DEW FORMATION AND THE DRYING PROCESS WITHIN A MAIZE CANOPY

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Abstract. The amount of dew-fall and dew-rise to a maize canopy during one night, and the drying time during the early morning, were estimated by using the Bowen ratio energy budget technique (BREB) and the soil diffusivity technique (SD).

In addition, the distribution of the free liquid water within the plant community was measured at sunrise by using Leick plates and blotting papers. The course of the drying process within the plant canopy was also monitored by the blotting paper technique until the received night-time free liquid water within the canopy was evaporated. The calculated total amount of dew, estimated with the BREB and SD techniques, agreed with the measured amount to within 6%, though the measured drying process lagged about 1 hour behind the calculated one. Possible causes of this difference are the dripping effect and drainage down the stems, which were not included in the calculations. Initially, the drying process was faster in the upper layers of the canopy. Later, when the moisture distribution had become more or less even through the whole canopy, the drying rate became approximately uniform.

1. Introduction

During most nights, and after rain, free liquid water is present on plant surfaces in various shapes. This water can occur as droplets, clustered droplets or discrete patches (Leclerc *et al.*, 1985) as well as homogeneous films (Shuttleworth, 1978) depending on the state of the cuticle of the leaves. The rate of drying following a dewy night or shower of rain depends on the shape of the free water on the plants (Butler, 1985; Huber and Itier, 1990). Moreover, this drying process is very dependent on the architecture of the plant canopy and on general weather conditions.

The drying process is of practical importance for many plant processes (e.g. Wallin, 1963; Shoemaker and Lorbeer, 1977). For example, the duration of surface wetness controls the development of certain foliar diseases (Van der Wal, 1978). It is also very interesting from a scientific point of view since this process reveals the exchange mechanism inside a canopy without the complexities associated with the transpiration through stomata.

The objectives of the present study were to get better insight into the development of the free water profile within a crop canopy due to dew, and the course of the drying process during the early morning. To attain these goals, estimates were made of the total amount of dew deposition, the distribution of free liquid-water and the drying process within a maize canopy during an outdoor experiment.

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Moreover, simple model calculations were carried out to simulate the foregoing processes.

2. Theory

Free liquid water on plants can originate from three separate sources: the air (dewfall), the soil (dew-rise) and the plant itself (guttation) (Garratt and Segal, 1988). The last source, the so-called guttation, is essentially an internal plant process (Long, 1955) and was not expected to be a significant source of surface water in the present study.

Estimates of evapotranspiration can be made by using the Bowen ratio energy balance technique, BREB, above the canopy. Here, the energy budget of the crop canopy can be written (Rosenberg *et al.*, 1983):

$$Q^* + G + H + LE + S = 0\,, \tag{1}$$

where Q^* is net radiation, G soil heat flux, H sensible heat, E evapotranspiration, L latent heat for vaporization of water and S heat storage change of the canopy. Here, we adopt the sign convention that fluxes directed towards the earth's surface are positive. If the canopy temperature increases, heat storage is increased, which means with the present sign convention a negative sign for S. If the Bowen ratio, $\beta = H/LE$, is known, the evapotranspiration, E, becomes:

$$E = -\frac{Q^* + G + S}{L(1+\beta)}\,. \tag{2}$$

During the early morning, this equation provides an estimate of the rate of drying from the canopy and during night-time an estimate of the rate of dew fall (Jacobs *et al.*, 1990). At night Equation (2) represents a downward-directed moisture flux indicated here as E_d. It should be noted that during night-time the storage term, S, cannot be ignored. For example, in our case the heat capacity of the crop per unit ground area was about $4 \cdot 10^4\,\mathrm{Jm^{-2}\,K^{-1}}$, which means that when the crop temperature drops 10 K during the night, the heat loss of the canopy would account for a condensation of about 0.2 mm of water, which cannot be ignored in the dew formation process.

The transport of moisture in the upper soil layers can be estimated by using the soil diffusivity (SD) technique. The moisture transport equation for porous media (Philip and De Vries, 1957) can be written:

$$E_u = -\rho_w D_\Theta \frac{\mathrm{d}\Theta}{\mathrm{d}z} - \rho_w D_T \frac{\mathrm{d}T}{\mathrm{d}z} - \rho_w K\,, \tag{3}$$

where D_Θ and D_T are the liquid plus vapour diffusivities for moisture and temperature, respectively, ρ_w is the density of liquid water, K the hydraulic conductivity, Θ the volumetric moisture content and T the temperature. At the top of the soil, this term represents the soil evaporation, or, during night-time the amount of upwardly directed dew-rise.

Summing E_d and E_u yields the net moisture change for the plant canopy. In the early morning after sunrise, this represents the drying process while at night this summation represents the total dew accumulation.

3. Description of Experiment

The analysis of one night (29–30 August 1988) of dew formation and the following drying process is presented here. The experimental site was located in the centre of The Netherlands (51°59′ N, 5°45′ E), was 250 m by 200 m large and was surrounded by other agricultural fields on which mainly maize was grown. Maize (Zea mays L, cv Brutus) was planted on the experimental field in NNE–SSW rows with a row spacing of 0.75 m and with plants 0.11 m apart in the row (12 plants per m^2). The mean height, h, of the canopy was 2 m during the experimental period.

At the experimental site, the soil consisted of sand with a humic upper layer. This upper horizon consisted of gravel and coarse sand and had a thickness of approximately 200 mm. Between 200 and 400 mm, there was a podzolic horizon with less humus and iron bonds than in the upper level. From both layers, the moisture retention curve, the hydraulic conductivity and diffusivities were estimated. Further information can be found elsewhere (Kabat *et al.*, 1992).

Dry and wet bulb temperatures were measured above and inside the crop at heights of 0.2, 0.5, 1.5, 2.5, 4.5 and 6.5 m using aspirated psychrometers. The net radiation was measured with a Funk net radiometer at a height of 6.0 m. To avoid dew condensation on the domes, strong aspiration was executed with a homemade ventilation ring around the domes. At depths of 10 and 80 mm, soil temperatures were measured with Pt-100 elements and at a depth of 50 mm the soil heat flux was measured with two flux plates (TNO transducer WS 31-Cp). Corrections were carried out for differences in heat conductivity between sensor and soil as well as for soil heat storage effects (Fritschen and Gay, 1979). The upper soil moisture profile was measured at depths of: 20, 30, 40, 50, 70 and 100 mm by a dielectric soil moisture content meter (Halbersma *et al.*, 1987).

The signals were carried to a datalogger in a van about 100 m from the instruments. Here, the slow-response signals were sampled at 1 Hz and the unconditioned data were dumped on a digital magnetic tape for later analysis. More details about the site, instrumentation and measurement procedure can be found elsewhere (Jacobs and Van Boxel, 1988; Halbersma *et al.*, 1987).

To obtain an estimate of the distribution of free liquid water within the crop community, Leick plates (Leick, 1932) were installed at 4 locations at heights of $0.1h$, $0.3h$, $0.5h$, $0.7h$ and $0.9h$, where h is the height of the canopy. Each measurement height represented a layer in the canopy with a thickness of $0.2h$. At a central location, the plates were placed horizontally while at about 25 m north, west and south of this location, the plates were placed at an angle of 45°, where the bottom side was facing the central location. Five hours before sunset, the plates were conditioned in a Stevenson screen at a height of 1 m. One hour before sunset, the plates were weighed and installed inside the canopy. At sunrise the total mass of each plate was weighed again and the difference was assumed to be the amount of dew deposit on the plates. The water per unit area on the plates in each layer was multiplied by the leaf area of that layer. The leaf area of a layer is the leaf area distribution times the height of the layer, where the leaf area distribution is the one-sided leaf area per unit volume. The water amounts of the 5 layers were summed and the total was assumed to be an estimate of the total collected dew amount at sunrise. This water amount can be compared with the result obtained by summation of the BREB and SD results. More details about this technique can be found elsewhere (Jacobs *et al.*, 1990).

The drying process of the leaves was monitored by using circular standard blotting papers from so-called Piché evaporimeters, with a one-sided surface of 10.2 cm^2. At heights of the Leick plates and at random locations, the free liquid-water was collected at the top as well as at the bottom of the leaves. The blotting papers were attached to the leaves with special clips to ensure that the paper was evenly pressed to the leaf surface. The number of papers used per measurement ranged between one and four, dependent on the amount of water on the leaves but to ensure that all the water was absorbed. The blotting papers were attached to the leaves for about 5 min intervals beginning after sunrise and immediately weighed at the measurement site. To obtain a second independent estimate of the total dew amount in each layer, the amount of water per unit area measured with the blotting papers was multiplied with the leaf area of that layer. Since the sum of the total amount of water in the five layers at sunrise also represents an estimate of the total dew amount, it can be compared with the result obtained via the Leick plates and the BREB and SD techniques.

The general weather condition during the experimental night was as follows: the air temperature at 1 m above the canopy dropped from 13 °C at sunset to 8 °C at sunrise, the windspeed at 10 m height varied between 3–4 m s^{-1} during the night and the cloudiness varied between 1/8 to 3/8 with the minimum sky cover near midnight. The upper part of the sandy soil was wet (20% by volume) due to a rainy period during the three preceding days; the collected amount of precipitation above the canopy was 12 mm.

4. Results

The measurements were executed during the night of 29–30 August when the architecture of the plant canopy was more or less constant. This can easily be inferred from Figure 1, which depicts the courses of the crop height, h, and the leaf area index, LAI, during the second half of the growing season. The LAI is the one-sided surface of the leaves per unit ground surface.

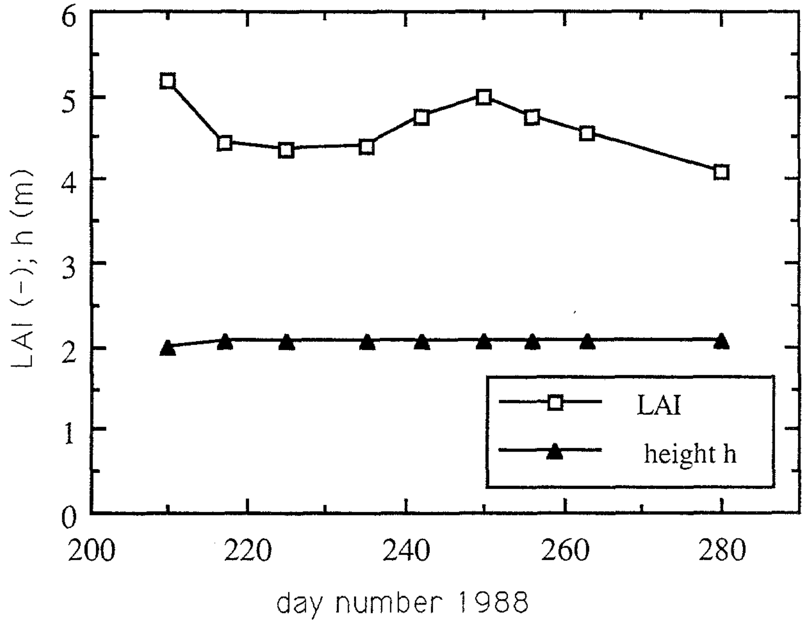

Fig. 1. The course of the crop height, *h*, and the leaf area index, LAI, during the second half of the growing season of 1988. The experiment was executed on 30 August.

The foliage area distribution, **a**, which is an important parameter for most within-canopy processes, has been depicted in dimensionless form in Figure 2. The foliage area distribution is the one-sided area of the leaves per unit volume, obtained by the leaf tracing method (Kvet and Marshall, 1971).

Figure 3 shows the amount of water per unit area, measured with the Leick plates at various locations and with various orientation angles. The variability of the amount of moisture measured at each level was small except at the lowest levels. The observed amount of water on the plates, averaged over the 4 measurement locations, is depicted in Figure 4. The mean liquid water distribution within the plant community can be assessed if it is assumed that the dew deposition process on the Leick plates is similar to the dew deposition process on the leaves. Multiplying the mean Leick plate data of a particular layer with the leaf area of that layer gives an estimate of the collected dew amount of that layer. This result in units of mm water has also been plotted in Figure 4.

The blotting paper data can also be used to obtain an assessment of the collected amount of dew. Here, the same procedure has been applied as for the Leick plates. In Figure 5 this result has been plotted as well as the previous results for the Leick plate data; the standard deviations of both sets of experimental data are indicated.

Figure 6 depicts the course of the accumulation of free liquid water during the night as well as the drying process during the early morning as calculated from

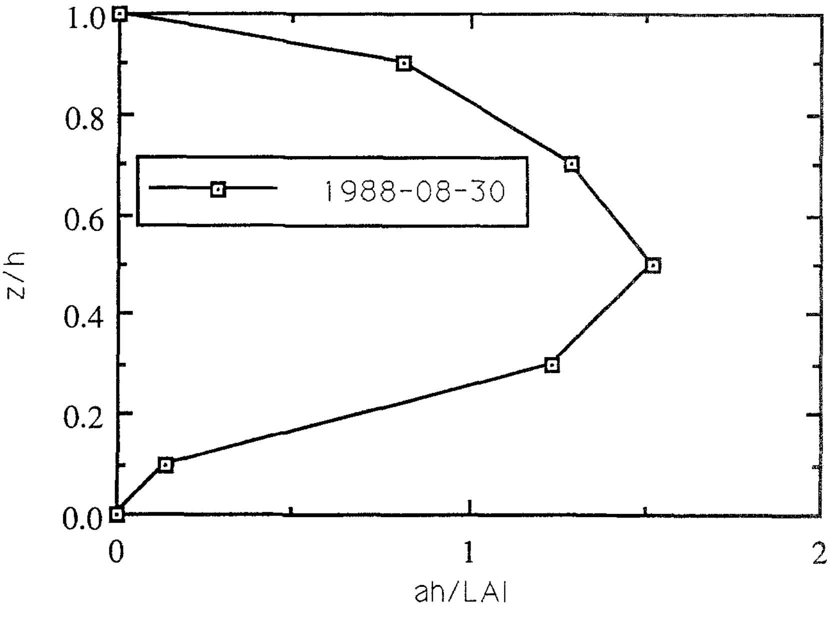

Fig. 2. The mean non-dimensional leaf area distribution, ah/LAI, as a function of the non-dimensional height, z/h, for 30 August 1988. The horizontal axis has been scaled with the leaf area index, LAI, so that the area under the curve with respect to the y-axis is equal to 1.

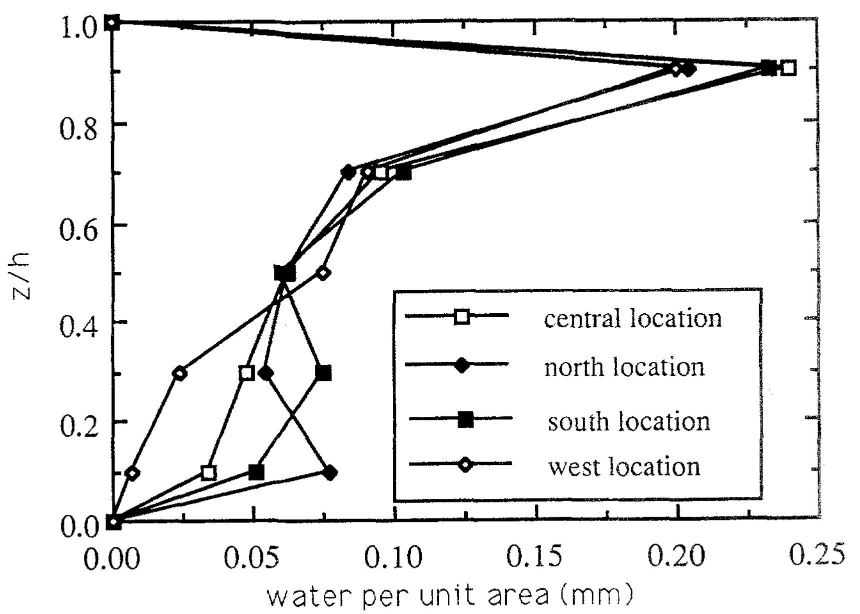

Fig. 3. The amount of water on the Leick plates measured on 30 August 1988 just after sunrise. Plate orientation: central location horizontally, all other locations at 45°.

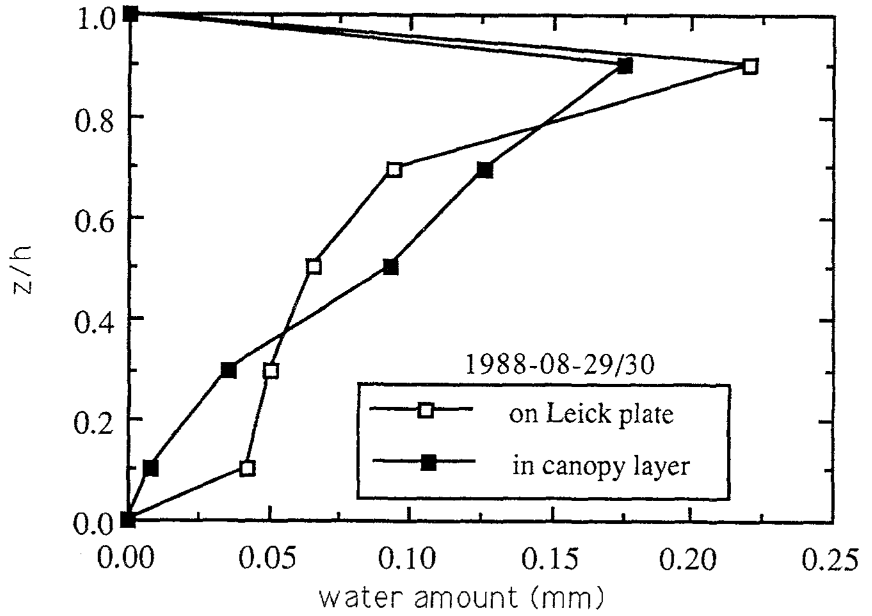

Fig. 4. The mean amount of collected water on the Leick plates (open squares) in units of mm water and the total liquid water contribution within the layers of the canopy (closed squares) obtained by multiplying plate data by layer leaf area.

the results obtained using the Bowen ratio energy balance technique (BREB) and the soil water diffusivity technique (SD). During the early morning, the actual drying process was measured by using the blotting paper technique. These results are also depicted in Figure 6. For this particular night, the dewfall was 0.41 mm and the dew-rise was 0.01 mm. This means that the dew-rise process was only about 2% of the total amount and in this case of minor importance, but agrees with the result found earlier (Jacobs *et al.*, 1990) during experiments carried out in spring time.

The course of the spatially averaged drying process in the various layers and on both sides of the leaves is portrayed in Figure 7. Here, the averaged amount of water per unit surface as measured by the blotting papers is depicted.

5. Discussion and Conclusions

We conclude that both the Leick plates and the blotting papers can be used to obtain reliable experimental estimates of the mean free water distribution formed during the night within a maize plant community. As can be seen from Figure 5, the experimental techniques, however, yield slight differences in the obtained moisture profiles. Indeed, both profiles agree within the standard deviation, but, there can be other possible causes responsible for these discrepancies.

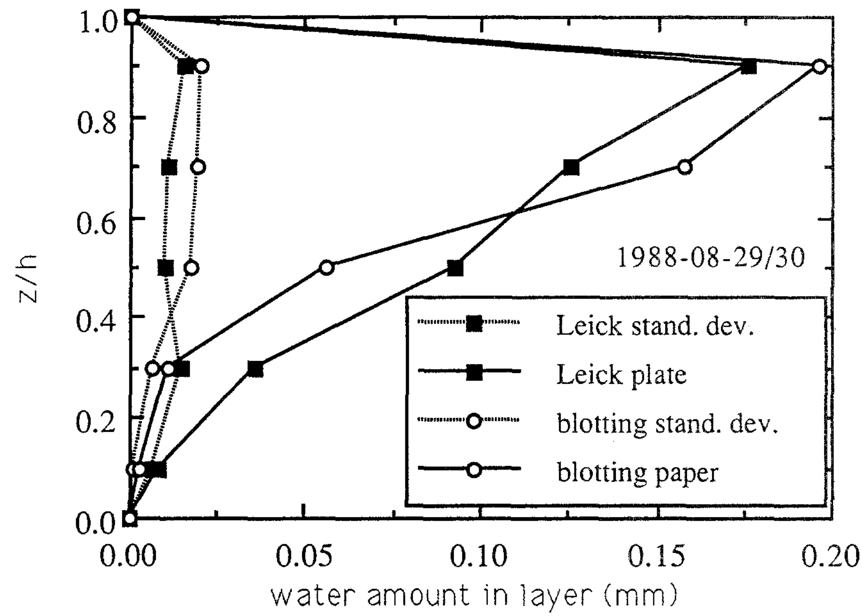

Fig. 5. The total liquid-water contribution within the 5 layers of the canopy obtained with the blotting papers (closed squares) compared with the Leick plate results (open squares). For both quantities, the standard deviation is indicated.

First, by the end of a dewy night and in the early morning, there always occurs some dripping from the leaves or drainage down the stems. This means that free liquid water is extracted from a higher region and is collected either in a lower region of the canopy or at the floor of the canopy into the underlying soil. In fact, the dripping and drainage mechanism will lead to a more even moisture distribution within the canopy (the top collects initially more dewfall) but will also lead to a reduction of the total moisture amount within the plant canopy. The Leick plates can only collect water by absorption and hold it in their pores. In this sense the plates should be expected to show an over-estimate of the actual free liquid moisture profile. The blotting papers, however, show the actual amount of liquid water present at the locations where the water is withdrawn. Figure 5 indeed shows a larger amount of water in the lower region of the canopy as must be expected by possible dripping and, or, drainage effects. The upper region, however, shows the opposite.

Second, there exists a difference in heat capacity between the plates and the leaves. The present plates have a slightly higher heat capacity than the leaves. Per unit surface area, the leaves had a heat capacity of 2.1 $\mathrm{Jm^{-2}\,K^{-1}}$, while the Leick plates had a numerical value of 2.4 $\mathrm{Jm^{-2}\,K^{-1}}$. Hence, during the night the plates cool more slowly than the leaves since their thermal time constant is slightly higher. This means that then the vapour flow to the plates will be reduced in

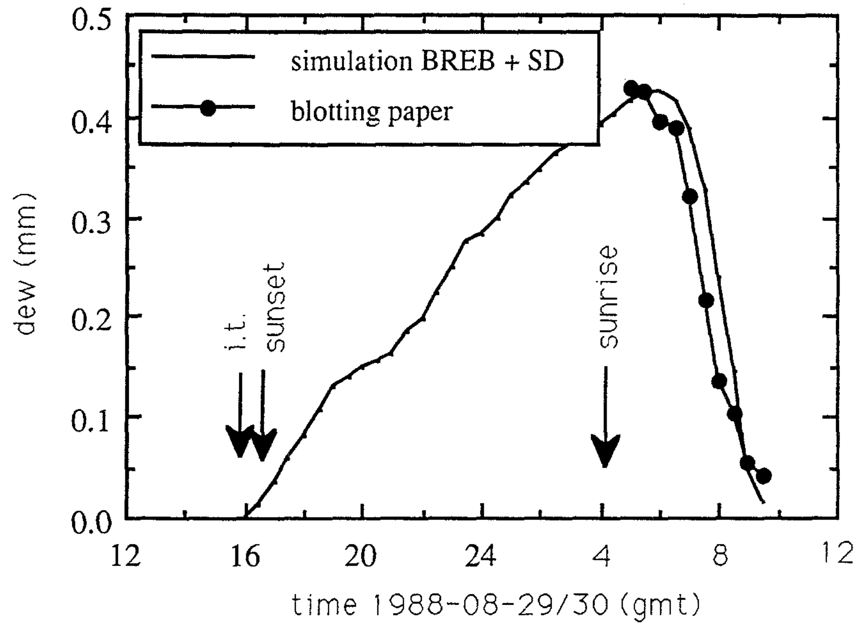

Fig. 6. The course of the amount of free liquid-water accumulation and the course of the drying process of the maize canopy. Ths solid line indicates the moisture accumulation calculated with the Bowen ratio energy balance technique (dewfall) and soil diffusivity technique (dew-rise). The dotted line represents the moisture results measured with the blotting papers. i.t. stands for installation time.

comparison to the leaves since the moisture deficit between plate and environment is lower than between leaf and environment. Moreover, in the upper region of the canopy, the dripping mechanism is most limited. This strengthens the conclusion that, of the two techniques, the blotting papers give more reliable end results, albeit at the cost of more labour. Nonetheless, the present Leick plates appear to give acceptable results for a maize canopy. It must be expected that the Leick plates will produce erroneous liquid moisture profiles in canopies with smoother leaves, or in canopies with fewer leaves where the drainage down the stems is considerable. A Leick plate simulates a leaf. Therefore it must be expected that for canopies where the plant area is dominated by the stem area, the Leick plates will be less reliable as well.

At every level, the water deposits collected by the various Leick plates and the blotting papers are quite variable. This is not due to uncertainties of the measurement techniques but is a characteristic of the deposition process within vegetation. Consequently, to get a representative spatially averaged moisture profile, it is necessary to measure always at more than one location.

The total amount of dew calculated with the Leick plates, or blotting papers, and the plant density distribution agrees, within 6%, with the results obtained with the Bowen ratio energy balance (dewfall) and soil diffusivity (dew-rise)

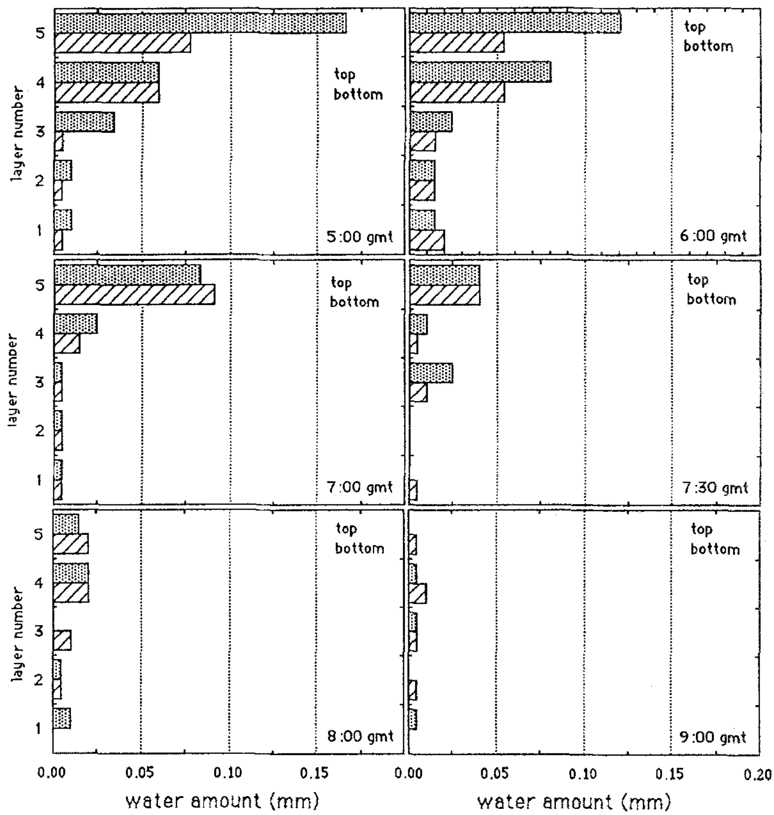

Fig. 7. The course of the drying process on both sides of the leaves and in the five different canopy layers.

techniques. This result supports the reliability of the method used to estimate correct liquid water profiles with Leick plates or blotting papers for a maize canopy.

From Figure 6 it can be inferred that both techniques indicate that the course of the drying process during the early morning is about the same. However, it also can be seen that the drying measured with blotting papers leads the simulated results by about 1 hour. A possible reason for this difference is again the dripping and drainage by flow down the stems reducing the actual free water amount in the plant canopy. Especially in the early morning, dripping and drainage effects will be enhanced when wind increases. Then the increased movement of the canopy stems and leaves causes water droplets to coalesce into large drops which can drip off or flow down the stems. This will lead to a redistribution of the free water within the canopy but can also lead to a reduction when drops reach the soil.

From Figure 6 it also can be inferred that late in the morning, the remaining free water is greater than the accumulated amount of evaporation would suggest. A reason for this discrepancy is that during the drying process, especially at the sunlit spots on the leaves, the canopy also starts to transpire simultaneously with the free water evaporation. This transpiration is included in the total evapotranspiration as calculated with the BREB technique.

It can be inferred from Figure 7 that the drying process within the canopy starts in the upper layers. This is to be expected since here the absorption of the irradiation and the consequent drying process are best in the early morning. However, as can be inferred from Figure 7, the evaporation of dew from leaves is quite a lengthy process. Also it can be inferred from Figure 7 that after the initial rapid drying in the upper canopy layers, the drying process happens more or less evenly over the whole canopy height. By the end of the drying period, the whole canopy becomes dry at the same time. Moreover, it is interesting to note that, as often mentioned in the literature (see e.g., Wallin, 1963), the upper sides of the leaves collect much more dew than the bottom sides; however, there is no difference in drying time for both sides. This characteristic feature has a practical advantage, namely, for making reliable estimates of the drying time, simple so-called large leaf models can be used. An example of such a model is that of Pedro and Gillespie (1982).

Guttation, sometimes called exudation (Slatyer and McIlroy, 1961), is an internal plant process which can contaminate the present measurement results of the blotting papers. Guttation produces free liquid water at the leaves themselves which means that when it occurs at a leaf where the blotting paper is attached, it will yield an over-estimation of the measured dew. Not much is known of this guttation mechanism except that it most likely can occur at injured leaves and during episodes of intensified plant root activity (Long, 1958). During the experimental period, no damaged leaves were selected for the blotting paper experiments; hence, the first mentioned cause can be ignored. Moreover, the present study was executed in late summer, where it may be expected that root activity is reduced. This means that it is reasonable to assume that the second guttation process can be ignored as well.

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