Simulating of leaf wetness duration within a potato canopy

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Abstract

A leaf wetness duration experiment was carried out in a potato field in the centre of the Netherlands during the growing season of 2003. A within-canopy dew simulation model was applied to simulate leaf wetness distribution in the canopy caused by dew and rainfall. The dew model is an extension of an earlier-developed energy budget model, distinguishing three layers within the potato canopy. To run the dew model successfully, information on the above-canopy wind speed, air temperature, humidity and net radiation as well as the within-canopy temperature and humidity must be available. In most cases leaf wetting starts in the top layer followed by the centre and the bottom layer, in that order. Leaf drying shortly after sunrise takes place in the same order. Leaf wetness lasted longest in the bottom layer. Rainfall was accounted for by applying an interception model. The results of the dew model agreed well with leaf wetness recorded with a resistance grid.

Additional keywords: dew, rainfall interception, simulation, *Phytophthora infestans*

Introduction

Rainfall, fog, drizzle, mist and dew are meteorological phenomena causing leaf wetness, i.e., free liquid water on plant leaves. Leaf wetness offers free water, for example, for plants and small animals in deserts to survive (Evenari *et al.*, 1982; Zangvill, 1996), affects plant growth (Wallin, 1967), but also plays an important role in the outbreak of foliar diseases caused by pathogenic fungi (Aylor, 1986; Van Den Ende *et al.*, 2000). When leaf wetness periods exceed a pathogen-specific length, and temperatures are appropriate, spores of fungal foliar pathogens such as *Phytophthora infestans* on potato and *Botrytis elliptica* on lily are enabled to infect, thus endangering crop yield. Such diseases are typically controlled by repeated fungicide applications preferably in a preventive strategy. With increasing environmental awareness and the high cost of fungicides, there is a need to reduce the excessive use of chemicals. Accurate determination of environmental conditions relevant to pathogen development can help to reduce the necessary fungicide input (Jones, 1986). So reliable estimates of leaf wetness duration improve decision making and assist in maximizing the efficiency of fungicide input. Leaf wetness simulation models, possibly in combination with knowledge of the state of the disease, can be employed to schedule fungicide applications. Previous research on leaf wetness duration has been carried out by e.g. Beysens (1995) for artificial leaves, Pedro & Gillespie (1982a, b) for top leaves in a crop canopy, Barr & Gillespie (1987) to test leaf wetness sensors, Hubert & Itier (1990) and Jacobs *et al*. (1994) to test drying of individual drops, and Luo & Goudriaan (2000) in a rice crop in which guttation dominated.

Rainfall and dew are the main environmental phenomena responsible for leaf wetness. Under rainy conditions, leaves intercept part of the precipitation, causing free water on the leaves. Dew can occur (1) by dewfall, a process during the night when water is extracted from the atmospheric water reservoir; (2) by dewrise, a process by which soil water evaporated during the night is intercepted by the canopy; and (3) by guttation, the exudation of plant water (Garratt & Segal, 1988; Beysens, 1995). The distribution of dew within a canopy is not homogeneous and changes in time, depending on the weather and on the leaf distribution and architecture of the plant canopy (Jacobs & Nieveen, 1995). If dewfall dominates, wetness usually starts in the upper layers of the canopy. Also drying starts in the upper canopy layer due to direct irradiation after sunrise. The longest wetness period is expected to occur in the lower canopy layers. Water dripping from leaves and stem flow at night can lead to accumulation of liquid water in the lower canopy layers where it may enhance wetness duration.

The objective of this paper is to get a better insight (1) into the interception of rainfall by and the formation of dew in the different layers of a potato canopy, and (2) into the drying of the different layers of the canopy. Leaf wetness was monitored during the potato growing season of 2003 and the measurements were compared with the results of an extended physical leaf wetness simulation model that was first developed by Pedro & Gillespie (1982a, b) to simulate the wetting and drying of field crop canopies.

Materials and methods[1]

Derivation of the dew model

The dew formation part of the model used in the present study is an extension of the model presented earlier by Pedro & Gillespie (1982a, b). The main difference is that their

[1] For abbreviations and symbols used see Appendix.

model was derived for the top leaf layer of a crop, whereas our model can be applied to every layer within a canopy. The energy budget of an arbitrary leaf layer in a canopy can be described by the following equation:

$$\Delta Q^*_{\mathrm{l}} + \Delta H^*_{\mathrm{l}} + \Delta \lambda^*_{\mathrm{v}}\ E_{\mathrm{l}} = 0 \tag{1}$$

where ΔQ^*_{l} [W m^{-2}] is the absorbed net radiation within this layer, ΔH_{l} [W m^{-2}] is the released sensible heat and $\Delta\lambda_{\mathrm{v}} E_{\mathrm{l}}$ [W m^{-2}] is the released latent heat within that layer. For simplicity reasons the energy storage and metabolic energy terms within this layer have been omitted since most of the time their contribution is relatively small (Jacobs & Nieveen, 1995).

The model assumes that data on net radiation, Q^* [W m^{-2}], are available either through measurement or estimation, as was proposed for example by Pedro & Gillespie (1982a, b). Within the canopy the net radiation flux is attenuated and we assume that this extinction follows the relationship proposed by Lowry & Lowry (1989):

$$Q^*_{\mathrm{l}} + (L(z)) = Q^* \mathrm{e}^{(-0.622\ \mathrm{L} - 0.055\ \mathrm{L}^2)} \tag{2}$$

where $L(z)$ [m^2 m^{-2}] is the integrated foliage area distribution, a [m^2 m^{-3}], from the top of the canopy, h [m], to the height within the canopy, z, according:

$$L(z) = \int_h^z a \mathrm{d}z \tag{3}$$

The absorbed net radiation, ΔQ^*_{l}, within this layer is:

$$\Delta Q^*_{\mathrm{l}} + Q^*_{\mathrm{l}}\ (L_{\mathrm{t}}) - Q^*_{\mathrm{l}}\ (L_{\mathrm{b}}) \tag{4}$$

where L_{t} and L_{b} are the integrated foliage area distributions from the top of the canopy to the top and the bottom of that layer, respectively.

The released sensible heat, ΔH_{l}, in the layer is simulated as:

$$\Delta H_{\mathrm{l}} = -\ 2\rho c_{\mathrm{p}} \alpha\ (T_{\mathrm{l}} - T_{\mathrm{a}})\ (L_{\mathrm{b}} - L_{\mathrm{t}}) \tag{5}$$

where ρ [kg m^{-3}] is the air density, c_{p} [J kg^{-1} K^{-1}] is the heat capacity, T_{l} [°C] is the mean leaf temperature in that layer, T_{a} [°C] is the mean ambient air temperature of that layer, and α [m s^{-1}] is the convective heat transfer coefficient of a one-sided leaf in that layer. In Equation 5 a factor 2 appears since both sides of the leaves are involved in the heat exchange process.

The convective heat coefficient, α, is calculated using the dimensionless Nusselt number, Nu, for forced convection and free convection. If forced convection dominates, the Nusselt number can be expressed as (Gates, 1980):

$$Nu = \frac{\alpha \rho c_{\mathrm{p}} D}{\lambda} = 0.664 Pr^{0.333}\ Re^{0.5} \tag{6a}$$

where D [m] is a characteristic leaf diameter, defined for long and narrow leaves as the mean width of the leaves, λ [W m^{-1} K^{-1}] is the molecular heat conductivity of still air, *Pr* is the Prandtl number and *Re* is the Reynolds number. The last two are defined as follows (Gates, 1980):

$$Pr = \frac{\nu}{a} \text{ and } Re = \frac{uD}{\nu} \tag{7a}$$

where u [m s^{-1}] is the mean wind speed, ν [m^2 s^{-1}] is the kinematic viscosity and a [m^2 s^{-1}] is the thermal diffusivity of still air.

Under free convection the convective heat transfer coefficient, α, is calculated from the *Nu* number according to (Gates, 1980):

$$Nu = \frac{\alpha \rho c_p D}{\lambda} = 0.50 Gr^{0.25} \tag{6b}$$

where *Gr*, the Grashof number, is defined as (Gates, 1980):

$$Gr = \frac{g\beta\,(T_l - T_a) D^3}{\nu^2} \tag{7b}$$

where g [m s^{-2}] is the gravity and β [K^{-1}] is the coefficient of thermal expansion. For a gas $\beta = 1/T_{abs}$, where T_{abs} is the absolute air temperature. Convection is forced if $Gr < 0.1\ Re^2$ (Gates, 1980). In the present model, distinction has been made between forced and free convection since the latter can occur very frequently when winds are light.

The released latent heat, ΔLE_l, in a leaf layer if the leaves are wet, is simulated as (Pedro & Gillespie, 1982a):

$$\Delta LE_l = -2\frac{0.622}{p}\rho\lambda_v\alpha'\,(e_{sl} - e_a)\,(L_b - L_t) \tag{8}$$

where p [Pa] is the air pressure, λ_v [J kg^{-1}] is the latent heat of vaporization, α' [m s^{-1}] is the convective mass exchange coefficient, e_{sl} [Pa] is the saturated vapour pressure at leaf level, and e_a [Pa] is the vapour pressure of the ambient air. From a similarity analogy between heat and mass it can be shown that (Gates, 1980):

$$\frac{\alpha}{\alpha'} = \left(\frac{a}{D_m}\right)^{0.667} = Le^{0.667} = 0.93 \tag{9}$$

where D_m is molecular mass diffusivity and *Le* is the Lewis number.

In the present model both the wind profile within the canopy and the air temperature profile need to be known. The wind profile within the canopy was derived by extrapolating the wind speed measured at a reference height to canopy height via a log-linear profile, and then applying the within-canopy extinction wind speed profile as suggested by Goudriaan (1977):

$$u(L) = u_c \exp\left(-M\frac{L}{LAI}\right) \tag{10}$$

where u_c [m s^{-1}] is the wind speed at canopy height, *LAI* is the one-sided leaf area index of the canopy and *M* is an extinction coefficient for wind speed that depends on the canopy architecture. For most agricultural crops *M* has a value of about 1.8 (Goudriaan, 1977).

During night-time and around sunrise and sunset the air within the canopy is well mixed. This results in a within-canopy temperature profile that is more or less constant with height (Jacobs *et al.*, 1992). In the present study the air temperature at two heights within the canopy was measured and for the within-canopy air temperature a linear profile was used.

Combining Equations 1, 5 and 8 and using Penman's elimination procedure as given in the following equation:

$$e_{sl} - e_a = (e_{sa} - e_a) - s\,(T_l - T_a) \tag{11}$$

where s [Pa K^{-1}] is the slope of the saturation vapour pressure curve, and $T_l - T_a = \Delta T$ is the temperature difference between leaf and ambient air, this temperature difference, ΔT, is found with:

$$\Delta T = \frac{\Delta Q_l - 2\,\dfrac{0.622}{p}\rho c_p \alpha' (e_{sa} - e_a)\,(L_b - L_t)}{2\rho c_p \alpha\,(L_b - L_t) + 2s\,\dfrac{0.622}{p}\rho c_p \alpha\,(L_b - L_t)} \tag{12}$$

Following Pedro & Gillespie (1982a), dew is formed if $e_a > e_{sl}$, and the amount of dew is calculated using Equation 8.

Derivation of the rainfall interception model

The rainfall interception part of the model is a combination of the models of Rutter (1975), Norman & Campbell (1983) and Mahfouf & Jacquemin (1989). The free water budget within a crop canopy can be calculated with the following equation (Rutter, 1975):

$$\frac{dW}{dt} = P_i - E_i - D_i \text{ if } 0 \le W \le W_{max} \tag{13}$$

where W [mm] is the interception reservoir, P_i [mm] is the intercepted rainfall, E_i [mm] is the evaporation of intercepted water, and D_i [mm] is the drainage and dripping effect. W_{max} [mm] is the maximum possible interception, which can be written as:

$$W_{max} = veg_h\; LAI\; h' \tag{14}$$

where LAI is the one-sided leaf area index, h' [mm] is the maximum water density on leaves and veg_h [–] is the horizontal vegetation density. In the literature the numerical value for h' varies between 0.05 and 0.2 mm, depending on leaf architecture. Because a potato plant tends to have a planophile leaf orientation, a value of $h' = 0.15$ mm is assumed in the present model (Rutter, 1975). We assume – even though this may not always be the case – that a small LAI is associated with a more erectophile leaf orientation, which means that water on canopies with a small LAI tends to flow more towards the stems. The veg_h coefficient in Equation 14 corrects for this effect. For veg_h the following relation was assumed (Norman & Campbell, 1983):

$$veg_h = 1 - e^{-0.8\mathrm{LAI}} \tag{15}$$

The intercepted rainfall can be written as (Mahfouf & Jacquemin, 1989):

$$P_i = P - T \tag{16}$$

where P is the above-canopy rainfall and T the throughfall, which follows the relation (Noilhan & Planton, 1989):

$$T = P\, e^{-0.5 LAI} \tag{17}$$

Corrections were carried out for drainage and dripping effects. Here, we followed Rutter (1975) for the combined drainage and dripping by using the equation:

$$D = D_s\, e^{b(W - W_{max})} \tag{18}$$

where D_s is the maximum drainage, set at 1.67 10^{-5} (mm s^{-1}) in the present study, and b is a drainage constant set at 3.7 mm^{-1} (Rutter, 1975). The evaporation of the free water caused by interception was worked out in the same way as the free water evaporation of the dew (see Equation 8).

Normally, during rainfall and dew formation free water on leaves is present in the form of drops of different size, which means that part of a leaf is wet and part of it dry (Hubert & Itier, 1990). In practice, however, a potato crop is mostly protected against fungal diseases with fungicides that contain so-called surfactants. The effect of such fungicides is that they reduce the surface tension of water, so that under wet conditions instead of drops a thin film of water is formed on the leaves. Hence a water film was assumed in the present model. It was also assumed that a leaf is either completely wet or completely dry.

After rainfall, within the canopy there will be a certain distribution of intercepted water, depending on the type (rain or shower) and the amount of rainfall. After a light shower, most of the water is concentrated in the upper layers of the canopy, but after a long period of rain the water is more or less equally distributed over all layers. In the present model the same interception was assumed for all types of rainfall periods.

Experimental layout

During the growing season of 2003, weather variables were recorded within and above a potato canopy in Wageningen, located in the centre of the Netherlands. The experiments were carried out from July until September in a commercial starch potato crop at the experimental farm of Plant Research International (51°58' N, 5°38' E, 7 m a.s.l.). Potatoes were grown in rows on ridges (height 0.25 m) 0.75 m apart. The distance between plants in the row was 0.32 m, resulting in a plant density of about 40,000 plants ha^{-1}. During the experimental period the maximum mean crop height was 0.85 m and the maximum LAI 3.6. The soil was clay and the water table was at an average depth of about 1.0 m.

In the middle of the field, between two plant rows, a 3-m mast was placed carrying instruments for recording various weather variables. Wind speed was measured at a height of 2 m using a locally made cup anemometer with a stall speed of 0.2 m s^{-1} and a distance constant of 0.90 m. At the top of the mast two global radiometers (CM 10; Kipp and Zonen, Delft, The Netherlands) recorded the incoming and outgoing short-wave radiation. A net radiometer (LVX055; Schulze Drake, Berlin, Germany) was placed at 2.0 m. Leaf temperature above the canopy was measured with two infrared thermometers (KT15; Heimann, Wiesbaden, Germany) placed at a height of 1.5 m. One sensor faced south whereas the other faced north. A tipping bucket rain gauge with a diameter of 0.16 m was installed in the crop 1.2 m above the soil surface.

Air temperature and relative humidity were measured above (1.2 m above the soil surface) and within (0.30 m) the canopy, with capacitive relative humidity sensors (HMP45AC; Vaisala, Helsinki, Finland). Leaf wetness was measured in the crop, with a resistance grid (237 wetness sensing grid; Campbell Scientific Inc., Logan, USA) 0.70 m above the soil surface. To protect the potato crop against *Phytophthora infestans* a fungicide was sprayed weekly.

The various variables were recorded every minute, using a portable logger (21X; Campbell Scientific Inc., Logan, Utah) and stored as 30-minute averages.

Results and discussion

Dry period

A period of 15 successive days (1–15 August 2003) was selected for a first check of the model during a period with little rainfall. The most relevant meteorological variables responsible for the dew formation process are presented in Figure 1, which shows that the daily cycles of net radiation during this period resemble those of sunny days with few clouds. Figure 1 furthermore shows that during night-time the within-canopy air temperature was somewhat higher than the above-canopy air temperature. During night-time a well mixed air layer is present within the canopy (Jacobs *et al.*, 1992), i.e., a layer with a more or less constant temperature. In contrast, the temperature in the air layer just above the canopy is stable, i.e., the temperature increases with height (Jacobs *et al.*, 1994).

In the model, the potato canopy was divided into three layers (top, centre and bottom), each with a leaf area index of 1.2. Figure 2 shows the accumulated dew simulations. The simulated dew and early morning drying results (Figure 2) suggest that the top layer collects most of the dew. Furthermore, the lower a leaf layer's position within the canopy, the less dew is collected. Also dew formation/interception/collection appears to start in the top leaf layer, followed by the centre and bottom layer. So huge differences in dew formation occur between the various leaf layers. This result is typical for a planophile crop canopy when dewfall is the predominant dew process. In an erectophile canopy, like maize, the same pattern of dew formation is found, but the differences between the leaf layers are less extreme (Jacobs & Nieveen, 1995).

The leaf wetness data recorded with the sensor 0.70 m above the soil surface can best be compared with the dew accumulated in the top leaf layer of the canopy. Model results for the top leaf layer along with these data are presented in Figure 3, where 0 for the wetness sensor data stands for dry and 0.1 for wet. Data recorded with the wetness

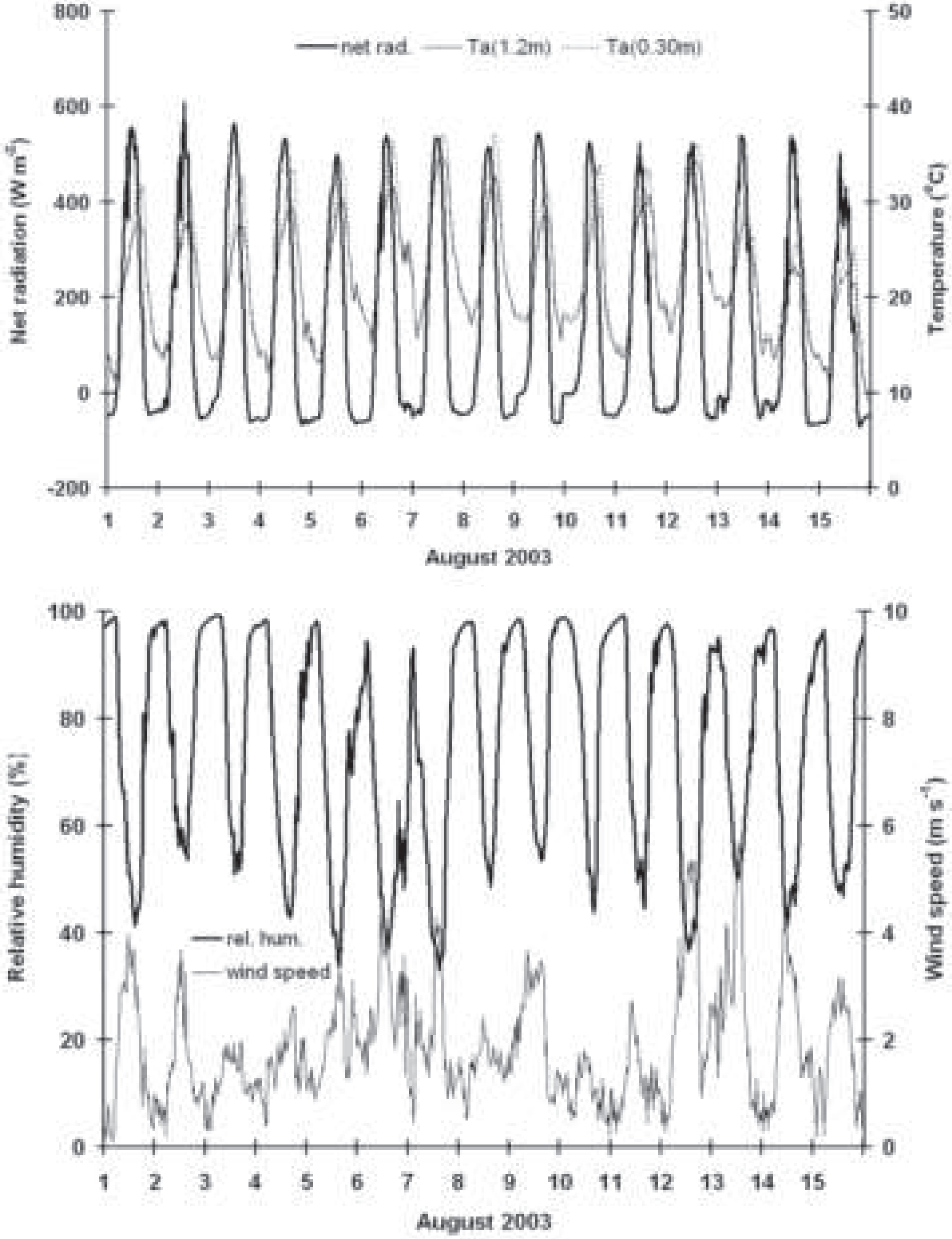

Figure 1. Course of meteorological variables during the dry period of 1–15 August 2003. Ta(1.2m) and Ta(0.30m) are the air temperatures within the canopy at heights of 1.2 m and 0.30 m, respectively.

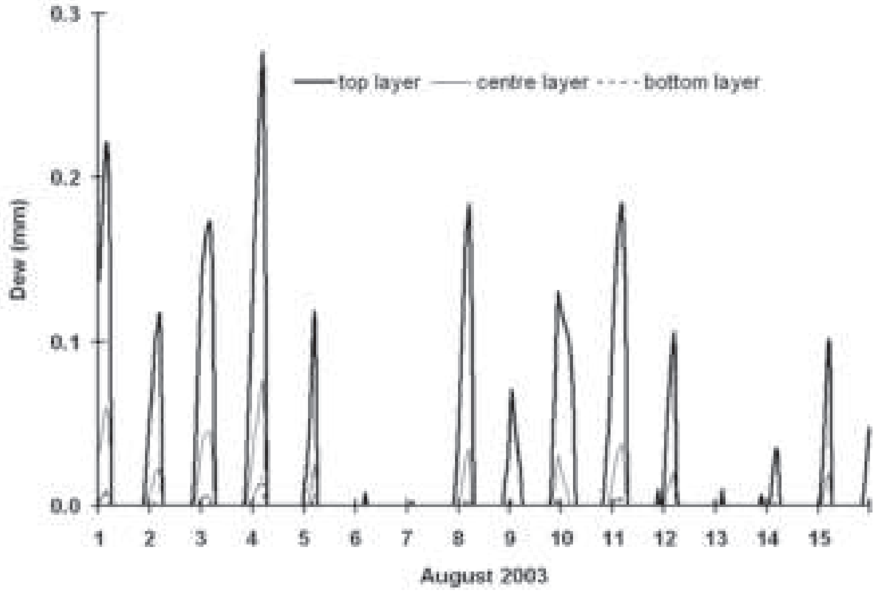

Figure 2. Course of simulated dew amounts during the dry period of 1–15 August 2003 for three leaf layers with a leaf area index of 1.2 each.

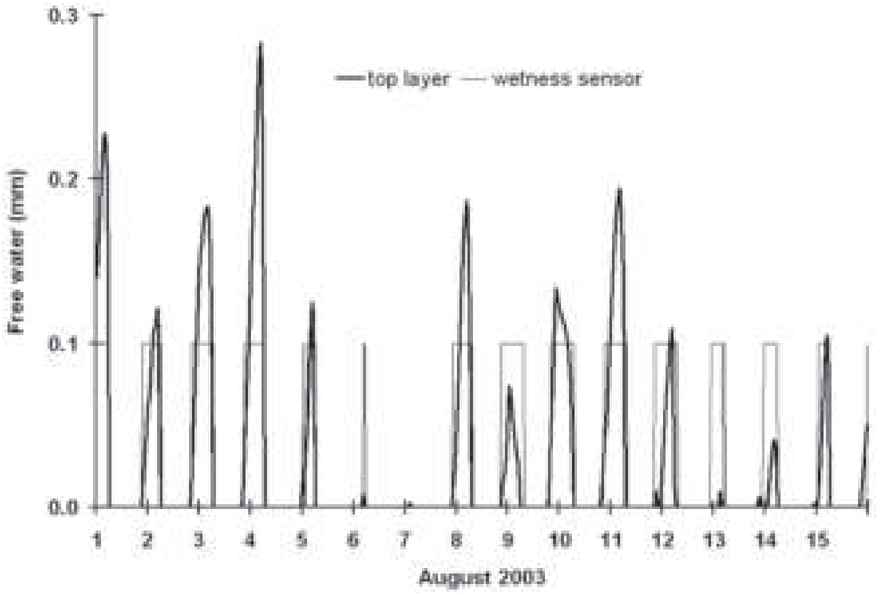

Figure 3. Course of simulated dew amounts in the top layer during the selected dry period of 1–15 August 2003, and wetness sensor recordings. Wetness 0 means completely dry, wetness 0.1 means completely wet.

sensor compare well with the simulated dew figures of the top leaf layer except that the measured wetness data display a time lag in the order of minutes. The reason for this small delay in time is that the wetness sensor consists of an electrical resistance grid covered with a porous latex paint. At the onset of dew formation it takes some time for the free water on the sensor to be absorbed by the porous paint layer, and at the end of the drying period to diffuse out of the paint layer and to evaporate into the ambient air.

Wet period

A similar analysis was done for a 16-day period (16–31 August 2003) with various rainfall events. For the most relevant meteorological variables during this 'wet period' see Figure 4. From the net radiation data we can infer that the weather during this period was very unsettled. Sunny days with few clouds alternated with cloudy days and with periods of heavy rainfall.

In Figure 5 the simulation results on dew accumulation in the three leaf layers are presented together with the recorded amounts of precipitation. The results show a match between simulated and measured dew events similar to the one found during the dry period. When precipitation occurs, the amount of rainfall nearly always exceeds the amount of dew. This means that if there is rainfall, the wetting process by rainfall nearly always dominates.

From the simulated amounts of free water on the leaves of the top layer and the recorded wetness data (Figure 6) we conclude that also during precipitation the model performs well.

Conclusions

In this paper we quantified leaf wetness duration and weather variables within and above a potato crop grown in the centre of the Netherlands. Dew model calculations were compared with measured leaf wetness to better understand the physical mechanisms that control the exchange processes of water vapour to and from the plant canopy. Moreover, the model distinguished three leaf layers in the canopy (top, centre and bottom) and was extended with a rainfall interception module. The following main conclusions can be drawn from our study:

1. Leaf wetness duration in the top leaf layer was well simulated by the multi-layer model. Simulated wetness duration agreed with the measured wetness duration, with a maximum difference of two times the period over which the records were averaged.
2. To run the model successfully, information on the above-canopy wind speed, air temperature and humidity and net radiation as well as on the within-canopy temperature and humidity must be available.
3. The agreement between model simulations and observations was good, both for periods where dew was the only wetting process and for periods with heavy rainfall.
4. The model results suggest that the leaf wetness period starts at the top of the canopy and from there descends into the canopy. The same sequence was found for the drying process within the canopy.

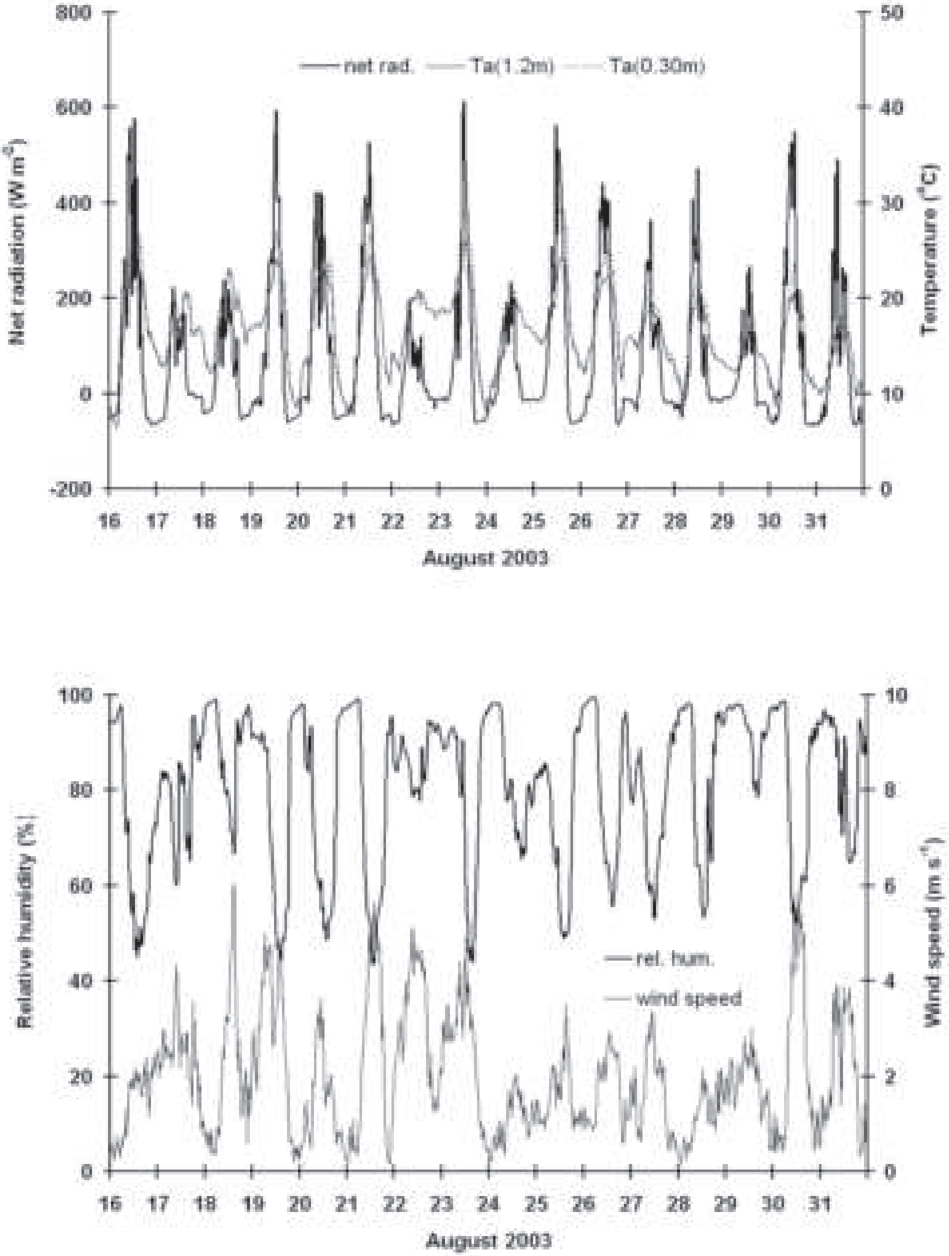

Figure 4. Course of meteorological variables during the wet period of 16–31 August 2003. Ta(1.2m) and Ta(0.30m) are the air temperatures within the canopy at heights of 1.2 m and 0.03 m, respectively.

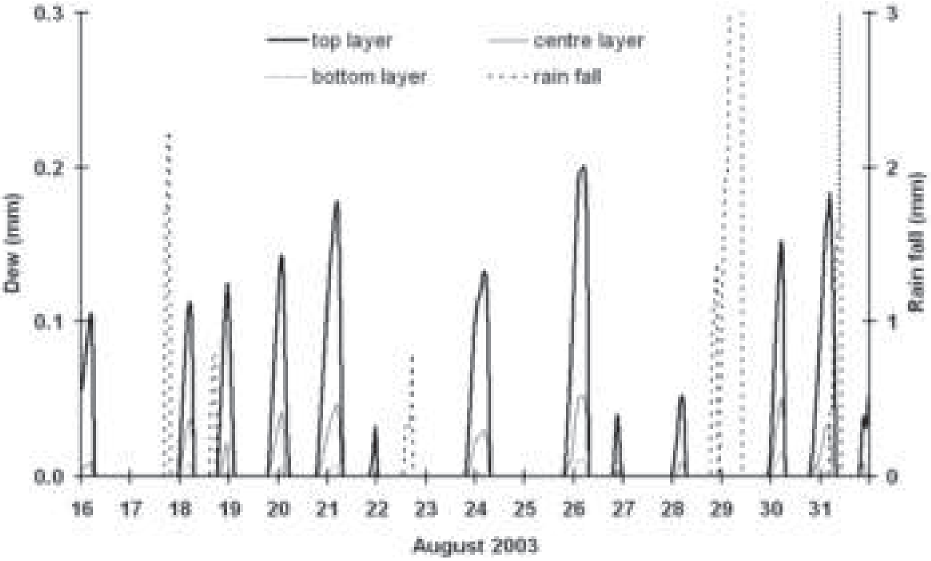

Figure 5. Course of simulated dew amounts during the wet period of 16–31 August 2003 for three leaf layers with a leaf area index of 1.2 each, and accumulated rainfall.

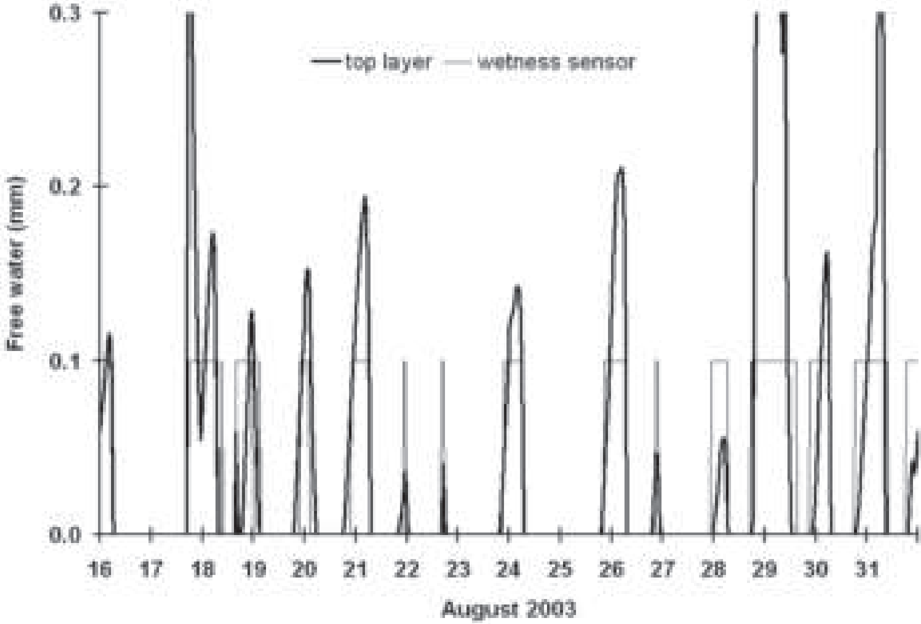

Figure 6. Course of the simulated free water amounts (dew plus rainfall interception) in the top layer during the wet period of 16–31 August 2003, and wetness sensor recordings. Wetness 0 means completely dry, wetness 0.1 means completely wet.

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Appendix

List of abbreviations and symbols

Abbreviation/ symbol	Description	Unit
a	thermal diffusivity	[m² s⁻¹]
a'	foliage area distribution	[m² m⁻³]
b	drainage constant	[mm⁻¹]
D	characteristic leaf width	[m]
D_m	mass diffusivity	[m² s⁻¹]
D_i	leaf drainage in layer	[mm]
D_s	maximum leaf drainage	[mm]
E	evapotranspiration/dewfall	[kg m⁻² s⁻¹]
E_i	evapotranspiration in layer	[mm]
e_a	vapour pressure air	[Pa]
e_{sl}	saturated vapour pressure at leaf	[Pa]
g	gravity	[m s⁻²]
Gr	Grashof number	[–]
H	sensible heat flux	[W m⁻²]
h'	maximum water density on leaf	[mm]
L	leaf area index in layer	[m² m⁻²]
LAI	leaf area index	[m² m⁻²]
Le	Lewis number	[–]
M	extinction coefficient for wind speed	[–]
Nu	Nusselt number	[–]
P	above-canopy precipitation	[mm]
P_i	intercepted precipitation	[mm]
Pr	Prandtl number	[–]
p	air pressure	[Pa]
$Q*$	net radiation	[W m⁻²]
Re	Reynolds number	[–]
s	slope vapour saturation curve	[Pa K⁻¹]
T	throughfall	[mm]
T_a	air temperature	[°C]
T_l	leaf temperature	[°C]
T_{abs}	absolute air temperature	[K]
T_o	surface temperature	[°C]
T_w	wet bulb temperature	[°C]
u	wind speed	[m s⁻¹]
u_c	windspeed at crop height	[m s⁻¹]
veg_h	horizontal vegetation index	[–]
W	interception reservoir	[mm]
z	height	[m]
α	heat exchange coefficient	[m s⁻¹]

α'	mass exchange coefficient	[m s^{-1}]
β	expansion coefficient	[K^{-1}]
Δ	difference	[–]
υ	kinematic viscosity	[m^2 s^{-1}]
λ	heat conductivity still air	[W m^{-1} K^{-1}]
λ_v	latent heat for vaporization	[J kg^{-1}]
ρ	density	[kg m^{-3}]