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Quarterly Journal of the Hungarian Meteorological Service
Vol. 116, No. 3, July–September 2012, pp. 221–236

Impact of atmospheric black carbon on some members of the heat and water balances

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(Manuscript received in final form February 10, 2012)

Abstract—Impact of atmospheric black carbon (BC) on albedo, evapotranspiration, and growing characters of field grown maize was investigated at Keszthely, Hungary, over the 2010–2011 growing seasons. Chemically "pure" black carbon was used in weekly pollution ($3\ g\,m^{-2}$). Low doses simulated the effect of particulates derived from vehicle exhaust and abrasion of tyres. Albedo of crop stand (0.3 ha/treatment) was measured with CMA-11-type pyranometers every 6 seconds. Maize grown in Thornthwaite-type compensation evapotranspirometers was included in the study. Dry matter yield of maize cob was determined in the end of the growing season.

Surprisingly, BC did not influence significantly the phenological phases and length of the crop year. Due to wet weather in 2010, seasonal water loss of BC treated maize increased only with 4%. Amount of seasonal total evapotranspiration of polluted crops was about threefold higher in dry 2011. The mean albedo of polluted canopy declined in both seasons. The surplus energy retention of BC polluted crops increased the canopy surface temperature of about 0.5–1.5 °C in midday hours, independently of the studied year. Significant yield loss in BC polluted maize stands was observed only in rainfed canopy. The production loss of dusted maize amounted 8.7% and 19.8%, in 2010 and 2011, respectively. Extra water of evapotranspirometers prevented yield drop-out of soot polluted plants. In arid years, BC had more severe impacts on maize characteristics and yield.

Key-words: black carbon, albedo, evapotranspiration, canopy temperature, dry matter, yield, maize

1. Introduction

Size and composition of atmospheric particulate matters (PM) are greatly variable. The class of particles having grain size of 2.5 – 10 μm is the coarse fraction. They are emitted to the air directly mainly from natural sources (earth crust, volcano eruption, deflation, erosion, etc). The fine fraction comprises particles below 2.5 μm. Fine fraction is forming by chemical and physical processes in the atmosphere. In the air of Budapest, the number of fine particles is higher (100,000/ml) than that of the coarse class (below 100/ml) after *Salma* and *Ocskay* (2006). The black carbon content is only about a few percent in the coarse fraction, while it may reach the 20% in the fine one. Diesel-exhaust particle may be elemental carbon up to 20 – 40% (*Balmes*, 2010). Soot has also been derived from incomplete burning (fossil fuels, biomass, etc.) as well as from industrial processes. Vehicle tyres are also sources of black carbon.

In EU standard, we are allowed to exceed the daily suspended particulate matter limitation of 50 $\mu g/m^3$ 30 times per year (WHO, 2000; *Krzyzanowski et al*., 2005). Unfortunately, already in the course of February, we often overstep this threshold at Hungary (examples are the years 2009 and 2010). This is due to the aged carriage park and the weather conditions in Hungarian winter.

Global scale influence of black carbon (BC), changing the radiative properties of the atmosphere (nucleation of clouds) and cryosphere (melting of ice cover) was published among others by IPCC (2007) or *Giere* and *Querol* (2010). The effect of soot on human health (*Behndig et al.*, 2011) and on some soil properties (*Hammes et al.*, 2008; *Nguyen et al.*, 2009; *Lorenz et al*., 2010) are also well investigated. Studies on health impacts of particulates show an increased number of hospital admissions from chronic obstructive pulmonary disease, asthma, and other respiratory diseases (*Postma et al*., 2011).

The importance of albedo modifications are widely studied in different observation levels. The local level contains relationship between crop life (physiological processes) and solar radiation. *Betts et al.* (2007) published that the global surface temperature change owing to vegetation changes is mainly due to the surface albedo changes. Land-use change in the past, involving variation from natural vegetation of relatively low albedo to arable crop growing with higher albedo has suppressed surface temperatures (*Monteith* and *Unsworth*, 1990). In an arable region of small size, *Matthews et al.* (2003) determined a 0.17°C cooling in response to 0.03 – 0.09 increase in albedo. In field level, *Ridgwell et al.* (2009) simulated more intense, 1 °C cooling in summertime surface temperature when increasing the albedo with 0.04.

Due to difference in crop stand morphology, significant variability exists not only between crop species, but among varieties of the same plant. The maximum of albedo modification due to crop varieties may reach the value of 0.04 (*Hatfield* and *Carlson*, 1979; *Febrero et al.*, 1998). One of the possible reasons of albedo variability within crop species may be the existence of wax or other leaf structural differences. Not only the crop species but the density of maize may impact the albedo. In thin maize stands (40,000 ha^{-1}), the decrease in albedo was significant, sometimes being as high as 8–10% when compared to dense canopy (100,000 ha^{-1}) with the same species (*Anda* and *Loke*, 2005).

Until now it remains unknown, how and to what extent the soot deposition effects the crop life. The aim of our investigation is to discuss the relationship between maize physiological properties and soot deriving from vehicle exhaust and tyres. A reproducible field trial was conducted, that is not extended in pollution studies even now. Despite that two decades have been passing, we still aimed the “stage of reproducible exposure experiment” that has not yet advanced (*Olszyk et al.*, 1989) in contaminated crops grown in the open air.

2. Material and methods

Field experiment was conducted to study the impact of black carbon on some maize crop characteristics and canopy microclimate. The place of the study was the Agrometeorological Research Station of Keszthely (46°45’N, 17°14’E, 102 m above sea level), during the vegetation periods of 2010 and 2011. The prevailing genetic soil type is the Ramann type brown forest soil with a mean bulk density of 1.46 $Mg\,m^{-3}$ in the top 1 m of the profile. The available water capacity is 150 $mm\,m^{-1}$. A Swiss-bred maize hybrid, Sperlona (FAO 340), was sown in the field using a plant density of 70,000 plants per hectare. A part of the crops was grown under rainfed conditions, while the others in growing chambers of Thornthwaite-type compensation evapotranspirometers (ET). This latter part of the experiment supplied a treatment of “ad libitum” watering level. The size of the evapotranspirometer’s growing chamber was 2×2 m in area, and 1 m in depth. They were filled with a soil monolith from the surrounding field, layered as in the natural state. Dimension of field plots differed from ET chambers, due to the needs of radiation (albedo) measurements. The area of rainfed plots reached 0.3 ha.

Except of unlimited watering of evapotranspirometers, the usual agronomic procedures (plant protection, weed control) recommended for the place by the local staff of the University of Agricultural Sciences, Keszthely, were applied.

The black carbon applied by the Hankook Tyre Company (Dunaújváros, Hungary) to improve the wear resistance of tyres was used as contaminant. More than half of the soot grains are below 18.8 μm, and 90% of the total soot quantity is below 50.6 μm (*Fig. 1*). The black carbon is chemically “pure”, i.e., it is free of other contaminants (heavy metals, etc.), so the reproducibility of the experiment is not problematic, unlike that of tests on other atmospheric air pollutants. Relatively small doses were applied (3 $g\,m^{-2}$), but they were repeated at weekly intervals. Due to lack of local information, in determination of applied dose, the extreme amounts of dust sediments published to vegetation surface during the growing season (*Prusty et al.*, 2005; *Freer-Smith et al.*, 2005), and the soot content of local road dust (*Salma* and *Ocskay*, 2006) were taken into account. The published road dust depositions included the background pollution. A motorized sprayer of SP 415 type was used to pollute the crops. The instrument acted as a pulverizer (dry application of BC).

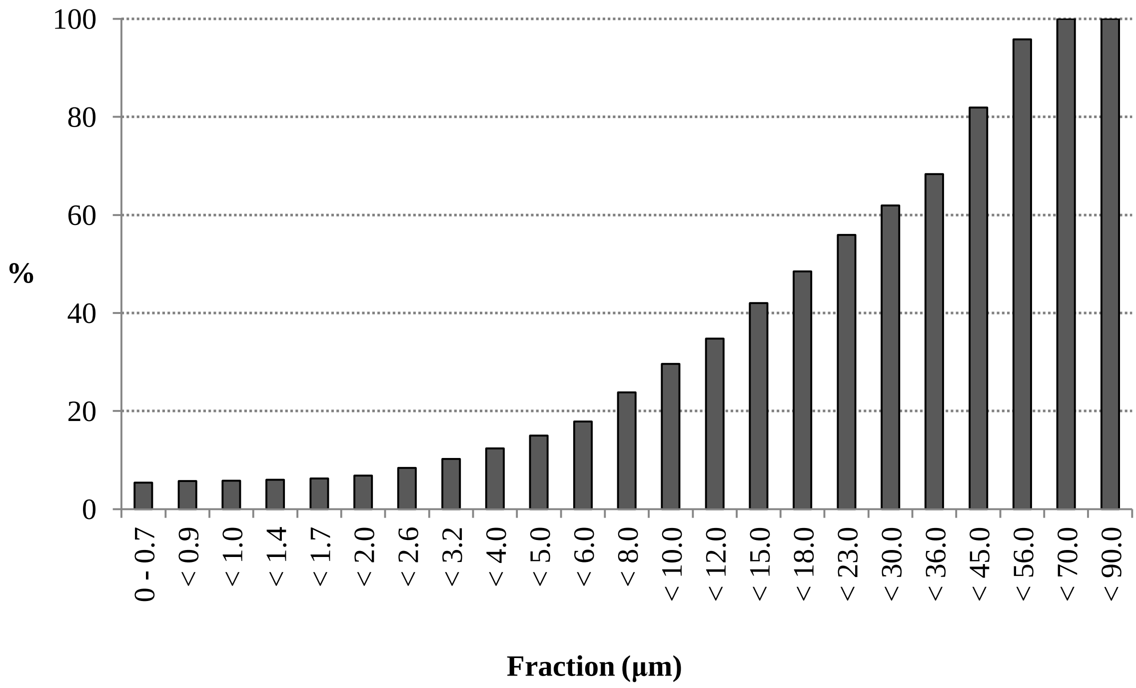

Fig. 1. Cumulative curve of the size distribution of black carbon.

Pyranometers of the CMA-11 type (Kipp & Zonen, Vaisala) were installed on columns of adjustable height in the centre of the 0.3 ha plots designated for albedo measurements. The height of the sensors was raised each week as the plants grew, so that they were always at least 1.5 m above the canopy. Data were collected using a Logbox SD (Kipp & Zonen, Vaisala) datalogger in the form of 10-minute means of samples taken every 6 seconds. Either these 10-minute means or the hourly or daily means calculated from them were used for the analysis.

Canopy temperature was measured by infrared thermometer of RAYNGER II. RTL type (Raytek., Santa Cruz, Calif. USA) with 2 ° field of view and an 8–14 µm waveband filter. For sample takings, the thermometer was hand-held about 1 m above the canopy at an oblique angle three, four or five times per reading at midday (from 12:00 to 3:00 p.m.). After canopy closure, temperature readings were taken daily in clear-sky and calm weather conditions. The emissivity was set to 0.96.

The grain yield was measured in plants from the 10 m^2 at the center area of each plot. In case of ET, the whole growing area of the chambers (4 m^2) was included in yield analysis. The samples were oven dried at 60 °C to a constant weight for 5–7 days and then weighed.

Meteorological data were obtained from the local QLC-50 automatic climate station.

Due to the fixed nature of evapotranspirometers, the experiment was laid out in a block design with four replications, while the dry plots were arranged in a randomized complete block design. The non-irrigated plots, also used for solar radiation measurements, had an area of 0.3 ha. Data analysis was performed using the STATA 5.0 computer package (STATA 5.0, 1996). The t-test was used to determine significant differences between the dry matter yields of polluted and control plants and of rainfed and ET-grown plants. In time series analysis, two-tailed t-test was applied. The significant level was settled to 5% ($P<0.05$).

3. Results and discussions

3.1. Crop and weather characteristics in the seasons

In 2010, the seasonal and monthly mean temperatures were in good correspondence with the long-term mean with the exception of July. In July, mean air temperature was 1.8 °C higher than the 1901–2000 average. Mean air temperature was 1.1 °C higher than the climatic norm in the season of 2011. The only exceptional month in 2011 was also July, when the air temperature was close to the average. The growing season of 2010 was substantially wetter than the mean, having 38% higher rainfall sum than the average over many years (*Fig. 2*). May, August, and September received more than double amount of rainfall. In July, however, the precipitation dropped off the long-term mean, the air temperature was high. Oppositely to the previous summer, the growing season of 2011 was extremely dry (the driest season from the beginning of weather observations at Keszthely). The amount of rainfall hardly exceeded the half of the long-term average (51%).

In spite of the variable weather of the two studied summers, the black carbon did not influence either the duration of the vegetation period or the length of phenological phases irrespective to water supplies.

Like a tendency, a moderate increase in the final height of dusted crops (about 20−40 cm) was measured independently on water level or season. This positive modification might be attributed to warming effect of black carbon, mainly during the cooler periods of the crop year, at the beginning of the growing season. In spring, higher air temperature may increase the intensity of photosynthesis producing more photosynthate used in the course of crop growing. The warming impact of soot was detected in the surface temperature of polluted crops.

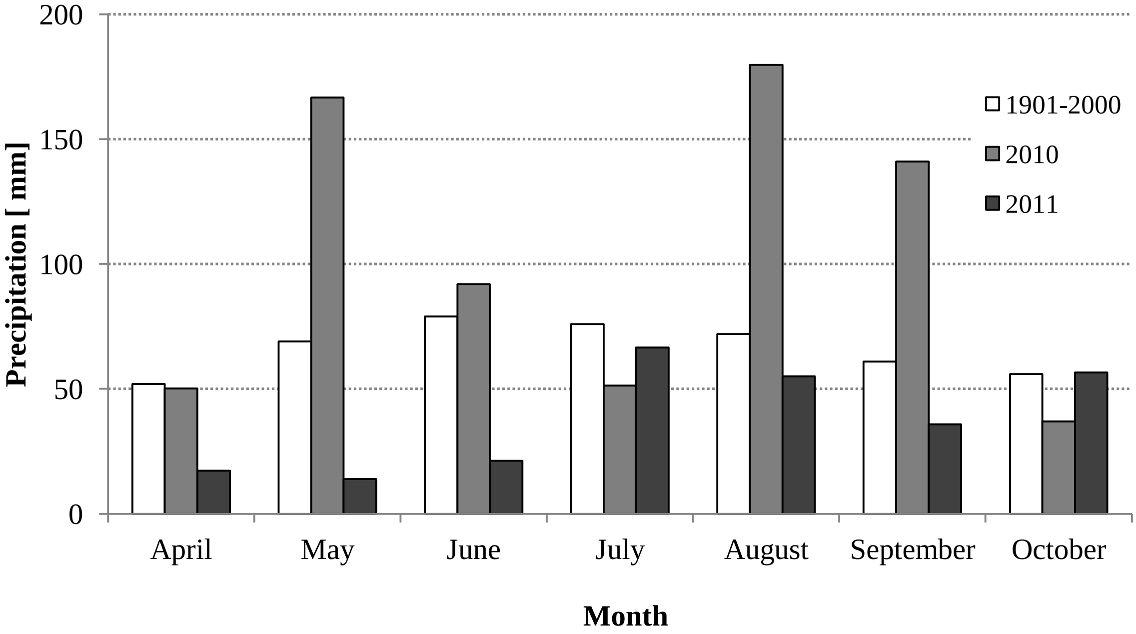

Fig. 2. Monthly sums of precipitation at Keszthely. The values were compared to the climate norm (1901–2000).

The excessive rainfall in 2010 approximated the assimilatory surface sizes of different treatments. Irrespectively to the extra water supply, the seasonal mean of leaf area index (LAI) in the plots was close to that of measured in the ET chamber (data not shown). In 2011, the warmer spring and early summer moderately increased the size of LAI comparing to the results of the previous year (*Figs. 3a* and *b*). Later on, drought of 2011 generated an intense leaf shriveling, and finally the yearly mean assimilatory surfaces were similar in the two studied seasons. Deviations in seasonal mean value of LAI between the two studied years were below 5% with the exception of non-irrigated control (6.8%).

In the wet summer of 2010, the yearly mean LAI of polluted maize remained unchanged. The black carbon was only drawn out the leaf withering in ET chambers. In polluted ET the green leaves lasted a week longer. The drying off of polluted crops in ET began a week later that increased the withering of dusted maize. It was excluded from the length of the growing season as it acted after full ripe of maize. In 2011, the seasonal mean LAI of polluted crops increased with 14.8 ($P<0.05$) and 11.4% ($P<0.05$) in non-irrigated control and ET, respectively. In rainy weather the rain might wash out the pollutant from the leaf surface on a larger extent. At about 15–20% of the dust has been removed by rain in our observation. The washing out was also modeled in laboratory, before conducting the field trial.

One of the most important plant characteristics is the season long-integrator, the yield. We expressed it in terms of ear dry matter (DM) production. The excessive water supply in ET could not amount the grain DM production of maize, probably due to rainy summer in 2010. In the next season, the “ad libitum watering” of ET significantly rose the maize yield with 13% comparing to the production of non-irrigated control plots ($P < 0.01$). This is in accordance with earlier local investigations (*Anda*, 2001).

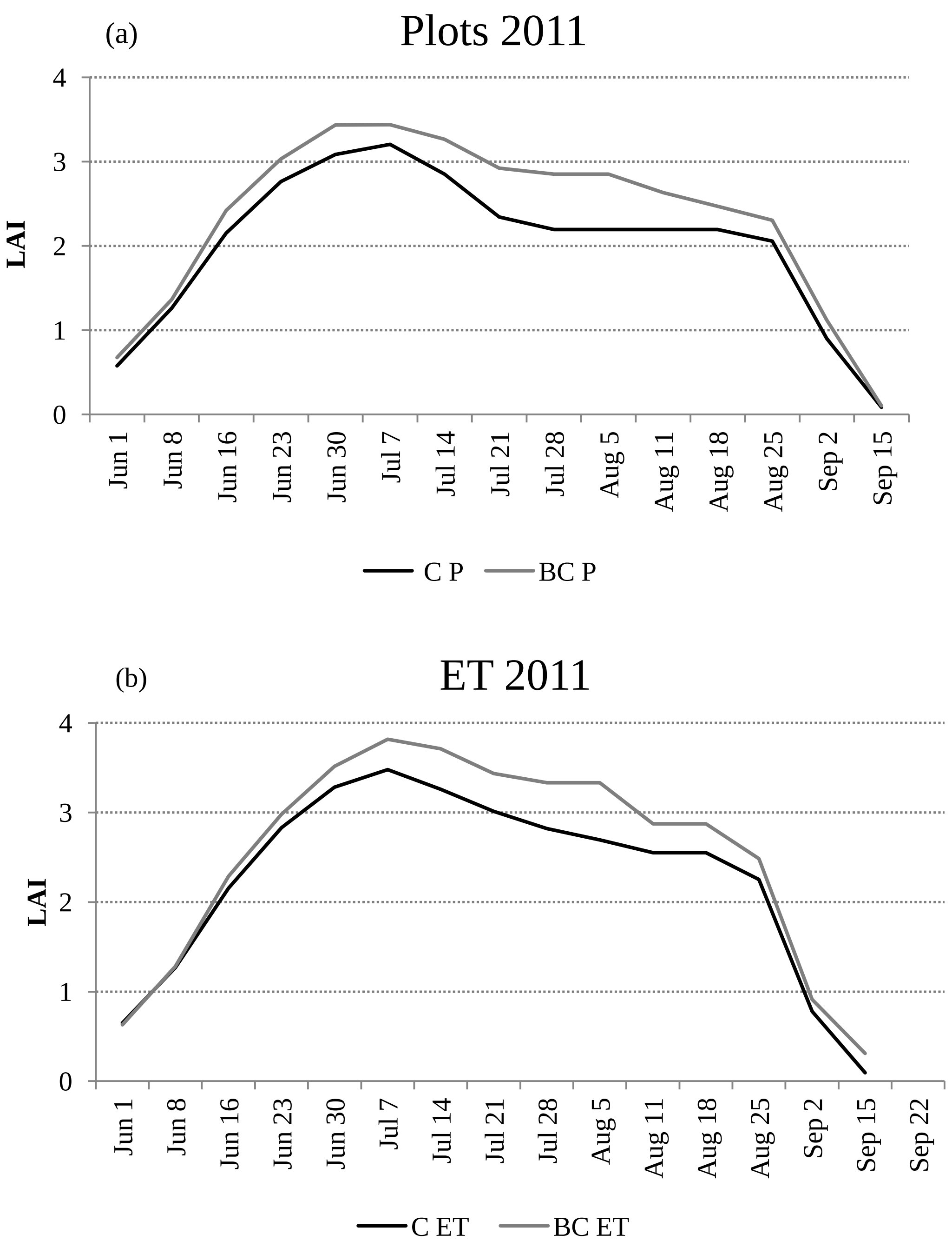

Fig. 3(a) and (b). Seasonal variation in weekly LAI of plots (P) and ET growing chambers (ET). C and BC stands for control and polluted treatments, respectively.

The black carbon pollution significantly declined the grain DM of maize grown in the rainfed plots. The yield loss was close to 9% ($P < 0.05$) in 2010, while yield depression doubled ($P < 0.05$) during the dry 2011. The same was not observed in dusted ET. A moderate, but not significant deterioration of DM production, including the grain DM of maize grown in the ET chambers was obtained. Finally, the surplus water of ET chambers reduced the yield loss of polluted grain maize irrespectively of variable weather conditions of the two seasons.

3.2. A few members of the heat and water balances

3.2.1 Reflection coefficient, the albedo (a)

Incoming solar radiation is partly reflected from the canopy, partly transmitted to the crop stand, and partly absorbed by the crops. The fraction of incoming short wave solar radiation that is reflected from the surface is called albedo. The albedo is the measure of lost radiation energy from the canopy surface.

In earlier studies, the mean albedo of maize is placed somewhere between 0.18 and 0.22 (*Davies* and *Idso*, 1979; *Hatfield* and *Carlson*, 1979; *Oke*, 1987; *Campbell* and *Norman*, 1998). In the two seasons investigation, after canopy closure, the mean albedo was 0.17 in the control canopy. The highest daily mean values of 0.21 and 0.20 (2010 and 2011) were measured in July, while the minimum albedo (0.11) was found in the end of September, when the crops were completely dried. The black carbon significantly decreased the seasonal mean albedo with about 0.03.

The size of albedo depends on surface characteristics – mainly the color and roughness – and on sun elevation. The black carbon makes the crop color darker declining the size of its albedo. Averaged over the whole measuring period, the mean albedo of polluted maize was 17.5% and 21.7% lower ($P<0.05$) in 2010 and 2011, respectively, than the albedo of control maize *(Fig. 4)*. Soot pollution resulted in a decline in the albedo leaded to higher energy retention of polluted crops. This amount of energy might be high enough to modify the physiological processes as well as crop microclimate.

Over the observations, the greatest deviation in daily mean albedo found for the wax ripe period was 30% in the polluted crop stand. At the beginning of the vegetative period, mainly until canopy closure, alteration in mean albedo of polluted crops fell well below 10%.

Shape of albedo's diurnal variation followed the regular one; while the greatest values were measured at low solar angles (afternoon hours), the minimum albedo was obtained at high elevation (*Fig. 5*). Irrespectively of treatment, the variability of albedo is more pronounced for the morning and afternoon hours. The sample day of *Fig. 5* contains twenty-minute averages of albedo for July 21, 2010. This day was extremely hot with extra strong insolation and high temperatures. The variability in the shape of albedo's curve was the most compensated in the course of cloudless days. These observations were also valid for the season of 2011.

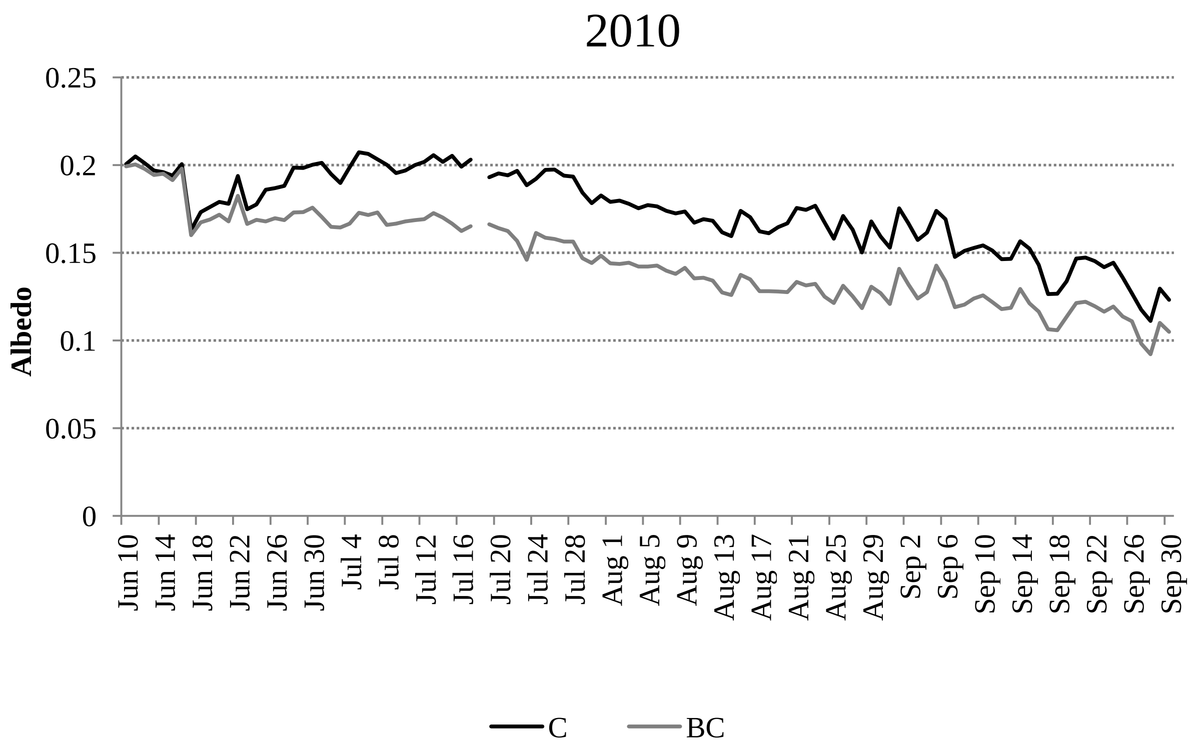

Fig. 4. Daily means of albedo during 2010 and 2011. C and BC denotes control and polluted crop stands, respectively.

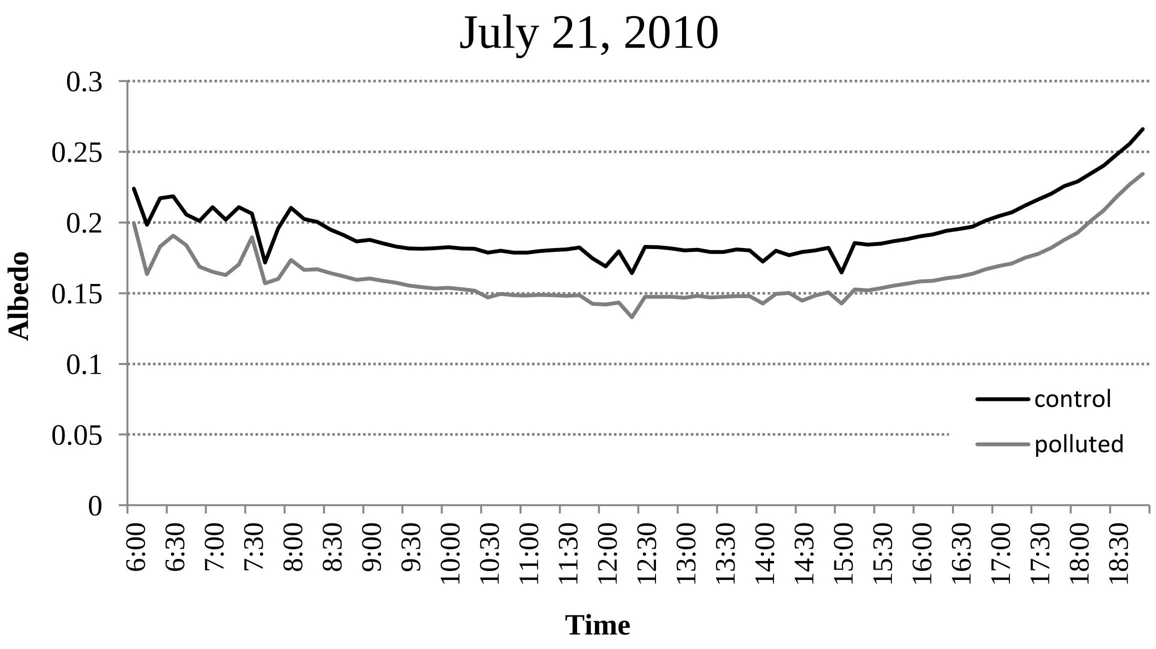

Fig. 5. Diurnal variation in the albedo of maize. Black and grey lines represent the albedo of control and polluted crops, respectively.

Irrespectively to studied summer, daily variation in the albedo's difference due to pollution remained the same as in the control at about in the half of the sample days. In the other half of the days, more pronounced soot impact on albedo was found at low solar elevation reaching values of 0.05−0.09 (*Fig. 6*). Equalized differences can be clearly detected at high insolation.

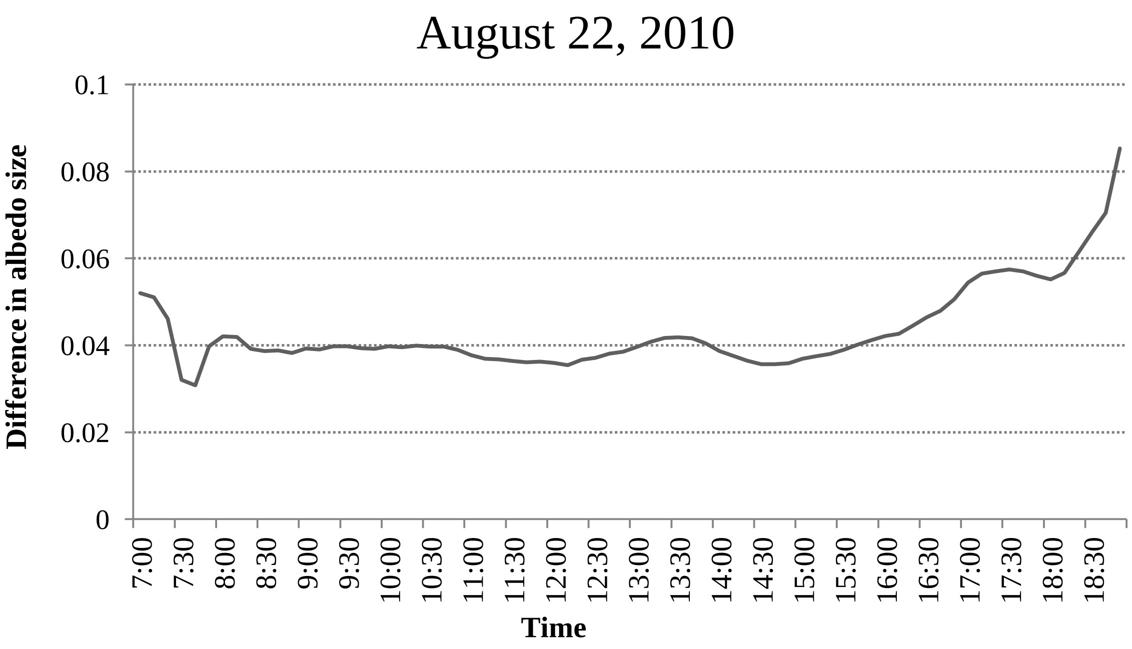

Fig. 6. Differences (contol data - polluted data) in the twenty-minute mean of albedo on August 22, 2010.

3.2.2. Maize evapotranspiration

For maize in ET, the seasonal totals of evapotranspiration were 403.7 and 572.1 mm in 2010 and 2011, respectively. Increment in water loss of the arid season was 34.5% ($P < 0.01$). Soot pollution also rose the evapotranspiration of maize. In the wet season of 2010, only slight difference was observed (3.9%). The impact of black carbon increased by 9.6% during the arid 2011. Analyzing the evapotranspiration on daily basis showed that differences between treatments were consistent in time with and without pollution. The top water uses were 7.0 and 7.9 mm day^{-1} in control and polluted maize, respectively on July 19, 2010. The maximum water losses were 8.8 and 10 mm day^{-1} in the middle of July, 2011.

Variability in evapotranspiration is influenced by atmospheric and plant (biological) factors. The solar radiation and transpiration surface size (LAI) are the most important governor factors of plant water losses. Analyzing the evapotranspiration relationships, radiation properties were characterized by albedo, crop features were taken into account by transpiration surface size in the polluted and control treatments separately (*Figs. 7* and *8*). Data collected after canopy closure was included in the study, since information from the early vegetative period deteriorated the relationship between the variables. The number of observation pairs was 81. The observed relationship agreed well in both seasons, this is why the data of 2010 are presented only.

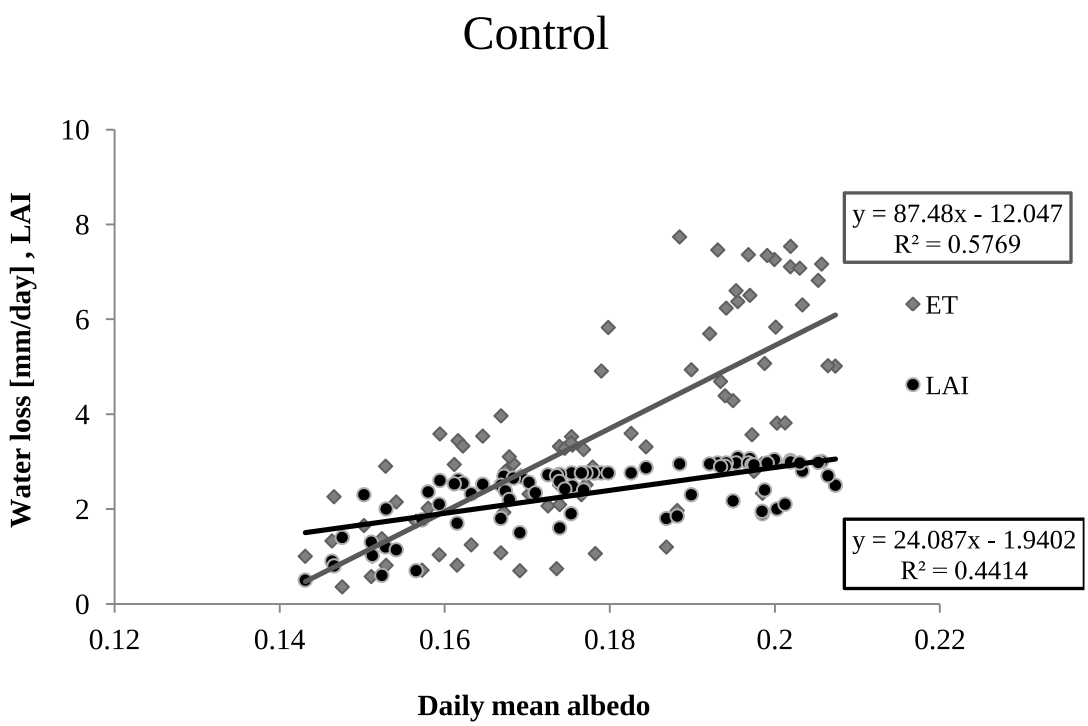

Fig. 7. Impact of albedo on evapotranspiration and leaf area index in control canopy. The number of measurements was 81.

Linear relationship exists between daily mean albedo and evapotranspiration of both treatments. Low water losses were measured in the end of the season when albedo also declined. After canopy closure (the end of June), growth in albedo results almost the same increment in crop water losses, irrespectively to the soot pollution. The reason of this surprising relationship is probably due to the drying off of leaves during the last third of the vegetation period. Withering opens the canopy, declines both transpiration and albedo. There was hardly enough difference in line interception between control and polluted treatments.

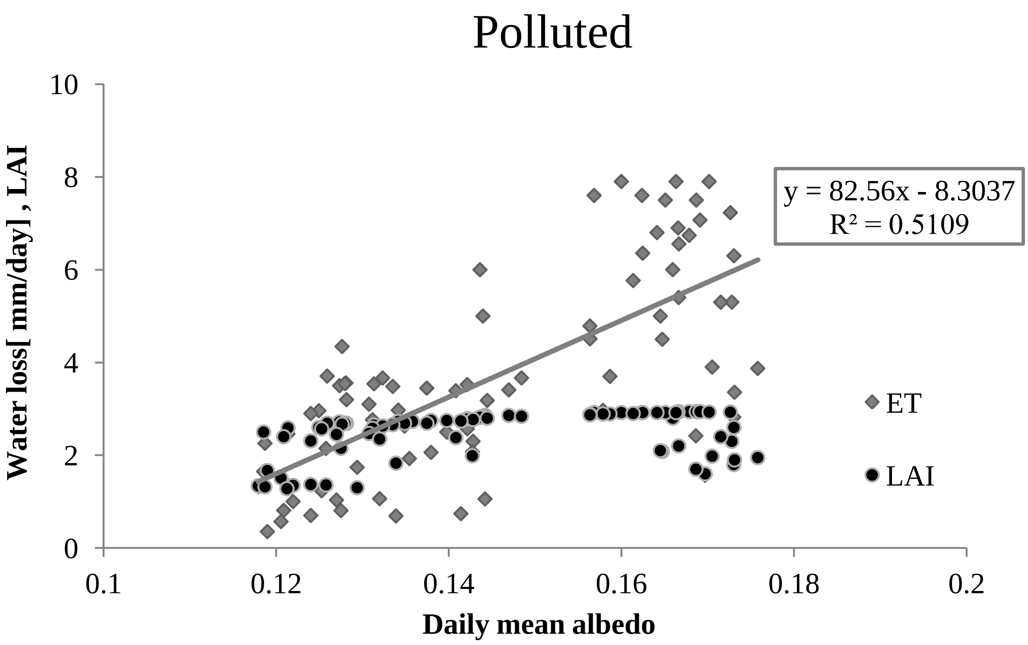

Fig. 8. Impact of albedo on evapotranspiration and leaf area index in polluted canopy. The number of measurements was 81.

The albedo-LAI relation was weaker than the albedo-water loss relation both treatments. In the control maize, linear relationship in albedo and evapotranspiration surface size may be acceptable, but not in case of polluted crops. Albedo of maize with BC was independent of the transpiration surface size after canopy closure. *Oguntunde* and *van de Giesen* (2004) found closer connection between albedo and LAI (correlation coefficient 0.970) in maize for the whole vegetation period. Only the linear shape of relationship agreed with earlier results (albedo data of open canopy are excluded from the study).

For a long while we know that temperature determines the plant growth and particularly development rates. *Warrington* and *Kanemasu* (1983) published that leaf initiation, leaf appearance and elongation are strongly related to temperature in maize. From the thermal time concept, strong correlation is assumed between air and crop temperatures (*Jackson*, 1982). Canopy temperature gave the best results in growth predictions when compared to soil and air temperatures (*Jamieson et al.*, 1995). In spite of the arising error, when extreme humidity and cloudiness mask canopy temperature differences with respect to the temperature differences in the air, the surface temperature is widely applied also in semi-humid regions (*Bajwa* and *Vories*, 2007).

The direction of change in canopy surface temperature resulted from black carbon pollution was irrespective to water supply. The size of change in non-irrigated crops exceeded the temperatures of crops grown in ET. As a rule, difference in crop temperatures between control and polluted plants in ET dropped at about half of those measured in the non-irrigated control plots. As the direction of soot impact on canopy surface temperature was independent of the seasons, detailed discussion is given for 2010 only. In 2011, the size of seasonal mean temperature change in ET resulted from pollution was almost the same as measured in the earlier season. In non-irrigated polluted control plots, more intense crop temperature modification was observed, and the increment in the seasonal mean of polluted maize reached the 1.6 °C (data not shown).

Altogether, 13 days were suitable for canopy temperature measurements in the wet growing season of 2010. We could only take one and two samples in June and August, respectively. In July, when monthly mean temperature was 1.8 °C higher than the climate norm, the crop temperatures were also extremely high, similarly to the larger part of the season in 2011. In spite of the extra water supply in ET, crop temperatures exceeded 31–32 °C three times during July. (The number of these occasions was the same in rainfed plots.) High crop temperatures in 2010, exceeding air temperatures, could not have been the result of water deficiency, but can be attributed to the influence of heat stress. The precipitation might be quite sufficient to supply the maize water need even in the rainfed plots. Finally, soot increased with 0.97 °C the seasonal mean of crop temperature observed at solar noon. Due to the same crop temperature change in ET and control treatments, the impact of BC measured in control is presented (*Fig. 9*). The same data for 2011 was 1.6 °C.

4. Conclusions

With the exception of leaf withering, maize polluted with low doses of BC ($3\ g\ m^{-2}\ week^{-1}$) produced similar development (length and appearance of phenological phases). The polluted crops retained their green leaves a week longer in wet 2010. Like a tendency, the final crop height increased with 0.2–0.4 m in both seasons. It is important to mention, that this increment was not proved statistically.

The albedo of a crop stand is a key regulator in atmospheric circulation and plays an important role in mechanistic accounting of many ecological processes (*Oguntunde* and *van de Giesen*, 2004). The authors found that the albedo is avaluable input in agricultural practice as well as in different types of modeling (crop production models, eco-hydrological models, regional weather and climate models). Soot pollution significantly declined the mean albedo with about 0.03 after canopy closure. This value meant 17.5% and 21.8% higher energy retention of polluted crops in 2010 and 2011, respectively. A portion of the higher energy retention increased the midday canopy temperatures of dusted maize irrespectively to the season characteristics. In a global climate model, decreasing cropland albedo by 0.04 drives a more than 1 °C warming in summertime surface air temperatures in a wide latitudinal band spanning North America and Eurasia (*Betts et al.*, 2007). These findings are close to our field observations. *Ridgwell et al.* (2009) published more moderate temperature variations; albedo increments of 0.04 and 0.08 produced only 0.11 °C and 0.21 °C surface cooling, respectively.

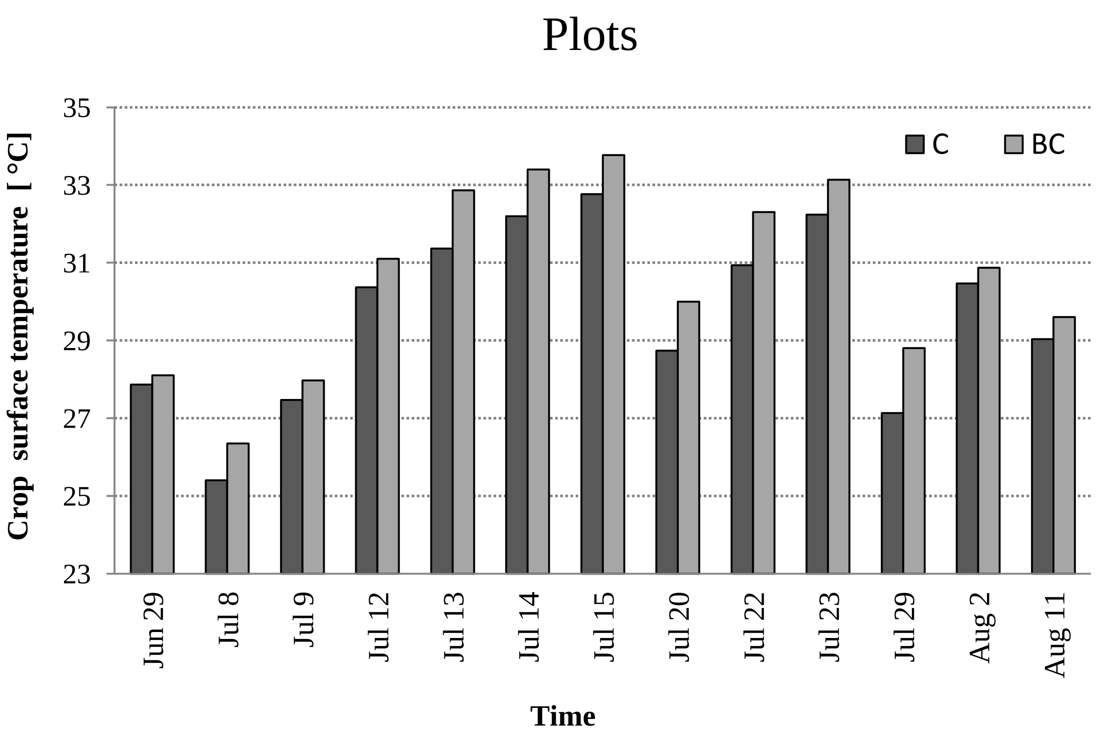

Fig. 9. Canopy surface temperatures measured at solar noon on clear-sky conditions during 2010.

The impact of BC on maize seasonal water loss was reasonable over the wet growing season of 2010. This might have been due to ample precipitation of the summer. Oppositely to 2010, the growth in seasonal water loss of polluted maize increased until 11% in the arid 2011. The physiologically desired crop temperature in ET was achieved with more intense transpiration during 2011 than in 2010.

After canopy closure, a linear relationship exists between daily water loss and albedo even in BC polluted crops. Linear connection between LAI and albedo is acceptable only in case of control maize. In polluted maize stand, the change in albedo seems to be independent on green leaf area size in maize after canopy closure.

Reasonable yield decline was measured in polluted maize plots irrespectively of season's weather. In polluted rainfed plots, the drop-out of DM grain yields were 9% and 20% in the two consecutive seasons. Irrespectively to the weather, the extra water supply in ET decreased the yield loss of polluted maize. The irrigation may be the proper tool to cope the negative impacts of atmospheric origin black carbon pollution.

Acknowledgement—The financial and infrastructural support of the State of Hungary and the European Union in the frame of the TÁMOP-4.2.2/B-10/1-2010-0025 project is gratefully acknowledged.

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