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Radiation Balance Components of Maize Hybrids Grown at Various Plant Densities

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With 3 figures and 3 tables

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Abstract

Components of the energy and heat balances were examined in two maize hybrids grown at three different plant densities (40, 70 and 100 thousand plants per hectare). One of the hybrids was drought tolerant, while the other was bred for cultivation under irrigated conditions. An increase in plant density influenced not only the size of the leaf area, but also the distribution of the leaves at various plant heights. The extinction coefficient, which provides a quantification of radiation penetration, was higher in the irrigated treatments. By contrast to the other two treatments, the plant canopy in the thinly sown stands remained open throughout the vegetation period, and thus behaved quite differently to the closed stands, making it impossible to compare them. Smaller albedo values were recorded for the hybrid bred for irrigation and in thinly sown stands. The low plant density allowed more energy to reach the soil, from which it was reflected, making a considerable contribution to the final temperature in the stand. The latent heat, in keeping with the quantity of water transpired, was the greatest in the densely sown stands. There was little difference between the latent heat values of the normal and dense stands in either hybrid, indicating that they both had a similar sensitivity to increased stand density. If sufficient water is available it would appear that the stand density could be increased even for the drought-tolerant hybrid.

Key words: albedo — extinction coefficient — hybrid — plant architecture — *Zea mays* L.

Introduction

In the course of development the architecture of the stand may differ, not only between varieties, also within the same variety, leading to differences in the distribution of radiation within the stand, which in turn may be responsible for differences in productivity indices per unit area (Barnes et al. 1990, Maddonni and Otegui 1996).

Among the indices related to radiation utilization, the easiest to measure, and thus the most frequently cited, is the albedo, the loss of radiation directly by reflection from the top of the stand. Non-reflected radiation penetrates into the stand and acts as a source for energy-demanding processes, while a remnant reaches the soil surface. The attenuation of the radiation, which is decisively affected by the architecture of the stand, is often characterized by the empirically determined extinction coefficient (k), despite serious doubts as to whether the conditions required for the approximation (random distribution of foliage in a horizontally homogeneous canopy) can ever be fulfilled in plant stands. This index is generally quoted as being between 0.40 and 0.66 in fully developed maize stands in the temperate zone when the sun is high in the sky (Monteith 1965, 1973, Jones and Kiniry 1986, Boons-Prins et al. 1994, Kiniry and Bockholt 1998, Fernando et al. 2000, Tsubo and Walker 2002, Birch et al. 2003, Lizaso et al. 2003). However, lower values are also to be found in the literature. Pommel et al. (2001), for example, quote a value of 0.34, while at the site of the present experiments k-values of 0.29–0.59 were recorded. Measurements made in a non-irrigated stand by Farre et al. (2000) also suggested lower values of the extinction coefficient.

For the same leaf area, the higher the value of k, the greater the radiation absorption (Oker-Blom and Kellomaki 1983). Differences in k can be attributed to differences at the population level in such parameters as the average plant height (Edmeades and Lafitte 1993) or leaf number (Dwyer et al. 1992). It was demonstrated by

Campbell et al. (1981) that water deficiency reduces the light attenuation of maize. Farre et al. (2000) found k-values of 0.5 in irrigated maize and 0.2–0.3 in dry treatments, while Madakadze et al. (1998) found a tendency for early maturing cultivars to have lower k-values because of early leaf senescence.

The aim of the experiment was to determine radiation and heat balance components in two maize hybrids from the same maturity group grown at three plant densities under irrigated and non-irrigated conditions. An attempt was made to explain changes caused by variety, plant density and water supplies in the radiation penetration of the stand, as quantified by the extinction coefficient, in terms of stand architecture. Various components in the architecture of adult maize plants were analysed to determine how they were influenced by less frequently investigated treatments, so that the accuracy of the input data used in models could be improved. The paper was not designed to discuss differences in yield between the two varieties.

Materials and Methods

The heat balance components of fully developed maize grown with different water supplies and plant densities were investigated at the Agrometeorological Research Station in Keszthely during the 2002 and 2003 vegetation seasons. The observations made in 2002 were repeated in 2003, but as the direction and magnitude of the treatment effects recorded in 2002 did not change significantly in 2003, the results are illustrated mainly using the 2002 data.

The maize hybrids used were *Norma SC* (FAO 370; Agricultural Research Institute, Martonvásár, Hungary), a prolific dent variety tolerant of water stress, and *MVNK 424 SC* (FAO 480; Agricultural Research Institute), a prolific dent variety suitable for irrigated conditions.

In the course of the studies ‘normal’ plant density was taken to be 70 000 plants per hectare, the density widely used under Hungarian climatic conditions for grain maize. This value was raised to 100 000 plants per hectare in the ‘dense’ stand and reduced to 40 000 plants per hectare in the ‘thin’ stand.

Of the two water supply treatments, the rainfed variant was sown in field plots, while Thornthwaite compensation evapotranspirometers (lysimeters) were used for the *ad libitum* treatment. These were metal containers with a volume of 4 m^3 (2×2 m in area, with a depth of 1 m), filled with the soil of the surrounding field, layered as in the natural state. The working principle was to record the components of the water balance each day, expressing evapotranspiration as the residual term. The surroundings of the lysimeter chambers were irrigated daily. The treatment codes used in the experiment were as follows:

Treatments	Codes
Variety	
Norma SC	N
MVNK 424 SC	MV
Density	
70 000 plants/ha	n
40 000 plants/ha	t
100 000 plants/ha	d
Water supplies	
Rainfed plots	p
Lysimeter	ET

The reflected radiation and that reaching the bottom of the stand were measured using LI-190 pyranometers linked to a LI-COR 1000 (Li-Cor, Lincoln, NE, USA) data logger. The quantity of radiation reflected was expressed as the albedo (a), i.e. the ratio of the reflected (R) to incoming global (G) radiation:

$$a = \frac{R}{G} \tag{1}$$

In each treatment five sensors were placed on sunny and shaded patches at the bottom of stands of various densities. The number of sunny and shaded patches chosen was calculated on the basis of digital photographs taken of various stand densities. Data were collected on fine days with no wind, when the sun was high in the sky, by taking photographs of flat pieces of evenly coloured red cardboard placed on the soil in the stands, using an HP Photosmart 318 (HP Company, Palo Alto, CA, USA) digital camera (2.31 megapixels: 1792×1200 pixels). Because of the irregular location of the shaded and sunny patches, segmentation was analysed using the region-growing method applied in image-processing programmes. Three different types of pixels were distinguished (shaded, bright and with diffused light), which were masked using the Magic Wand technique and then counted (Adamsen et al. 1999, Hafsi et al. 2000).

The incoming radiation values were provided by the automatic QLC-50 (Valsala, Helsinki, Finland) equipment at the local meteorological station. The measurements were carried out at an incident angle of 53–56° between 12.00 and 13.00 LMT between 15 and 20 August 2002. The investigations were repeated on the same days in August 2003.

The Beer–Lambert equation was applied to calculate the canopy extinction coefficient, k:

$$KLAI_i = \ln(I_i/I_i) \tag{2}$$

where I_i, is the radiation measured at the bottom of the ith layer, I_0, radiation reaching the top of the stand and LAI_i, the LAI of the layer.

The leaf area was measured or calculated from values taken with a LI-COR 3000A (Li-Cor) automatic planimeter on 10–12 sample leaves from each canopy level. In each case a record was made of the mean and maximum leaf width, the distance of the leaf storey from the soil and the total plant height.

Apart from the water supplies and plant density, the cultivation techniques normally used at the given location were applied, as recommended and inspected by experts from the local agricultural university.

Due to the fixed nature of the lysimeters, the irrigated part of the experiment was laid out in a block design with three replications. The dry treatments were arranged in a randomized, complete block design with three replications. Each plot consisted of 50 rows 0.70 m apart and 50 m long (0.175 ha). Analysis of variance was carried out according to SPSS 9.0 (SPSS Inc. 1996) with treatment factors considered as fixed effects. Water level × density × hybrid interactions occurred for most parameters measured. Individual Least Standard Deviation (LSD) tests were used to determine significant differences between the treatments.

Results

Architecture of the stand

Leaf area of individual plants

Irrespective of the water supplies, the leaf area per plant in Norma was greater than that of Martonvásár (MV) at all three plant densities, although the difference was only significant in the thin and dense stands. Thedifference, which was not always significant, amounted to 200–800 cm^2 per plant on the rainfed plots, while in the ET treatment the range was 200–1100 cm^2 per plant (Table 1). The leaf area per plant tended to be smaller at low plant density in Norma, while this reduction was significant (11.3 %) in MV. An increase in the plant density caused a significant decrease in the leaf area per plant in all cases. This decline was less severe in ET, where the extra water supplies had a compensatory role, being 7.6 % in MV and 13.5 % in Norma. In the rainfed plots these values were 32.5 % for MV and 18.6 % for Norma. This trend in the leaf area per plant suggests that the plant density should only be increased if sufficient water is available to support the higher plant number. Irrespective of the water supplies, plants grown at low plant density had greater mean and maximum leaf width than those grown at normal density. The increase in the mean width was 12.8 % in MV and

Table 1: The maximum leaf area per plant and per unit soil surface (LAI) in fully developed maize stands in August, 2002

	Nt	Nn	Nd	MVt	MVn	MVd
Leaf area per plants (cm^2)						
Plots						
Mean	4832.492	5063.02	4203.14	4314.882	4759.412	3427.945
S.D.	256.4117	267.5033	110.2767	188.645	56.385	29.70827
ANOVA: PR > F						
	0.341879		**0.006757**	**0.017386**		**3.48E-06**
				0.048006	0.126751	**0.000299**
ET						
Mean	5837.78	5436.697	4725.15	4749.492	5007.402	4650.418
S.D.	443.123	827.57	37.3133	170.941	59.865	8.261
ANOVA: PR > F						
	0.5169		0.231	0.0692		**0.000**
				0.0165	0.443	**0.028**
	0.027	0.517	**0.001**	**0.042**	**0.006**	**2.69E-07**
LAI						
Plots						
Mean	1.933	3.544	4.203	1.726	3.332	3.428
S.D.	0.103	0.187	0.110	0.075	0.039	0.030
ANOVA: PR > F						
	0.000		**0.006**	**0.000**		**0.028**
				0.048	0.127	**0.000**
ET						
Mean	2.335	3.806	4.725	1.900	3.505	4.650
S.D.	0.177	0.611	0.037	0.068	0.042	0.008
ANOVA: PR > F						
		0.016	0.060		**0.000**	**1.29E-06**
				0.017	0.443	**0.0276**
	0.027	0.517	**0.001**	**0.042**	**0.006**	**2.69E-07**

Table 2: Combined statistical results (ANOVA) with cross effects

	d.f.	Extinction coefficient (k)	Radiation on the soil surface (I)	Albedo (a)	LAI	Area/plant
Density (d)	2	***	***	***	***	***
Hybrid (h)	1	***	ns	***	***	***
Water (w)	1	***	***	ns	***	***
D × h × w	7	ns	ns	ns	**	ns

	k	I	A	LAI	Area/plant
R^2	0.822	0.8383	0.6126	0.9747	0.838
RMSE	0.0305	43.024	0.0112	0.1996	313.73

6.1 % in Norma. In the normal and dense stands the leaf widths did not change significantly.

Assimilatory surface of the plant stand

The leaf area above unit soil surface was quantified in terms of the leaf area index (LAI) (Table 2). As in the case of the leaf area per plant, the LAI values of Norma surpassed those of MV, irrespective of the water supplies and plant density. The extra water supplies provided in the ET treatments increased the assimilating surface per unit area in both hybrids, the increase in the LAI being 0.4–0.5 in Norma irrespective of the density, while in MV the increase was only 0.2 in the normal and thin stands and 1.25 in dense stands.

Irrespective of irrigation, the greatest assimilating surface was produced in treatments with high plant density, which gave significantly higher values than the normal stand. In dense, irrigated stands of Norma the LAI was 26 % greater than in stands with normal density; for MV this figure was 35 %. Irrespective of the water supplies, a thin stand caused a greater modification in the LAI than a dense stand. Plants of MV responded more sensitively to a reduction in the plant density, exhibiting a decrease of 63.5 % in the LAI in the rainfed plot and 59.4 % in the ET, compared with 58.8 % and 47.9 % in Norma.

The reflection coefficient, the albedo (a)

The measure of reflected radiation from various surfaces is the albedo, which represents a loss of energy from the point of view of plant physiological processes. Of the two hybrids tested, the albedo values of MV were 4–10% lower than those of Norma, depending on the water supplies and plant density (Fig. 1), although the difference was only significant in the thin stand at both water supply levels.

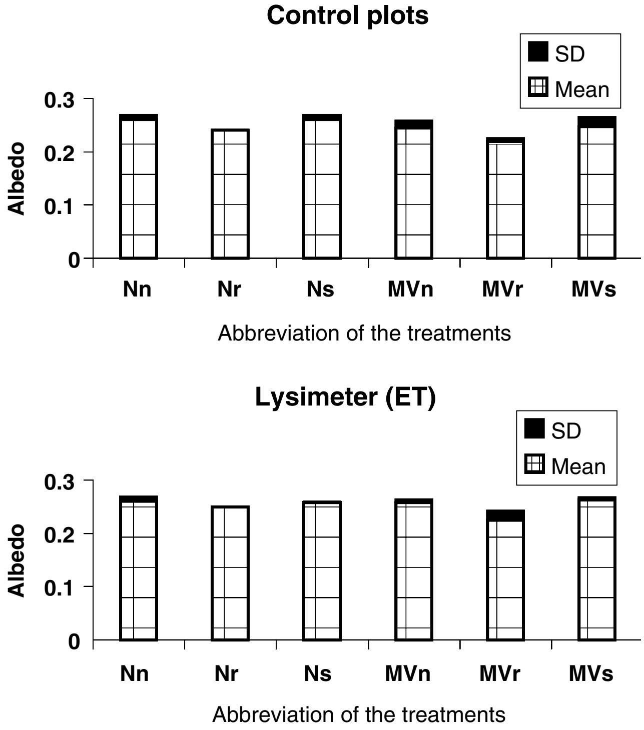


Fig. 1: Distribution of the leaf area of two hybrids grown at three plant densities at various levels of plant height from the ground upwards

Like the variety effect, supplementary water supplies also resulted in a slight, approximately 5 %, reduction in the albedo, leading to a marginal percentage increase in the energy retention of the enlarged leaf area, compared with that of plants in the dry treatments.

Irrespective of the water supplies, the albedo of hybrids grown in a thinner than normal stand declined significantly, i.e. the thin stand absorbed more energy than plants grown at normal density. As a result of thinning the albedo of MV decreased by 6.3 % in the field plots and by 13.5 % in the ET treatment. For Norma the reduction amounted to 8.0 % in the rainfed plots and 3.9 % in ET.

The extinction coefficient (k)

The value of the extinction coefficient, which expresses the extent of radiation attenuation, was not constant during the vegetation period. The maximum, k = 0.66, was recorded at silking, while lower values were observed before and afterwards (Lizaso et al. 2003). As the present measurements were made after silking, between 15 and 20 August, when the maize was in the milky ripe stage, the values of 0.3–0.5 recorded at an incident angle of 53–56° were in agreement with earlier observations. It is clear from the data that the variability in the extinction coefficient experienced in the literature was also characteristic of the present investigations, and the value of the coefficient depended on all three treatments, i.e. on the hybrid, the plant density and the water supplies (Fig. 2).

Irrigation increased the value of k in all the treatments, although not to as great an extent as that reported by Farre et al. (2000). In the irrigated treatments the greatest differences were observed for both varieties in the normal stand, where the extinction coefficient was 15.7 % lower in Norma and 13.9 % lower in MV than in plots with only natural rainfall. In the thin stands the rise in k in the irrigated variant was less pronounced (Norma: 6.5 %; MV: 9.8 %). The least change was observed in the dense stands, where the difference was < 4 % in both varieties. The increase in k as a result of irrigation could be attributed not only to the greater leaf area formed by plants with supplementary water supplies, but also to the greater shading provided by the more turgid leaves developed because of the extra water.

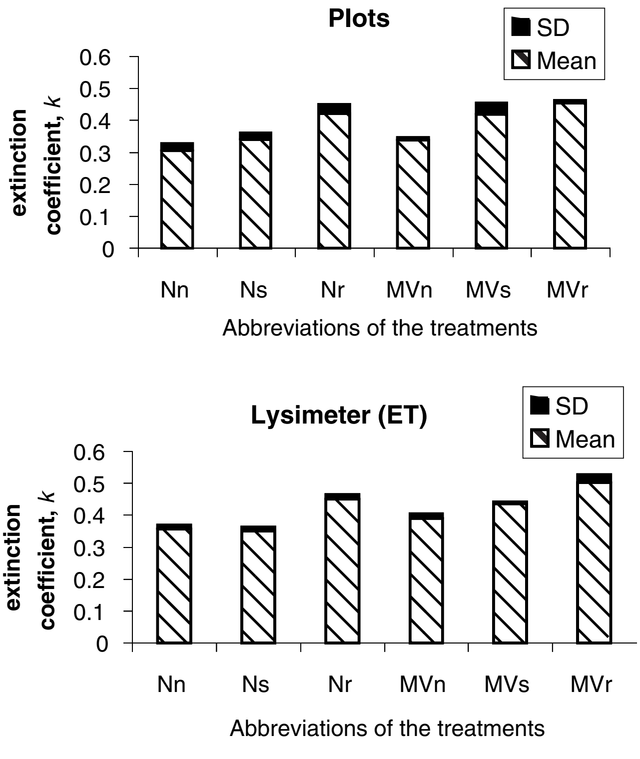


Fig. 2: Mean albedo (amount of reflected radiation expressed in the ratio of global radiation) calculated for the sample days for each treatment, with standard deviation

MV had a higher extinction coefficient (although the difference was not always significant) in all the treatments than Norma, which was unexpected, as its leaf area was smaller. The differences in k in the normal and thin stands were between 7 and 13 % in both water supply treatments, being significant in the ET treatment. The greatest (and significant) change was recorded in the dense stand of MV, where the difference was 20.9 % on the rainfed plots and 21.5 % in the ET treatment. This difference could not be explained purely by the change in the leaf area. There is probably some difference between the hybrids in the angle formed between the leaves and the stalk, the leaves of Norma being more erect. On the basis of model calculations, the possible extent of morphological adaptation of maize leaves because of a change in irradiation was found by Pommel et al. (2001) to be 2–11 %.

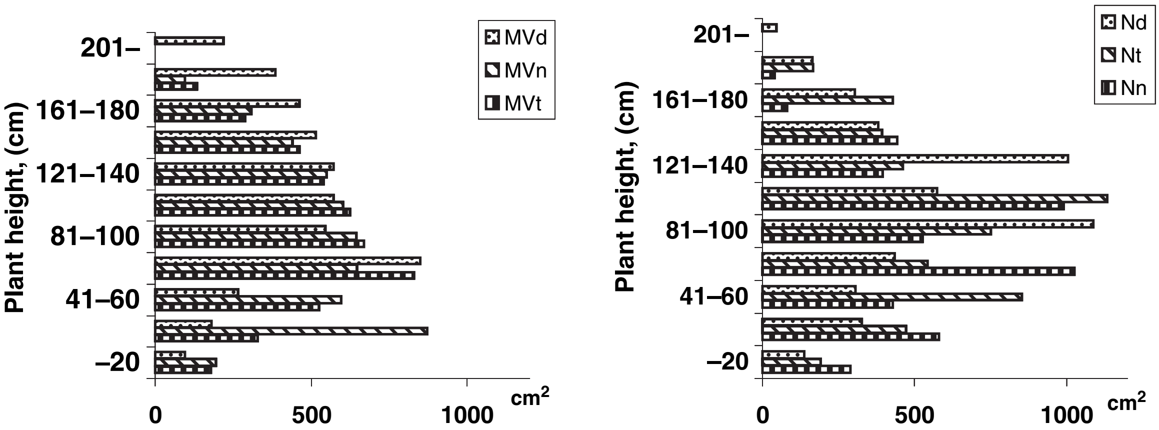
Irrespective of the water supplies, the extinction coefficients of dense stands of MV increased significantly compared with those of normal stands, by 18.4 % in the rainfed plots and 21.5 % in ET. In the ET treatment the k-value of Norma gave practically no response to an increase in stand density, and only a slight change was observed in the rainfed plots. The very high k-values recorded in thin stands despite the small leaf area could be the result of the special stand structure, the average height of which was 0.3–0.5 m lower than that of the normal and dense stands, which in itself could be sufficient to substantially modify the k factor (Edmeades and Lafitte 1993). Under Hungarian climatic conditions, a plant density of 40 000 plants per hectare is not generally applied. This plant density results in an extremely low LAI, the maximum value of which remains below the critical value (2.0–2.5) required for a closed stand, so that the stand remains ‘open’ throughout the vegetation period. The level at which leaf density was the greatest also changed, now being in the middle third of the stand. As the main question facing grain maize production is the possibility of raising the normal plant density, rather than reducing it, and as a comparison of the k factors only makes sense in the case of closed stands, the effects of thinning were not further investigated.

Discussion

A change in plant density led to a significant modification of the leaf area, both per plant and per unit area, in both varieties. The change was the most drastic in the thin stands, where the reduction in the leaf area was 50 % or more in the 40 000 plants per hectare treatment. In the ET treatment, the leaf area of the plants responded more sensitively to an increase in plant density than in the rainfed plots, but this change was not as great as that induced by the thin stand. The leaf area-increasing effect of irrigation was manifested irrespective of the variety or the density, the greatest effect being observed for MV in the dense treatment (30 %), while the smallest difference in leaf area was recorded for both hybrids in the normal stands (5–7 %).

The vertical distribution of the leaf area, which strongly influenced plant radiation properties, was modified by the plant density in both varieties. In the irrigated treatments the plant height in the dense stand increased by one leaf storey (20–50 cm), probably because of competition for light. The plants were shortest in the thin stand for both varieties, being 30–50 cm shorter than those in the normal and dense treatments. A change in the plant density caused a shift in the height at which the foliage was the densest, irrespective of the water supplies. This was 60 cm from the soil in the normal stand, 80–120 cm in the thin stand and

Lysimeter (ET)



Control plots

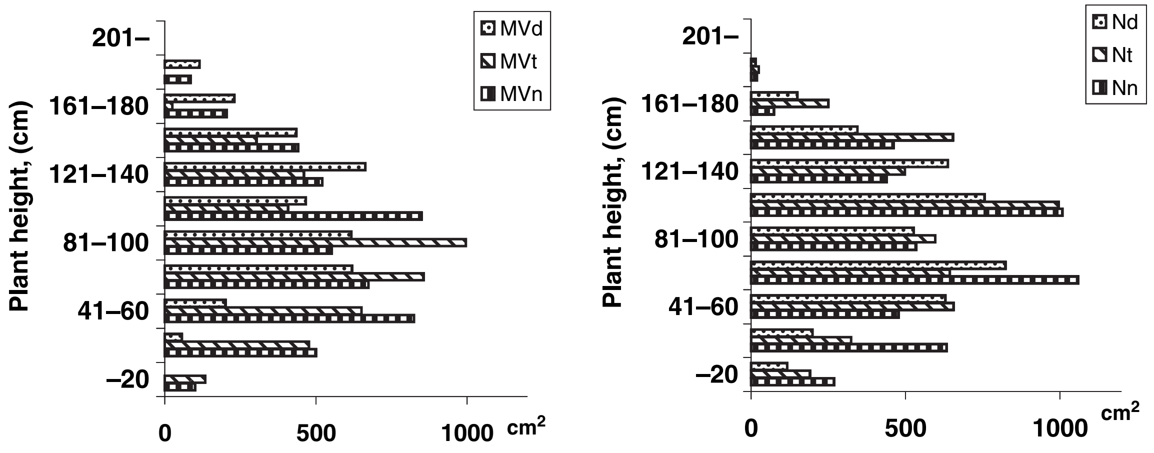


Fig. 3: Values of the extinction coefficient, k (measure of radiation penetration) measured at an incident angle of 53–56°, averaged over the four sample days

Table 3: Heat balance components (Wm^{-2}) for maize in the middle of August 2002

	Treatments					
ET (Wm^{-2})	Nn	Nt	Nd	MVn	MVt	MVd
aG	234	225	231.75	231.75	202.5	236.25
Energy in the soil surface	314	335	219	290	340	212
Latent heat flux	247.7	224	259.8	272	248	281.6
Sensible heat flux	104.3	55	189.45	106.25	41.5	170.15

above 140 cm in the dense treatment (Fig. 3). After flowering, higher plant density caused a 2-week shortening of the lifespan of leaves near the soil in the dense stand compared with the normal stand, because of greater shading, irrespective of the irrigation treatment, so this may have been the cause of the change in architecture. Any alteration in plant architecture influences the energy balance of the canopy. Because of the change in plant density caused by the change in the leaf area and its vertical distribution, the radiation properties may have been modified as well.

Radiation loss as a result of reflection from the plant surface is determined by the albedo, which appears on the debit side of the radiation balance of the plant stand. The reflected radiation is determined not only by the nature of the surface, but also by the solar angle. For this reason, measurements were carried out at noon only. It is important to have an accurate knowledge of the energy balance components (albedo), as it is these which determine the latent and sensible heat, the source of energy for energy-demanding processes, and the energy bound by biochemical processes.

The albedo of the MV hybrid tended to be a few percentage lower than that of Norma. This was so even in thin stands, where the decrease was significant, sometimes being as high as 8–10 %. In stands where there was a relatively intense soil effect, the albedo was lower, i.e. the energy retention of the soil-plant system in the thin stands increased, if only by a few percentage.

Irrigation increased the extinction coefficient, which expresses the radiation penetration of the stand, by 3–13 %, depending on the plant density. The change in the coefficient as a result of an increase in plant density cannot be fully explained in terms of the LAI. It was impossible to compare the thin stand with the normal plant density variant, as the stand remained open throughout the vegetation period at a plant density of 40 000 ha^{-1} (LAI < 2.0–2.5), whereas in both the normal and dense treatments the stands of both hybrids were closed when the measurements were made. There is little point in comparing the radiation permeability of open and closed stands even within a single plant species.

The components of the heat balance are summarized in Table 3. The greatest reflected radiation (aG) was recorded in the dense stands. There was far less reflected radiation from the thin stands; in other words, the energy remaining in the soil–plant system was greater than in the denser treatments. As could be expected from the size of the LAI, the amount of radiation reaching the soil in the thin stand, where the shading surface was the smallest, was considerably greater than in the normal and dense stands, while there was only a very slight difference in the amount of radiation reaching the soil. Before the evaluation can be continued, it is first necessary to make a brief review of evapotranspiration (latent heat) data.

The transpiration of the MV hybrid, which was specifically bred for irrigated conditions, was only 5 % higher than that of Norma under *ad libitum* water supply conditions at all three plant densities. In terms of water consumption per unit soil surface, the water loss from the dense stands was only 10–15 mm more than from normal stands. The difference in cumulative evapotranspiration between the thin and normal stands was substantial, however, being more than 50 mm for both varieties. Higher values were again recorded for MV when transpiration was measured per unit leaf area, the water consumption being 7–14 % more, depending on the plant density. Because of the higher LAI, Norma plants transpired 18.4 % more water per unit soil surface in the dense treatments and MV 25 % more. In terms of transpiration per unit leaf area the water wastage of thin stands was the most pronounced for both varieties, with values 40 % higher than those measured in normal stands.

Trends in the annual transpiration values in the various treatments were clearly reflected in the data of the four sample days. In parallel with higher transpiration, higher values of latent heat were also recorded for MV, and in both hybrids the dense stands utilized the most energy for evapotranspiration, while the difference between the latent heat values of the normal and dense stands was smaller. Irrespective of the hybrid, the latent heat values of the thin stands were well below those of the other two plant density treatments, as expected from their low water consumption. At first sight the sensible heat of the thin stand, obtained by subtracting the latent heat from the energy retained by the canopy, appears to be very low. However, it must not be forgotten that the energy reaching the soil is the greatest at the lowest plant density, and this, in the course of reflection, acts as a heat source for both the vegetation and the air above the soil. The heat balance components of any stand can only be interpreted correctly if the properties of all three components of the soil–plant–atmosphere system are considered simultaneously. This means that in the case of sensible heat values, the energy reflected from the soil cannot be ignored when analysing the temperature relationships in stands of various densities. Only this complex view is able to give a true interpretation of the warmer conditions in a thin stand compared with closed canopies.

From the practical point of view it can be stated that, on the basis of the heat balance, both hybrids were suitable for cultivation at greater density. However, MV is only capable of manifesting its favourable density tolerance traits under irrigated conditions.

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