follows: scenarios with +3.8, +4.8, +6.0, and two with +9.0° C; the latter two differed only in the quantity of precipitation. One of them assumed a more moderate, while the other one did a more vigorous drying. For evaluating the results of the model runs we used a matched t-test that was performed by the STATA 5.0 (1996) statistical program package. This process reduces the two-sample t-test to a one-sample test, in order to eliminate the possibility of repetition of the model runs (or standard deviation calculation). The test compares the mean value of the sample to an expected one value.

According to the zero hypothesis if the mean value of the differences is 0 then the two samples are statistically the same. If the mean value of the differences does not equal to 0, then the two samples are significantly different. The significance level was set at 5% in the process.

3. The results

3.1 Development of canopy inside air temperature

In the place showing results at the corn-cob level, where vital processes are most intensive, the increased outer temperature has increased the canopy inside air temperature. The degrees of the warming up were not significantly different from the sun's altitude, though at the warmer scenarios the time of the development of maximum temperatures has generally been occurring one hour later, at 3 pm instead of 2 pm.

Keszthely was not unaffected by global warming between 1997 and 2006 as regards the canopy inside air temperature. During the comparison the canopy inside air temperature rise at corn-cob level followed the rise of the outer temperature compared to the 1961-1990 climate normally serving as a basis in many researches; it was significantly 0.6 °C compared to the average of the years between 1961-1990 on an average July day.

Doubling the outer CO_2 concentration (the single input parameter out of the inputs of the basic run (1961-1990)) has significantly increased (by 0.3 °C) the canopy inside air temperature at corn-cob level; this indicated the stimulating impact on the closure of pores by the higher CO_2 concentration on the movements of stomata.

The comparison between the results of the two runs of IPCC origin shows that the connection of warming up and doubling the CO_2 concentration together interacted in a way inducing a "milder" change in canopy inside air temperature. This corresponds with the former experience of *Prasad et al*. (2006).

At the last two, increased (but not extremely increased) global warming scenarios the compensating effect of canopy on the air temperature at corn-cob level endured, however it strongly depended on the humidity supply. Assuming less decrease in precipitation (-10%) the presence of the canopy could mitigate the 9 °C outer warming up by 1.2 °C. This is likely owing to the stronger shadowing effect of a larger green surface, which could be developed as a result of the better water supply. If we connect the warming up of the abovementioned temperaturewith a more significant decrease in precipitation, and we analyse it assuming the presence of a lesser shadowing green surface together with this, the compensating effect is immediately halved, to about 0.7 °C.

3.2 Development of plant temperature at corn-cob level

With regard to the plant temperature and corn-cob level air temperature, our results were in accordance with the communication on maize by *Anda and Lőke* (2006), where very similar changes of the two temperature values were reported. Plant temperature measured at corn-cob level showed a moderate rise when doubling the CO_2 concentration; it showed a significant increase of 0.2 °C (daily average) being independent from the time of the day. It is in connection with the effect of the increased CO_2 concentration that narrows the stomata and lessens evaporation; it results in a slight increase in plant temperature due to the lack of plant cooling.

The corn-cob level plant temperature in the recent past – similar to the air temperature – rose significantly, by 0.6^{o}C (daily average), but this difference compared to the basic run (1961-1990) – contrary to the corn-cob level canopy inside air temperature – was varying daily by nature.

The rise in plant temperature determined for the downscaling of A2 and B2 scenarios for Hungary did not reach the value of the outer warming up simulated for the run, namely the plant temperature compensating effect of the canopy can be obtained, similar to the canopy inside air temperature.

In the case of lower simulated warming up the degree of compensation is lower, only a couple of a tenth °C. A2 scenario brought the psychological breakthrough after which – with simulating a warming up of a higher degree (from 6 °C up) – the plant temperature compensating effect worked but it was less than the degree found in the canopy inside air temperature.

The effect of the presence of the canopy that mitigates the increase in inside plant temperature compared to the increase in outer temperature emerged even in the case of the last two scenarios, namely depending on water supply. It was 0.9 °C at the scenario with better precipitation supply, and only about half of it, 0.5 °C in the case of the drier treatment. The

plant temperature compensation of the canopy, however, did not reach the canopy inside air temperature compensation at corn-cob level. The more intensive plant temperature increase compared to air temperature refers to the increased stress-condition of the plant (*Anda* 2001).
On the basis of the simulation analysis performed at Keszthely it can be asserted that the warming up increases plant temperature, but not to the same extent as the outer air temperature rises. The presence of the canopy slightly compensated the rise in plant temperature, even at simulation with rather high warming up. Compensation degree depended on the water supply, too.
A better water supply brings more intensive development of the green surface so provides a stronger shadowing effect; this also affected the development of plant temperature (*Dióssy* 2008).

3.3. Stomatal resistance and evaporation

In each scenario the daily average stomatal resistance significantly increased compared to the index of the period of 1960-90 used as a control.
In the recent past during July the average value of stomatal resistance increased significantly by 14.6%, probably as a result of a higher temperature and less precipitation.
As a daily average, the doubled external CO_2 gas concentration itself narrows the stoma openings to about a half (47.9%). This effect is even more intensive (above 60%) at a low solar position, mainly in the morning. Environmental factors are jointly present in the proximity of the plant, so their effects emerge in an integrated way, too.
In the two runs with IPCC scenarios the daily average stomatal resistance values did not differ statistically either from each other or the resistance of the scenario doubling only the CO_2 concentration. This shows that the stoma-narrowing effect of the increased CO_2 concentration can also be produced by the modification of other environmental factors (e.g. change in water supply).
According to some previous observations, July with a temperature above the average – even with unchanged precipitation – goes together with less leaf area production. The incidental lack of water would even aggravate the growth depression of maize.

The basic run was the treatment with lowest stomatal resistance with regard to the unit green surface of the canopy. This value has risen by more than 30 s/m during the period of 1997-

2006. Taking the leaf area index as being constant it can be unanimously attributed to warming up and precipitation decrease. In the location of the investigation doubling the CO_2 concentration resulted in an increase of 47.9% in stomatal resistance related to unit leaf area, having all other external factors unchanged. A strong warming up associated with a significant precipitation decrease, according to the most extreme (last) scenario it would even double stomatal resistance related to the unit green area.

Neither the daily nor the monthly average transpiration water loss has changed in the past decade. Probably it is the joint consequence of the increased atmospheric CO_2 concentration and the tendency of a precipitation decrease in July. If we double the 1961-90 level of the atmospheric CO_2 concentration, the evaporation decrease due to the narrowing of stomata is about 0.5 mm in the daily average that is equivalent to a modification of 14.3%. (It represents a monthly amount of transpiration water decrease of 15 mm for the whole of July.) The intensity of water loss is larger in the case of scenarios with an air temperature increase of 9 °C, if there is enough available groundwater, namely in the case of moderate (-10%) precipitation decrease (29.9%). In the case of a soil humidity decrease of 30% the increase in evaporation is much smaller, 13.7%, since in this case the lack of water was probably a serious limitation factor. In the case of a relatively higher warming up (6 °C), the increased external atmospheric CO_2 concentration partially compensates. However, it can only work if precipitation does not have any significant changes. Drastic fallback of precipitation can immediately overwrite the results since the adverse impact of lack of water affects depressively all vital processes of the plant.

3.4. Changes occurring in the process of carbon assimilation

In Keszthely the higher air temperature and the slightly increased atmospheric CO_2 concentration have significantly risen the photosynthesis intensity of maize by 6% in the recent past. The tendency-like, slight precipitation decrease of the decade is also contained by this scenario. According to the 6% increase, the change in the external environmental factors has positively affected the productivity index of locally grown maize and the intensity of photosynthesis so far. The doubling of concentration in itself (taking constant of all environmental and plant characteristics at 1961-90 level) causes a production increase of 35.1% (significant at 5% level).

According to the results of both IPCC scenarios relevant to Hungary, the increase in the intensity of photosynthesis is statistically justifiable, though to a lesser extent compared to the increase in CO_2 gas concentration. This value is 24% for scenario B and more moderate, 14.5% for A2. The decrease in the intensity of photosynthesis occurred in the case of scenarios with simulating a warming up above 6° C. The extent of the decrease exceeds a couple of percent if there is an additional precipitation decrease together with warming up, namely in the case of a warming up by 9° C, where the precipitation decrease was 30% (significant difference at level of 5%). In the case of changes according to the last scenario the drop of photosynthesis intensity was estimated as 24.5% by the simulation model.

Our own investigations justified the former statement of *Prasad et al.* (2006) which says that the impact of the increased CO_2 gas concentration, which enhances the intensity of photosynthesis cannot be realised due to the accompanying warmer plant and air temperatures. Therefore it is not appropriate to calculate with the emergence of a monthly average summer warming up of above 6 °C; this positive effect is associated to one of the sources of global warming, the higher CO_2 concentration.

3.5 Development of the energy consumption of the canopy: changes of sensible and latent heat

Between 1997 and 2006 the sensible heat has not risen significantly, only by 3.4% compared to the values of 1961–1990.

The doubled CO_2 concentration significantly raised the amount of sensible heat by 19.6% on daily average. It is in accordance with the increasing stomatal resistance and the decreasing evaporation as well as the consequences thereof.

The daily average amount of sensible heat of A2 and B2 runs did not differ either from each other or from the value of the basic run.

The higher the simulations of warming up were by scenario, the lesser the values of the amount of sensible heat of the various scenarios were compared to the control run.

In the case of the treatment simulating a warming up by 6 °C, the decrease of sensible heat is 10.3% (significant at 5%) on daily average; it refers to the fact that in the case of this warming up the water necessary to cool the plant demanded more energy than was necessary to set the appropriate plant temperature in July of each year during the period 1961–1990. It is also important that there was sufficient surplus water so that the plant was able to evaporate (if there is not enough water supply for the plant, the energy increases the ratio of sensible heat). This idea is confirmed by the statistically approved difference in the development of sensible heat deriving from the run of the two different water supplies in the case of an air temperature rise of 9 °C. In the case of the scenario representing a precipitation decrease of 10% the reduction of sensible heat was the largest of all scenarios: 68.1% compared to the basic run, while in the case of the more serious drying (30%) the amount of sensible heat decreased only by 32.7% compared to the control.

At both treatments the energy demand to be used for evaporation and cooling of the plants is very high (warming up of 9 °C as condition!), which represents such a serious water demand that can be fulfilled by the canopy partly to the detriment of the sensible heat as compared to the basic run. In the case of treatment with less drying the plant has more water. Evaporation has a very high energy demand – see the high specific heat of water –; in the extremely hot instances this energy demand can only be realised by the maize through extremely high energy investment compared to the basic run.

The conditions of the last scenario, the extreme air temperature assumes a much stronger transpiration compared to the basic run; to this, the source of the surplus energy is partly the relative energy used as sensible heat in the control run. In the last scenario the decrease of water supply was increased to 30%; it has not been able to cover the water demand of the plant with given environmental conditions yet. Therefore a part of the energy (compared to the run with higher water supply) could not appear as latent heat but it increased the amount of sensible heat, so it resulted in halving the drop in energy use compared to the control scenario. The reduced amount of sensible heat compared to the basic run in the treatment with a precipitation decrease of 30% means that even under these harder environmental conditions there was some reserve in Keszthely, and the plant was able to accommodate to the harder conditions.

In the case of latent heat we found a significant decrease of 14.2% compared to the years between 1961 and 1990 when the CO_2 level was doubled. At the same time, this value is the quantified representation of the influence of global warming on water balance of plants moderating evaporation (based on energetics) (*Dióssy* and *Anda* 2008). In Keszthely this is the positive ”result” of the increase of CO_2 concentration causing global changes, which narrows the stomata of maize. It cannot be neglected that this mentioned impact could only emerge in the case of doubling the CO_2 concentration ceteris paribus – it is impossible as far as we know.

Warming up above 6 °C increased the latent heat ratio compared to the basic run in a statistically justifiable way at all scenarios. It meant an increase of only 4.1% in the case of the more moderate air temperature increase of 6 °C. We found the highest difference (increase of 30.2%) in the case of the scenario of 9 °C, with less drying. In the case of this treatment there was enough water that could be evaporated by maize, so the degree of sensible energy consumption exceeds the amount of energy used for transpiration in the period of 1961–1990 by one-third. In the case of a precipitation decrease of 30% the smaller water supply provided less possibility, and the energy consumption compared to the basic run exceeded the control value by 13.9%. The reason for the decreasing latent heat was obviously the more limited water supply. The lesser transpiration intensity does not enable development of the optimum plant temperature; the result thereof is the damage of biochemical processes and the depression of the quantity of produced dry matter. The latent heat ratios of simulations performed with two different water supplies was justifiably different from each other at the 5% level.

4. New scientific results

1. The canopy inside air temperature of each scenario has significantly warmed at high probability level compared to the basic run. In the past decade its temperature was 0.6 °C compared to the 1960-1990 period. Warming up of the canopy changed proportionally to the increase of external temperature. Comparison of the canopy inside air temperature of the different runs shows that the change of either the air temperature or the CO_2 concentration in itself does not result in an expected outcome since these factors may strengthen or suppress each other's effects. Simulation modelling is an adequate tool in the process of cognition since it handles the plant and its environment together. The impact of precipitation can be similar to temperature; in accordance with this, the different precipitation supplies of the extremely hot scenarios caused a significant difference in the canopy inside air temperatures. The significantly different reactions regarding canopy inside air temperature of both runs containing an air temperature increase of 9 °C compared to a warming up of 6 °C deserve attention. The presence of a plant canopy, however, mitigated the degree of warming up at corn-cob level, likely owing to the shadowing effect of the canopy. We should not ignore the fact that the compensating effect of the canopy depends on the canopy structure, which is determined by the humidity supply.

2. Values of the corn-cob level plant temperature calculated by different scenarios compared to the values of the basic run; the two IPCC scenarios compared to each other as well as the plant temperatures of both treatments with increased temperatures of 9 °C compared to the scenario with warming up of 6 °C – these all represented slight differences but significant at the level of 5% at least. On the basis of the simulation analysis related to Keszthely, it can be established that warming up increases plant temperature, but not to the same extent as the external air temperature rises; the compensating effect of the canopy worked even in the case of a serious temperature increase, though the degree thereof was also strongly dependent on the water supply. The optimum plant temperature of maize is about 23-24 °C, and according to local measurements performed around noon in Keszthely in July, the actual canopy temperature has also exceeded this value several times recently. The only chance of protection against the local effects of global warming is to provide a cooling medium, the additional water supply for the plants; this requires the re-consideration of the former irrigation practice.

3. The ratio of the two largest energy consumptions, sensible and latent heat did not change significantly in maize, assuming an average July. Still, the change of several percent should not be underestimated, since the value of the entire energy assimilation is the same during the photosynthesis. The two types of energy use are not independent from each other, and especially the impacts of water supplies have a primary role. It can be justified by the comparison of the sensible heat of the two runs with a temperature rise of 9 °C; it shows that the reduced drying (-10% precipitation) implied a stronger decrease of sensible heat than the treatment with more drying did. The decrease of water supply was able to cover the water demand of plants to a lesser extent with given environmental conditions, therefore a certain part of the surplus energy simulated in the scenario could not appear as latent heat but it increased the amount of sensible heat. The reduced amount of sensible heat compared to the basic run in the treatment with a precipitation decrease of 30% means that even under these harder environmental conditions there was some humidity reserve in Keszthely, and the plant tried to accommodate to the harder conditions. It is uncertain whether this option is available elsewhere in the country.

4. One of the causes of global warming, the raised CO_2 concentration itself narrowed the stomatal openings by 14.3%; it is the quantified value of the impact of global warming on

plant evaporation, referring to Keszthely. This is a positive impact since plant transpiration could decrease in the majority of the years by this figure during July when water is scarce.

5. Based on our examinations, the impact of the increased CO_2 gas concentration, which enhances the intensity of photosynthesis cannot always be realised due to the accompanying warmer plant and air temperature. Therefore it is not expedient to calculate with the emergence of a monthly average summer warming up of above 6 °C in Keszthely; this positive effect is associated to one of the sources of global warming, the higher CO_2 concentration. But it is worth calculating below this value; it was proven e.g. by the increase of 6-7% in carbon assimilation in the recent past. The assimilation values are different, depending on their calculation to the leaf area or to the soil surface unit. Iterations to soil surface show a much more significant decrease in the intensity of photosynthesis, since in this approach the decrease of green surface due to warming up develops much more intensively. This fact mitigates the decrease in the assimilating green surface and would also reduce crop failure. In our opinion, water seems to be the bottleneck of the future; farmers have to prepare to face the lack of water, even if nowadays the forecast of precipitation changes is rather uncertain.

6. Transpiration increase emerged in the case of simulations with warming up of over 6 °C, but out of the scenarios with an air temperature increase of 9 °C, the intensity of water loss of maize is really high in the case of that scenario where there is enough available groundwater, namely in the case of the treatment with a moderate (-10 %) precipitation decrease. It was found that the increased external atmospheric CO_2 concentration slightly compensates, but only if precipitation does not have any significant changes.

5. Publications on the subject of the dissertation

5.1 Scientific articles in English

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Dióssy L. /2009/: Klímavédelem és önkormányzatok. Klímavédelem és Területfejlesztés Nemzetközi Konferencia. Keszthely 2009. június 5.

5.3 Oral presentations in English

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5.4 Poster presentations in English

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