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# Microclimate simulation of climate change impacts in a maize canopy

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**Abstract—**Effects of possible climate modification on maize plant features have been evaluated by using the simulation model of *Goudriaan* for local climatic conditions and locally measured plant characteristics. Moderate climate modifications were hypothesized. According to the purpose of detecting local impacts of climate change, researches were made on the microclimate of maize canopies. In the energy transport of the plant stand, no shift has been experienced to the direction of the latent heat as it was expected because of the effect of warming up and decrease of precipitation. The changes of stomatal resistance and inside canopy air temperature suggested that the natural water supply will probably not cover the water demand of the plant, if the climate change is more intensive, therefore farmers must prepare to irrigated cultivation and to apply different agro-technical methods to save the water supplies of the ground.

*Key-words:* climate change, microclimate simulation model, maize, Keszthely, Hungary

## *1. Introduction*

Climate change and variability may have an impact on the occurrence of food security hazards at various stages of the food chain, from primary production through to consumption (*Tirado et al.,* 2010). Worldwide agriculture has to face major changes in land use in the coming decades, and agriculture needs to meet rising claim with less resource while satisfying quality and environmental demands (*Stein* and *Goudriaan,* 2000). Agriculture is one of the fields that are highly affected by climate change also in Hungary (*Jolánkai,* 2010), therefore, researches in this field and developing adaptation strategies are very important. Prognostics of the impacts of climatic changes for the Carpathian Basin

(Hungary) in air temperature and precipitation in the range of 0.5–4°C global change were described by *Mika* (2002). The main statement of the scenarios is that the local weather would get warmer (1–5°C) and drier ((–40) – (–66) mm) in the first some decades of the global warming (*Mika*, 2002). *Bartholy et al*. (2004) estimated the regional effects of climate change at Lake Balaton – Sió Canal catchment area (where the experimental site of the researches is situated) by a stochastic-dynamic downscaling model using the ECHAM/GCM outputs. *Bartholy et al.* (2004) predict a decrease of 25–35% of precipitation amount in the summer half-year and 0–10% decline in the winter half-year at a climate corresponding to double $CO_2$ level. These statements were enhanced by *Bartholy et al.* (2008), *Szépszó* and *Horányi* (2008), and by the *Hungarian Meteorological Service* (2010) according to further regional climate model simulations.

Crop simulation models are often used to predict the impact of global atmospheric changes on food production (*Ewert et al.,* 2002). Plant canopies' role and their capability of modifying local microclimate has come into focus in the issue of adaptations to climate change. *Easterling et al.* (1997) provided an approximation of the potential for strategically positioned shelterbelt systems to reduce climate change-related stress on maize in the USA. *Guilioni et al.* (2000) examined the influence of temperature on plant's development rates and worked out a model that uses meteorological data to estimate the temperature of a maize apex. *Goudriaan* and *Zadoks* (1995) analyzed the combined effects of pests and diseases under changing climate by using modeling tools, because climatic change not only affects the potential yield levels, but it may also modify the effects of pests and diseases.

*Fodor* and *Pásztor* (2010) used the 4M crop simulation model to quantify some indices of the agro-ecological potential of Hungary and its future development under climate change. Their results indicate that the Hungarian agriculture cannot avoid the effects of climate change, and these effects will be mostly negative. The yields of the spring crop as maize, sunflower, etc. will decrease, while higher yields might be expected for the autumn crops. *Gaál* (2007) analyzed the modification of the climatic conditions of maize production in Hungary using HadCM3 and B2 SRES scenario for the periods of 2011–2020 and 2031–2040. The results concluded that with higher temperature, maize hybrids of 2–3 FAO group of longer vegetation period could be cultivated, but the limiting factor will be the precipitation.

*Dióssy* and *Anda* (2008) focused the attention on the impacts of drastic climate change on the energy consumers of maize canopy in Hungary. The energy distribution for sensible and latent heat fluxes of the applied scenarios were not significantly modified (*Dióssy* and *Anda*, 2009; *Anda* and *Dióssy*, 2010). *Dióssy* (2008) reports the effect of global warming on the inside air temperature of maize canopies. According to the degree of warming up, the air temperature in the canopy increased.

At the Agrometeorological Research Station of Keszthely, observations of the microclimate have been made for several decades. As field experiments are time consuming and expensive, another method is the use of crop growing models that can quantify the effects of management practices and environmental circumstances on crop growth and productivity (*Knörzer et al.*, 2011). At Keszthely for more than one decade, information was gained by using simulation model about crop microclimate that could rarely be registered earlier. Numerical models are often used to simulate the complex energy and mass transfer processes in soil-plant-atmosphere system (*Sauer* and *Norman*, 1995). In this study, the Crop Micrometeorological Simulation Model (CMSM) constructed by *Goudriaan* (1977) was applied. Using the earlier data of Keszthely station, and the downscaled information for the country and the watershed area of Lake Balaton, the aim was to simulate the impacts of some expected climatic conditions on the microclimate and the physiological processes of the maize stand.

## *2. Material and methods*

### *2.1. The selected site and origin of input data*

The inputs, both meteorological and plant features used in the simulations were collected at Keszthely Agrometeorological Research Station (46°44'N, 17°14' E, 114.2 m ). The required above-canopy meteorological parameters are daily runs of air temperature, air humidity, wind speed, net radiation and/or incoming global radiation (*Stigter et al.,* 1977). Meteorological data were measured by a QLC-50 automatic climate station by 10 sec sampling time that was established in 1996. Hourly meteorological data were formed for the requirements of the model. Our sample day was an average day in July, when the plants were fully developed. The reference level of the model inputs was taken into account by calculated aerodynamic depths for every stage of plant development (*Goudriaan*, 1977). The roughness length and zero-plane displacement for maize was adapted from *Monteith* (1973). Wind speed was estimated at a reference level using combination of friction velocity and the logarithmic wind speed profile above the canopy (*Goudriaan*, 1977). In case of the wind speed, measurements were made at 10 meters above the ground.

Test plant, the mid-season maize hybrid Norma (FAO 450) has been sown and cultivated since the 1970s at a plant density of 7 plants $m^{-2}$ on plots of 0.7 ha. The inputs of the model were site and plant specific parameters (plant height, leaf density in three layers), different soil characteristics (soil moisture content and physical properties), and hourly meteorological data from local measurements which were transformed from the standard observation level of 2 m above soil surface to the reference level required by the model (*Anda* and *Kocsis,* 2008). The height of reference level depends on actual plant development.

In the past 40 growing seasons, the leaf area and its density were measured in the field on the same 10 sample plants weekly, using an LI-3000A portable planimeter. The soil moisture content in the upper 1 m was also measured in the field gravimetrically every 10 days at 10 cm intervals. The actual soil water content was expressed in terms of soil water potential. The physical properties of the local Ramann type brown forest soil were determined at the beginning of the investigations.

### *2.2. The applied Crop Micrometeorological Simulation Model (CMSM)*

*Goudriaan'*s (1977) simulation model and its improved version (*Goudriaan* and *Van Laar,* 1994) follow the division of the radiation inside the canopy and its utilization in different energy-intensive processes (*Anda* and *Lőke,* 2003). The theoretical background of the Crop Micrometeorological Simulation Model (CMSM) is the physics of the energy-transfer and transport processes. CMSM is based on the traditions of model-developing work of Wageningen group (*Van Ittersum et al.,* 2003).

The productivity of crops is directly related to their capture of resources (water, light) and the efficiency with which they convert these physical resources into biological materials (*Yi et al.,* 2010). One part of the radiation energy that reaches the plants reflects, the second part penetrates into the stock, and the third part is fixed by the plant stand (*Jones,* 1983; *Anda* and *Lőke,* 2003). As the vertical structure of the plant stand is not homogeneous, the height of the plant is usually divided into different number of layers, the characteristics of which can be regarded as more or less homogeneous (multi-layer model). The resistances between air layers in the canopy are not neglected, and gradients in air properties inside the canopy are also taken into account (*Goudriaan,* 1989). The number of the layers can be influenced by the characteristics of the canopy, the aim, and the element to be examined (*Goudriaan,* 1977; *Anda et al.,* 2002). CMSM is a static model according to the air conditions and dynamic for the soil and plant data (*Hunkár,* 1990; *Páll et al.,* 1998; *Hunkár,* 2002). Exchange processes at the soil surface are important from a modeling perspective in that the soil surface is the interface between the soil and atmospheric systems (*Sauer* and *Norman,* 1995).

Within the parameters calculated by the model, sensible and latent heat fluxes, air temperature inside the canopy, plant temperature, stomatal resistance, and intensity of the photosynthesis were involved into our simulation examinations. The sensible and latent heat fluxues were described as *Bowen ratio* ($\beta$) that is the proportion of the sensible and latent heat fluxes. These parameters were presented on the border of the upper third of plant height in the study. This is the place of cob formation, where the intensity of physiological processes is the highest.

Model results were analyzed by *paired t-test* using *STATA 5.0* (1996) statistical program package in order to prove the significant deviations.

Scenarios were set up to simulate the effects of climate change on the maize stand. Carbon-dioxide concentration was raised of the intercellular spaces in accordance with the changes of the carbon-dioxide concentration of the atmosphere on the basis of the data of the literature (*Jackson et al.,* 1994).

In each layer there are energy sources and sinks. The intensity and direction of the source and loss of the different forms of energy must be determined. On the basis of detailed calculations, the model creates profiles for the meteorological elements inside the canopy.

The theory of the CMSM is the calculation of the radiation distribution among different environmental processes. The sensible heat flux ($H_i$) [J m$^{-2}$] in the *i*th layer is (*Goudriaan* and *Van Laar,* 1994):

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

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

The latent heat flux ($\lambda E_i$) [J m$^{-2}$] in the *i*th layer can be calculated as follows (*Goudriaan* and *Van Laar,* 1994):

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

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

Basis of the assumption of leaf resistance simulation is that mass transport processes – both water vapor and carbon-dioxide – occur via stomata, so that the ratio between their resistances is equal to the ratio between their diffusivities. In case of maize a linear relationship exists between net $CO_2$ assimilation and inverse leaf resistance at constant $CO_2$ concentration of substomatal cavity. This connection served to simulate the leaf resistance, since net $CO_2$ assimilation can be deducted precisely from the absorbed short wave radiation (*Goudriaan,* 1977). Exceeding the saturation point of $CO_2$ assimilation (200 J m$^{-2}$ s$^{-1}$ for sunny maize leaves), the leaf resistance approaches its minimum value (*Stigter* *et al.*, 1977). Rate of net $CO_2$ assimilation ($F_n$) [kg $CO_2$ $m^{-2}$ $s^{-1}$] was found by an empirical representation of measured curves (*Van Laar* and *Penning de Vries,* 1972, *Goudriaan,* 1977):

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

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 $m^{-2}$ $s^{-1}$], and
$\varepsilon$ 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. Dependence of leaf temperature was considered as a dependence on ambient air temperature. Dark respiration was at about –0.1 of $F_m$ (*Goudriaan*, 1977). From the net $CO_2$ assimilation calculated by Eq. (3) the leaf resistance is calculated with:

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

where

$r_H$ is resistance against heat transmission [s $m^{-1}$],
1.66 is the ratio between diffusivities (for $CO_2$ 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 assumed as 'regulatory' $CO_2$ concentration [ppmv], and
1.32 originates from calculation of 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 in *Goudriaan* (1977).

After calculation of the sensible and latent heat, the estimation of the crop temperature in the *i*th layer ($T_{L,i}$) [°C] was as follows (*Goudriaan,* 1977):

$$T_{L,i} = T_{a,i} + (H_i - H_{i-1}) \frac{r_{H,i}}{\rho c_p}, \quad (6)$$

where

$\rho c_p$ is the volumetric heat capacity of the air [J m$^{-3}$ K$^{-1}$],

$T_{a,I}$ is the air temperature [°C], and

$r_{H,I}$ is the resistance against heat transmission [s m$^{-1}$].

There is an analogy in calculation of canopy inside air temperature and crop temperature. When $i$=1, $T_{a,i-1}$ is the temperature from the reference level. The zero level (if $i$=1, $i-1$ is the level zero) is the place of the reference height.

Validation of the model outputs (crop temperature, leaf resistance, some elements of microclimate, photosynthesis) were carried out locally (*Anda* and *Lőke,* 2002, 2005; *Lőke*, 2004, *Anda et al.*, 1997) using RMSD (*Willmott,* 1982) and the model does not need further adaptation.

*2.3. The applied scenarios*

For the reason of climate change impact simulation in case of maize, scenarios that represent moderate climatic variations (compared to the model runs carried out by *Diόssy* and *Anda,* 2008) for Hungary were established. By most of the publications regarding local climate modifications, precipitation decrease is to be continued in the future. 25–35% decrease is expected in case of modelling doubled $CO_2$ concentration together with air temperature increase (1.3–2°C in summer) for Lake Balaton – Sió Canal catchment area, on the western part of Hungary, where Keszthely is situated (*Bartholy et al.*, 2004). The inputs of plant architecture, the size of the assimilatory surface and its density were chosen from the local measurements of the past four decades by using the principle of analogy. Plant data (LAI) of those seasons were used, when the air temperature and soil water content were similar in July as in the scenarios, respectively. In Scenario 1, continuous linear changes were supposed to be on the basis of the meteorological data of July between 1977 and 2006 at Keszthely. $CO_2$ concentration rise that should be pared to 0.6 ºC temperature rise was 440 ppmv (*Mika*, 2007). In Scenarios 2 and 3, the atmospheric $CO_2$ concentration was increased to 760 ppmv (*Table 1*) with higher rise of the air temperature and decrease of the soil moisture.

*Table 1.* The applied scenarios

| **Scenario** | **Air temperature** | **Soil moisture** | **$CO_2$** | **LAI** |
|---|---|---|---|---|
| Control | average in July | average soil moisture | 380 ppmv | 3.0 |
| Scenario 1 | + 0.6 ºC | – 10% | 440 ppmv | 2.8 |
| Scenario 2 | + 1.3 ºC | – 25% | 760 ppmv | 2.3 |
| Scenario 3 | + 2.0 ºC | – 35% | 760 ppmv | 2.0 |

## 3. Results

The incoming radiation, that is absorbed in a given crop layer after reflecting from the canopy or proceeding towards the soil, becomes the energy source of the heating processes (sensible heat flux), and evapotranspiration (latent energy flux). If there is no water restriction, evapotranspiration is the main energy consumer of the plant stand. The diurnal mean *Bowen ratio* is shown in *Fig. 1*, and the statistical analysis showed that significant deviation cannot be observed from the control run in any of the scenarios (*Table 2*).

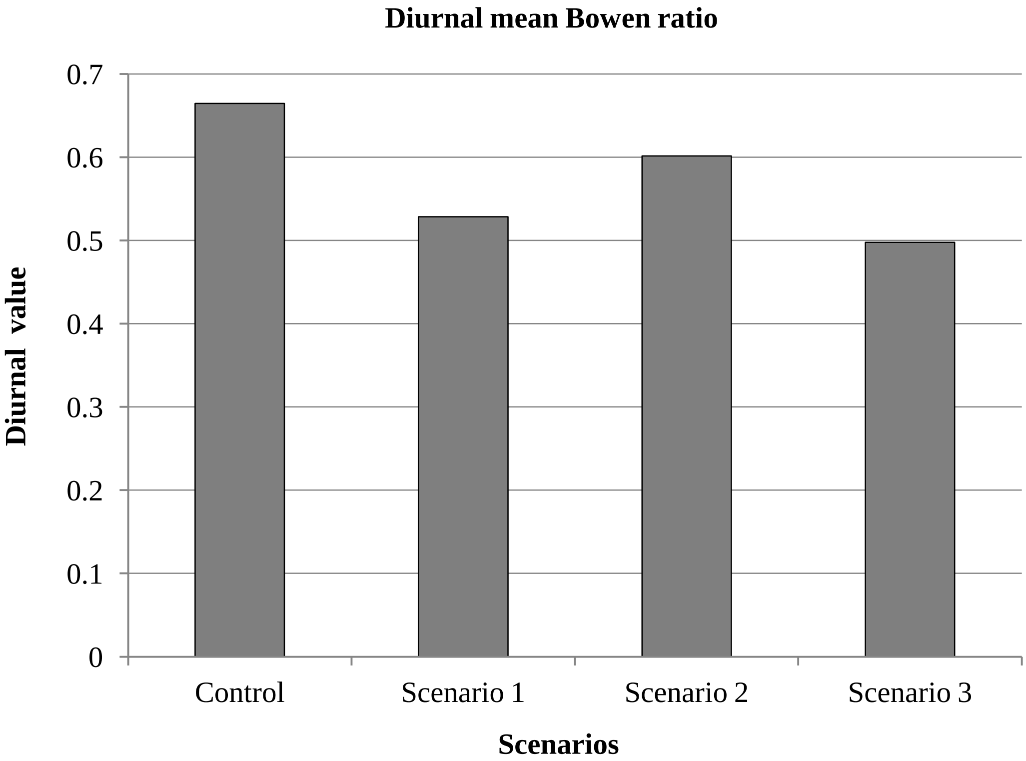


*Fig. 1*. Diurnal mean Bowen ratio.

*Table 2*. Results of the statistical analysis in case of the Bowen ratio

| | **Paired t-test** | |
|---|---|---|
| | **Mean (1–24 hours)** | **p value** |
| Control | 0.66 | – |
| Scenario 1 | 0.53 | 0.21 |
| Scenario 2 | 0.60 | 0.65 |
| Scenario 3 | 0.50 | 0.13 |

The intensity of the photosynthesis and transpiration are influenced by the concentration of $CO_2$ because of its effect on the stomatal resistance. In order to get a higher yield, the plant must reach a balance between the as high as possible $CO_2$ amount that is needed for the photosynthesis, and gets into the leaves through the openings of the stomata, and the level of the amount of water that leaves the foliage which must be as low as possible in our climate. The two opposing processes are connected by the pores.

The stomatas can be regarded as closed when the stomatal resistance surpasses 2000 s m$^{-1}$. The stomatal resistance of the maize surpassed this value at night (between 8 pm and 7 am). On a daily average (between 8 am and 7 pm) the resistance rose by 16.76%, 61.55% and 69.1% in Scenarious 1, 2, and 3, respectively comparing them to the control run (*Fig. 2*). On the basis of statistical examinations, these deviations indicate significant changes.

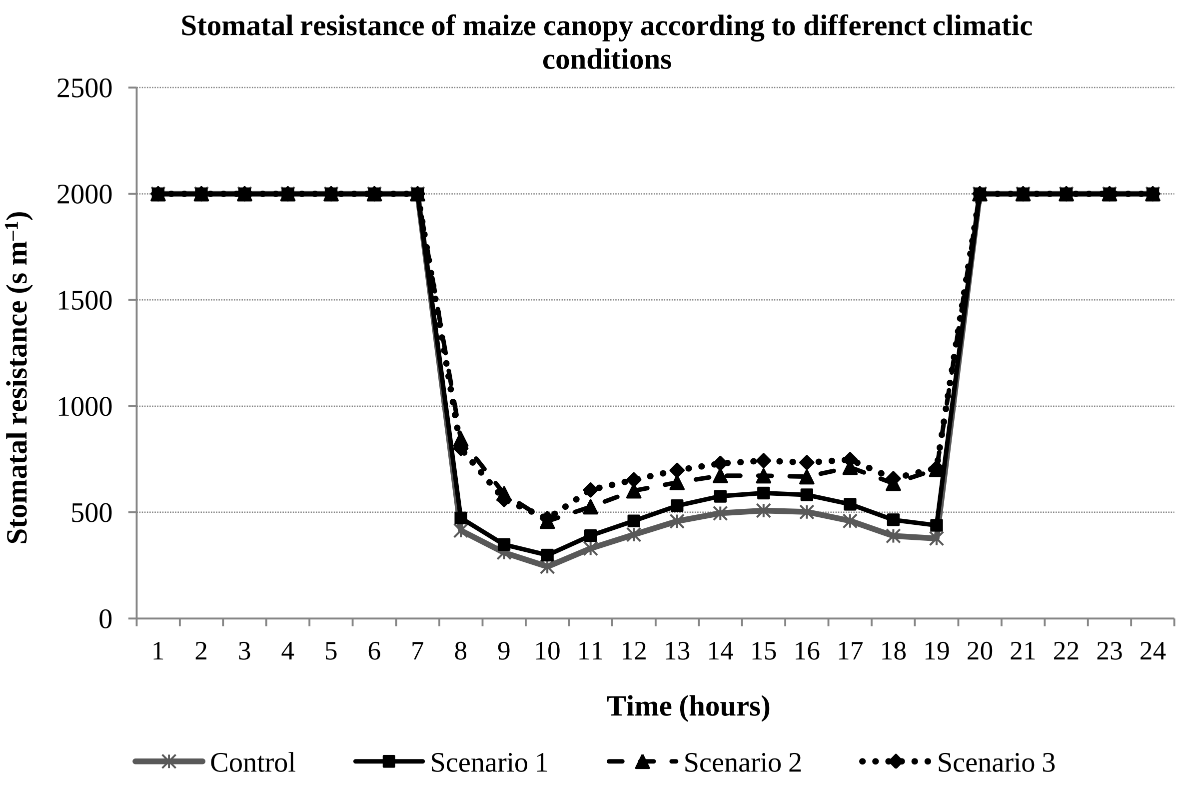


*Fig. 2.* Stomatal resistance of maize canopy according to different climatic conditions.

In the course of the production of organic matter, the process of photosynthesis uses carbon-dioxide from the surrounding air and water from the soil. The final benefit of the process is the difference between the amount of the organic matter created in the process of assimilation and used amount of assimilates in the course of respiration (mainly at night). The intensity of the respiration (between 8 pm and 6 am) did not seem to be sensitive to climate change. The intensity of the photosynthesis, in the average of the values of day time, slightly decreased in the 1st and 3rd scenarios (*Table 3*), which indicates that the available carbon-dioxide (440 ppmv and 760 ppmv) could not compensate the reduction of precipitation (that was represented by ground water potential decrease in the model runs) and although the water consumption became more economical because of the narrowed stomatas, the amount of carbon-dioxide that got into the foliage was also restricted. In the 2nd scenario the 760 ppmv carbon-dioxide concentration could compensate the effects of the restriction of water supply and the intensity of photosynthesis increased. While in the 1st and 2nd scenarios the change of the intensity of photosynthesis indicates a significant deviation comparing to the control, the 3rd scenario does not show a significant modification (*Table 4*).

*Table 3.* Deviations between the control run and the scenarios for photosynthetic intensity

| | **Mean deviation from the control run in daytime hours (8–19 hours)** |
|---|---|
| Scenario 1. | –2.99% |
| Scenario 2. | 4.48% |
| Scenario 3. | –7.31% |

*Table 4.* Results of the statistical analysis in case of the photosynthetic intensity

| | **Paired t-test** | |
|---|---|---|
| | **Mean (1–24 hours)** | **p value** |
| Control | 5.55E–07 | – |
| Scenario 1. | 5.36E–07 | 0.0174* |
| Scenario 2. | 5.98E–07 | 0.0093* |
| Scenario 3. | 5.26E–07 | 0.1954 |

*Significant difference if p is lower than 0.05.

In the Scenarious 2 and 3, the 24-hour average value of the inside canopy air temperature surpassed the additional air temperature rise while the average rise in the Scenario 1 was lower than the input temperature rise. The results of the plant temperature showed a higher rise in all scenarios than the rise of the ambient air temperature. In case of the average values of the daytime rise, the average growth in the cob level canopy temperature of all the three scenarios is lower than the added temperature rise. The reason for this phenomena can be the self-shade of plants by day, and the leaves gave a special protection against sunshine, therefore, the inside canopy air temperature was more moderate than the temperature rise around it. In the case of the plant temperature, the average rise is almost the same or a little lower than the input temperature rise. The plant could keep its own temperature close to the temperature of the air surrounding it. Despite the decrease of the water supply and warming, the plant did not seem to suffer of heat-stress. The changes in all scenarios (regarding both temperature characteristics) show significant deviations (*Table 5* and *6*).

*Table 5.* Results of the statistical analysis in case of the inside canopy air temperature

| | **Paired t-test** | |
|---|---|---|
| | **Mean (1–24 hours)** | **p value** |
| Control | 21.56 | – |
| Scenario 1 | 22.05 | 1.72E-03* |
| Scenario 2 | 23.14 | 3.28E-07* |
| Scenario 3 | 23.63 | 1.44E-08* |

*Significant difference if p is lower than 0.05.

*Table 6.* Results of the statistical analysis in case of the crop temperature

| | **Paired t-test** | |
|---|---|---|
| | **Mean (1–24 hours)** | **p value** |
| Control | 20.75 | – |
| Scenario 1 | 21.49 | 4.41E-07* |
| Scenario 2 | 22.65 | 2.68E-08* |
| Scenario 3 | 23.21 | 5.31E-10* |

*Significant difference if p is lower than 0.05.

From the changes of the stomatal resistance and temperature of the air inside the canopy, it can be concluded that the natural water supply will not cover the water demand of the plant with the manifestation of the climate change, therefore, farmers must prepare for irrigation and application of agro-technical methods to save the water supplies of the ground. However, at the beginning of the climate change, the maize plant at Keszthely is able to compensate the unfavorable conditions and does not suffer damage when the water supply is moderately less.

## 4. Conclusions

Examining the microclimate of maize canopies it can be concluded, that in the energy transport of the plant stand no shift can be experienced to the direction of the latent heat as the effect of warming up and the decrease of precipitation. The increase of the stomatal resistance can be detected, while the intensity of the photosynthesis first increases, but when we assume stronger climate change, it decreases. Examining the changes of microclimatic elements, it can be concluded that besides the climate, the architecture of the plant stand has an important role as well. From the changes of the stomatal resistance and inside canopy air temperature it can be concluded that the natural water supply will probably not cover the water demand of the plant, if the climate change is more intensive, therefore, farmers must prepare to irrigation and to use different agro-technical practices to keep the water stores of the soil if they want to avoid yield loss.

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