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Sensitivity analysis of leaf wetness duration within a potato canopy

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ABSTRACT: A description and analysis is given of a wetness duration experiment, carried out in a potato field in the centre of the Netherlands in September 2005. The observations are used to design and evaluate a within-canopy dew model which provides the leaf wetness distribution within the canopy caused by dew processes and by precipitation. This within-canopy dew model consists of three layers (bottom, centre, top) each with equal contribution to the leaf area index. The model results compared favourably with experimental evidence. The sensitivity of the dew and precipitation interception on the amount of free water and the duration of the leaf wetness was analysed by varying the leaf area index and some important weather variables. The findings suggest that the leaf area index affects the amount of free water, but is barely sensitive to leaf wetness duration. Wind speed has hardly any effect on the amount of free water collection as well as on leaf wetness duration. The net radiation, however, appears to be sensitive to the amount of collected free water as well as the leaf wetness duration. Copyright © 2009 Royal Meteorological Society

KEY WORDS dew; precipitation interception; free water; sensitivity analysis; *Phythophthora infestans*; *Botrytis elleptica*

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1. Introduction

Free liquid water on leaves, or simply leaf wetness, can be caused by rain, fog, drizzle, mist and dew. When free water on plants exceeds a pathogen-specific length of time, and temperatures are appropriate, spores of pathogens can germinate and infect the host and endanger crop yield. Such diseases are often controlled by fungicide sprays, where leaf wetness is important for timing spray application schemes as well (Glenn *et al.*, 1999). With increasing environmental awareness and the high cost of fungicides, there is a need to curb excessive use of chemical control measures. Accurate determination of antecedent environmental conditions relevant to pathogen development can help to reduce the necessary fungicide input (Jones, 1986). Thus, reliable estimates of leaf wetness duration can improve decision-making in spraying and assist in maximizing the efficiency of the fungicide input. Moreover, reliable estimates can lead to a better understanding of the epidemiology of many aerially and splash-dispersed diseases. Leaf wetness simulation models, possibly in combination with knowledge of the state and progress rate of the disease, can be employed to schedule chemical applications (Skelsey *et al.*, 2005, 2008).

There is a long history of previous research on dew formation and leaf wetness duration. For example, Hofmann (1955), Monteith (1957) and Jacobs *et al.* (1994a) gave a sound physical basis for the dew process and Pedro and Gillespie (1982a, 1982b) developed a practical model to estimate the leaf wetness duration. The measurement of leaf wetness duration is important but difficult. Barr and Gillespie (1987), Hubert and Itier (1990) and Luo and Goudriaan (2000) developed instruments to estimate reliable leaf wetness duration within agricultural crops. The above studies were done to reduce fungal diseases within crop canopies. On the other hand, particular in arid and semi-arid regions, dew can contribute considerably to the water balance and can even be harvested for irrigation and drinking water (see, for example, Nikolayev *et al.*, 1996; Kidron *et al.*, 2000; Agam and Berliner, 2004).

Precipitation and dew are the main processes responsible for leaf wetness. Under rainy conditions, leaves intercept part of the precipitation, causing free water on the leaves. Dew can occur by dewfall, the process during the night whereby water is extracted from the atmospheric water reservoir, dew rise, the process whereby soil water evaporated during the night is intercepted by the canopy, and by guttation, an internal plant water excretion process (Garratt and Segal, 1988; Beysens, 1995). Wetness usually starts in the upper levels of the canopy if dewfall dominates. Drying also starts in the upper canopy due to direct irradiation interception after sunrise. The longest wetness period is expected to occur in the lower canopy levels (Jacobs *et al.*, 2005). Water dripping from leaves and draining along stems at night, or, after a precipitation

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event, can accumulate liquid water in the lower canopy levels, which may enhance wetness duration there.

The amount of free liquid water within a crop canopy is never spatially homogeneously distributed. Due to the spatial differences of meteorological variables, but also in differences of plant and soil parameters, e.g. spatial differences in Leaf Area Index (*LAI*), the amount of free water can vary considerably. Hence it is of value to analyse the effect of inhomogeneity of key variables and parameters on the amount of free water on the leaves and duration leaf wetness duration.

Leaf wetness was monitored in September 2005 within a potato crop canopy and measurements were compared to the results of a relatively simple physical leaf wetness simulation model that was developed to simulate wetting and drying of agricultural crops (Jacobs and Nieveen, 1995; Jacobs *et al.*, 2005). The research reported here aims: (1) to provide a better insight into the rain interception and dew forming processes in different layers within a potato canopy, (2) to assess the drying process within different layers within the canopy, and, (3) to study the sensitivity of weather variables and canopy parameters on the predicted leaf wetness period.

2. Dew formation, interception and drying

2.1. Dew

The dew part of the model used here is based on the energy budget of various layers within a plant canopy. In daytime, a plant canopy layer receives and absorbs short wave radiation as well as net long wave radiation, through which the leaves of this canopy layer increase in temperature. The result of this increase in leaf temperature is that convective and latent heat will be transported from the leaves towards their direct environment in order to cool down the plant layer. By these convective processes, the air within the canopy layer increases in temperature as well as in moisture content. In the early morning, if free liquid dew water is present on the leaves, not only transpiration of the plant takes place but also the evaporation of the free dew water on the leaves. The evaporation of the free dew water on the plants dominates the total evapotranspiration process until all the free dew water has evaporated.

At night-time there is only net long wave radiation and because the canopy temperature is higher than the air temperature above the canopy there will be a net loss of radiative energy for the canopy. For a certain layer within the canopy, the leaves within this layer cool down below the adjacent air temperature of the leaves. The result of this decrease in leaf temperature is that convective heat will flow from the air towards the leaves in order to reduce rapid cooling of the leaves. If the leaf temperature approximates the dew point temperature of the adjacent air, condensation, or dew, occurs at the leaf surface. During the night, dew water accumulates at the leaf surface until a maximum amount of liquid dew water is reached. The maximum amount of dew water depends on the structure of the leaves and on occasional night-time wind gusts through the canopy. After this maximum is reached, dew water can drip from the leaves and can run off along the stems of the plant. Details about the dew formation and early morning drying processes can be found in Appendix A.

2.2. Interception and drying

The interception part of the model is a mechanical model based on the water budget of a leaf. If there is precipitation, part of the precipitation will fall through the canopy and part will be intercepted by the leaves and stems. Next, part of the intercepted rain water will be evaporated from the plant and part will drip or drain from the plant. The maximum amount of water that can be intercepted is dependent on the architecture of the plant canopy as well as on the structure of the leaves.

Normally during precipitation and dew conditions, free water on leaves exists in drops of irregular sizes, which means that part of a leaf may be both wet and dry (Hubert and Itier, 1990). In practice, however, a potato crop is protected against fungal diseases when mostly so-called surfactants are used in fungicide applications. The effect of these fungicide sprayings is that they reduce the surface tension of water so that a small film of water, instead of drops, is formed on leaves. In the present model, a water film on leaves is assumed and, moreover, it is assumed that a leaf is either completely wet or dry. Details about the interception formation process and drying process can be found in Appendix B.

3. Experimental layout

Extensive measurements were made within and above a potato canopy in Wageningen, The Netherlands, during the final phase of the 2005 potato growing season. The experiments were done in September in a commercial starch potato crop at the experimental farm of Plant Research International (51°59.501′N, 5°38.923′E, 7 m a.m.s.l.). Potatoes were planted in rows on ridges (height 0.22 m) 0.75 m apart. The distance between plants within rows was 0.32 m, resulting in a plant density of approximately 4 plants m^{-2}. During the experimental period the mean crop height was $h = 0.90$ m with a leaf area index of 3.5. The underlying soil is clay and the mean water table was at a depth of about 1.0 m.

A 3 m mast was placed in the centre of the field between two rows of potatoes. Wind speed was measured at a height of 2 m using locally-made microcup anemometers with a stall speed of 0.2 m s^{-1} and a distance constant of 0.90 m. At 2.5 m, two global radiometers (CM 10; Kipp and Zonen, Delft, Netherlands) and two pyrgeometers (CG 1; Kipp and Zonen, Delft, Netherlands) measured the incoming and outgoing short and long wave radiation components. A tipping bucket rain gauge with a diameter of 0.16 m was installed within the crop at a height of 1.2 m.

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Just above and within the canopy (of height h), air temperature and relative humidity were measured with capacitive relative humidity sensors (HMP45AC; Vaisala, Helsinki, Finland) at heights of 1.10 m ($z = 1.2$ h), just above the canopy, and at 0.45 m ($z = 0.5$ h) within the canopy. Two relatively large resistance grids measured the leaf wetness (237-LC wetness sensing grid; Campbell Scientific Inc., Logan, USA) at 0.45 m ($z = 0.5$ h) and 0.30 m ($z = 0.3$ h) above the ground and with four small flexible grids (237-F wetness sensing grid; Campbell Scientific Inc., Logan, USA) measured at 0.60, 0.45, 0.30 and 0.05 m ($z = 0.7$, 0.5, 0.3 and 0.05 h), respectively.

Measurements were sampled every minute using a portable logger (21X; Campbell Scientific Inc., Logan, Utah) and stored as 10 min averages.

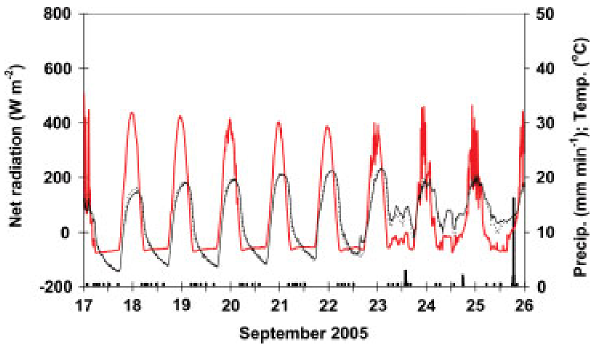

Figure 1. The course of the most important meteorological variables between 17 and 26 September 2005. Day numbers are plotted at midday UTC. Local summertime is UTC + 2 h. Bars: precipitation, thick solid line: net radiation, solid line: Ta (1.1 m), dashed line: Ta (0.45 m). This figure is available in colour online at www.interscience.wiley.com/ma

4. Results

4.1. General characteristics

A period of 10 successive days, 17–26 September 2005, was selected for detailed analyses. In Figure 1 the most important meteorological variables responsible for the dew formation process have been plotted. The daily cycles of net radiation and air temperature during the first 6 days resemble fine sunny days. During the last 4 days some strong rain events occurred, which provided a more complicated net radiation as well as temperature pattern. During night-time the within-canopy air temperature is somewhat higher than the above-canopy air temperature. During night-time a well mixed (i.e. a more or less constant temperature) air layer exists within the canopy (Jacobs *et al.*, 1992). In contrast, the air just above the canopy air layer is stable; i.e. the temperature profile shows an increase with height (Jacobs *et al.*, 1994). In Figure 1 the precipitation events are displayed. It is interesting to note that during nearly all nights, periods of very little ‘precipitation’ can be observed. As will be noted later, during the selected period in September the amount of dew was relatively high and tended to the maximum possible amount of $W_{\max}$ dew *per* night (Equation (B.2)). This dew was also collected in the rain gauge and could occasionally be detected by the rain gauge measurement system as ‘precipitation’. Because this type of precipitation does not originate from the sky, it is often called ‘occult precipitation’ (Acosta Baladón, 1995).

In the model as described in Appendix A, the potato canopy is divided into three layers, (top, centre and bottom), with an even contribution to the leaf area index of nearly 1.2 for each layer. In Figure 2, the accumulated dew simulations and early morning drying results are plotted for all layers along with the measurement results of some leaf wetness sensors (LWS). Figure 2 suggests that the top layer collects most of the dew. Moreover, a flat peak pattern was found for the collected dew in the top layer during most nights. During these nights the maximum possible dew/interception amount was reached that can be collected on the leaves. Furthermore, less dew is collected the lower a leaf layer is situated within the canopy. In addition, dew formation/interception collection appears to start in the top leaf layer, followed by the centre and bottom layer. Thus, large differences occur in dew interception between the various leaf layers. This result is typical for a planophile (i.e. horizontally oriented leaves) crop canopy when dew fall dominates the dew process. In an erectophile (i.e. vertically oriented leaves) canopy, such as maize, the same pattern of dew formation is found, but the differences between the leaf layers are less extreme (Jacobs and Nieveen, 1995).

Wetness sensors were placed at various heights within the potato crop canopy: results of two flexible leaf wetness sensors *per* layer are displayed in Figure 2. The units of the wetness sensors, however, are arbitrary. Here, the results of the wetness sensors mean that 0 is dry and 0.05 or 0.02 is wet. Roughly, measurements from the wetness sensors are in close agreement with the calculated wetness periods for the three canopy layers. Occasionally there are some discrepancies between simulations and measurements, particularly at the start of the wetness period as well as at the end of the drying period. It must be noted that the model simulations provide the mean free water amounts in the various layers, while the leaf wetness sensors measure the actual wetness at that particular location. In addition, possible reasons for discrepancies between model and measurements can also be caused by crop inhomogeneities (to be discussed later). In Section 4.2, below, it is assumed that the model reasonably mimics the mean physical reality to perform a sensitivity analysis with the most important model parameters to determine model sensitivity for these parameters.

4.2. Leaf area index effect

In a crop canopy, areas can be found with patches of bare soil and consequently with a locally lower *LAI*. On the other hand, areas can have a higher leaf density and thus a locally higher *LAI*. Hence, the model calculations were repeated using all meteorological variables and characteristics, but varying the *LAI*. From field observations with a movable *LAI* meter, it was found that a variation of

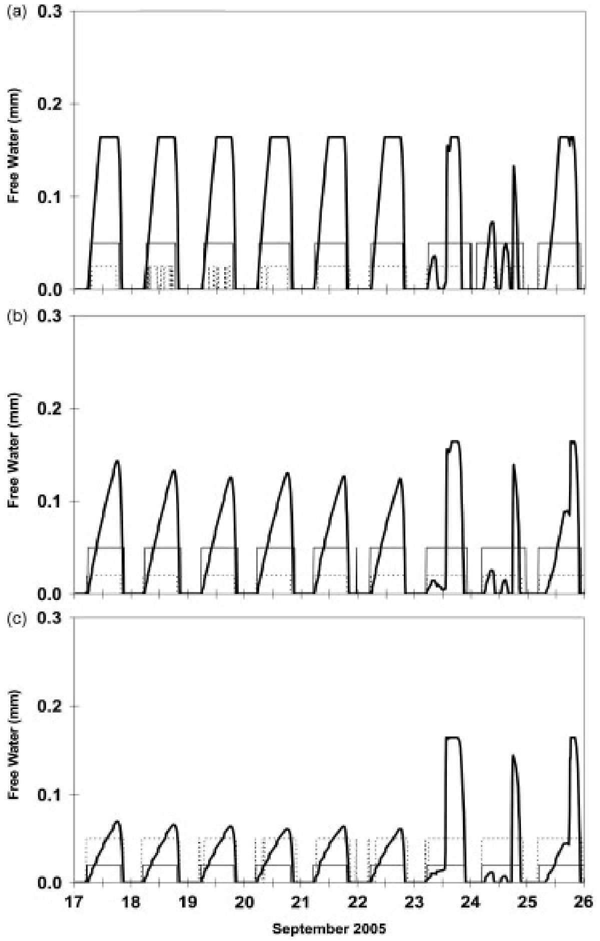

Figure 2. The course of the accumulated free water amounts between 17 and 26 September 2005, for the top (a), centre (b) and bottom (c) layers. Day numbers are plotted at midday UTC. The wet and dry periods are plotted (0 means dry, $\neq 0$ means wet) for two flexible leaf wetness sensors (LWS) at two different heights per layer. The mean height of the potato crop is $h = 0.90$ m. Local summertime is UTC + 2 h. Top layer (a): thick solid line: free water, solid line: LWS (flexible at 0.7 h) dotted line: LWS (flexible at 0.5 h); Centre layer (b): thick solid line: free water, solid line: LWS (flexible at 0.5 h) dotted line: LWS (flexible at 0.3 h); bottom layer (c): thick solid line: free water, solid line: LWS (flexible at 0.3 h) dotted line: LWS (flexible at 0.05 h).

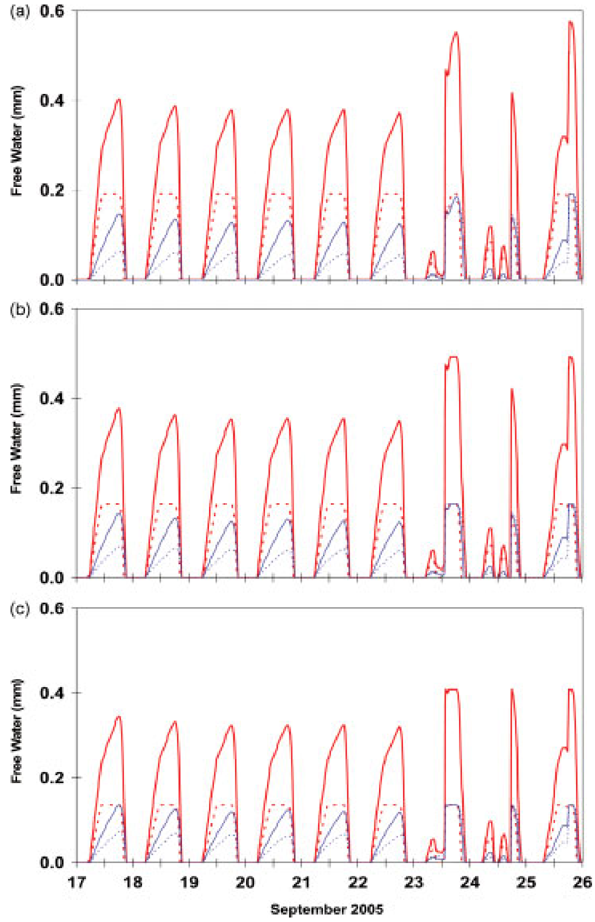

Figure 3. The course of the total accumulated free water amounts and the amounts per layer between 17 and 26 September 2005, for the top, centre and bottom layers for different leaf area indices. (a) Top panel: *LAI* = 4.0; (b) centre panel: *LAI* = 3.5; (c) bottom panel: *LAI* = 3.0. Day numbers are plotted at midday UTC. The height of the crop is $h = 0.90$ m. Local summertime is UTC + 2 h. Thick solid line: total free water, thick dotted line: free water top layer, solid line: free water centre layer, dotted line: free water bottom layer. This figure is available in colour online at www.interscience.wiley.com/ma

0.5 from the mean value is likely. Figure 3 contains the results, executed with three different LAI: $LAI = 4.0$ (a), $LAI = 3.5$ (b) and $LAI = 3.0$ (c).

According to Figure 3, the maximum amount of free water *per* layer depends nearly linearly on the *LAI*, which is consistent with Equation (B.2). Second, there is a subtle difference in the amount of collected free water in the various layers for different *LAI*. For example, for the bottom layer the collected amount of free water is somewhat higher for the case of $LAI = 3.0$ than for $LAI = 4.0$. The main reason for this difference is related to net radiation extinction (Equations (A.2) and (A.3)) within the crop canopy. For a low *LAI*, there is a higher net radiation loss in the bottom layer at night, hence a higher cooling and consequently a somewhat higher dew formation. The same reasoning leads to the opposite for the top layer, under the condition that the amount of collected free water is lower than the maximum possible free water. Third, from Figure 3 it can be inferred that the dew start time as well as the drying time is hardly affected by the *LAI* itself. If net radiative cooling occurs, free water is collected on the leaves, which does not depend on the *LAI*. In addition, because the free water amounts in the various layers are barely affected by the *LAI*, likewise the drying time is little affected by the *LAI*. For completeness it must be noted that there is always a difference in the leaf wetness periods between the various layers. For the pure dew events as well as for events with precipitation, it appears here that the longest drying time always occurs in the bottom layer, which is about 40 min later than in the top layer.

In general, it can be concluded that the *LAI* somewhat affects the free water amount. In the top canopy layer the free water amounts tends to decrease somewhat with decreasing *LAI*, while in the bottom layer the amount of free water tends to increase slightly with decreasing *LAI*. The centre layer barely shows any difference in the amount of free water. It also appears that the start time of

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the free water formation is not dependent on the *LAI* and that the end time of the leaf wetness period is also not dependent on the *LAI*. Finally, the drying time appears to be only dependent on the layer depth, i.e. the bottom layer shows a drying time of about 40 min longer than in the top layer.

4.3. Reference net radiation effect

Often no on-site measurements of the net radiation, Q^*, are available. Here, accurate estimates for on-site estimates of Q^* were obtained from the off-site nearby Wageningen University agro-meteorological observatory (www.maq.wur.nl, about 2 km south of the potato field) in addition to a limited number of on-site observations. Net radiation above a potato crop can be quite different from that above a short grass site, but it is expected that both net radiations are well correlated. The limited simultaneous measurements at both sites were used to check the estimates for net radiation above the potato crop. For the full month of September, all 10 min observations of the meteorological site and the potato site were compared. Because the net radiation behaves differently during daytime and night-time, a distinction was made between day and night. The upper panel of Figure 4 contains daytime results while the bottom panel contains the night-time values.

Figure 4(a) shows that the scattergram of the daytime net radiation results above the meteorological observatory correlates well with the net radiation above the potato site and has an unbiased linear relation of $y = 1.13x$ ($r^2 = 0.87$ with a standard error of estimate, *see*, $= 53$ W m^{-2} and $N = 1006$). Figure 4(b) shows the scattergram of the night-time net radiation results with an unbiased linear relation of $y = 1.35x$ ($r^2 = 0.72$ with a $see = 12$ W m^{-2} and $N = 1154$). A difference between both net radiations must be expected since both terrains have different albedos, which affects the daytime net short wave radiation, but also both terrains have different surface temperatures that affect the outgoing long wave radiation.

Figure 5 displays the free water amount of all layers as calculated with the net radiation measured above the potato crop, and as calculated with the net radiation measured above the meteorological observatory and corrected as shown in Figure 4. The start and drying times are within 10 min (the measurement average interval) for both calculations. From Figure 5 there are occasional discrepancies in the maximum amount of free water. This, however, hardly affects the wetness duration. Hence it can be concluded that net radiation measurements from a nearby observatory, coupled with a limited number of net radiation measurements above a crop, can be used for the local net radiation measurements.

4.4. Wind speed and radiation sheltering

An agricultural field can be surrounded by rows of trees, bushes or other sheltering obstacles. This means

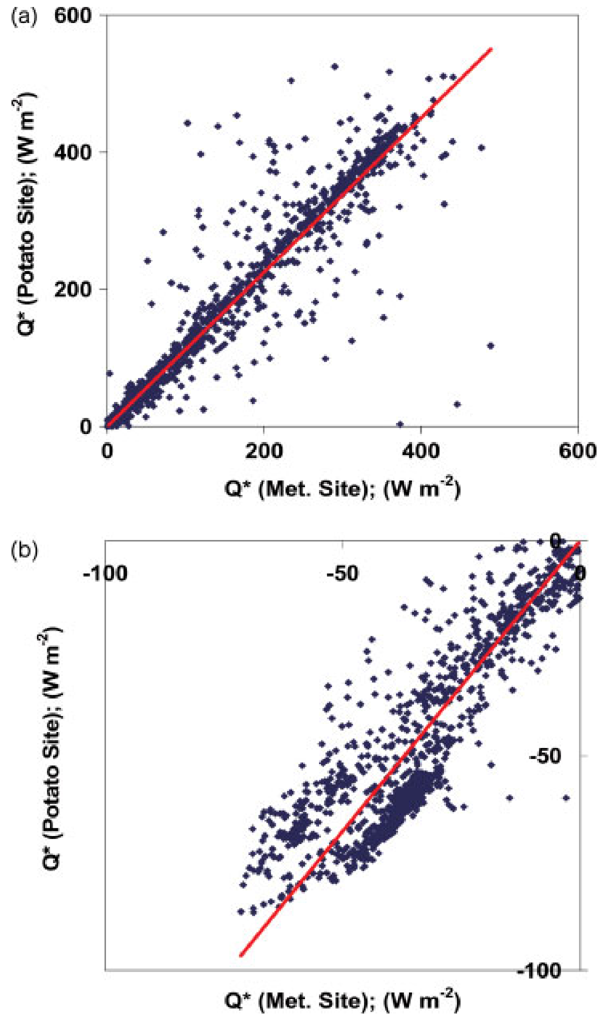

Figure 4. Correlation between the net radiation above the potato crop and a nearby (2 km south) meteorological observatory. Upper panel (a): daytime situation ($y = 1.13x$ with $r^2 = 0.87$). Bottom panel (b): night-time situation ($y = 1.35x$ with $r^2 = 0.72$). This figure is available in colour online at www.interscience.wiley.com/ma

that the short wave as well as long wave radiation components of the radiation budget can be affected by these shelters. Under sheltered conditions the wind speed is reduced whereas the turbulence is enhanced, which affects the convective exchange process mechanism. Concerning the radiation budget, the direct solar beam can be blocked during part of the daytime, which reduces the net radiation. During day- and night-time, however, the outgoing long wave radiation is partly intercepted by the obstacles, since the sky view factor is reduced. Consequently, the net radiative losses are smaller, which is important during night-time. In the following simulation it is assumed that part of the field is sheltered in such a way that during daytime the positive net radiation is reduced by 30% while during night-time the negative net radiative cooling is reduced by 30% as well. Moreover, due to wind sheltering, it is assumed that the wind speed at crop height is reduced by 50%. The results of this simulation are displayed in Figure 6. It is clear that the amounts of free water are lower in

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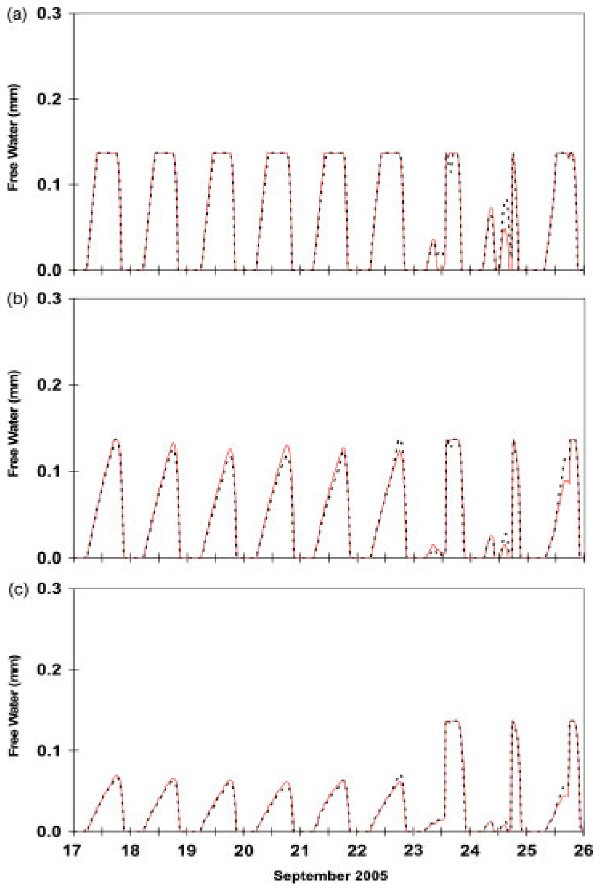

Figure 5. The course of the total accumulated free water amounts and the amounts *per* layer between 17 and 26 September 2005, for the top (a), centre (b) and bottom (c) layers calculated with the real net radiation above the crop and calculated with the estimated net radiation from the nearby (2 km south) meteorological observatory. Day numbers are plotted at midday UTC. Local summertime is UTC + 2 h. Solid line: Q* potato site, dotted line: Q* meteorological observatory. This figure is available in colour online at www.interscience.wiley.com/ma

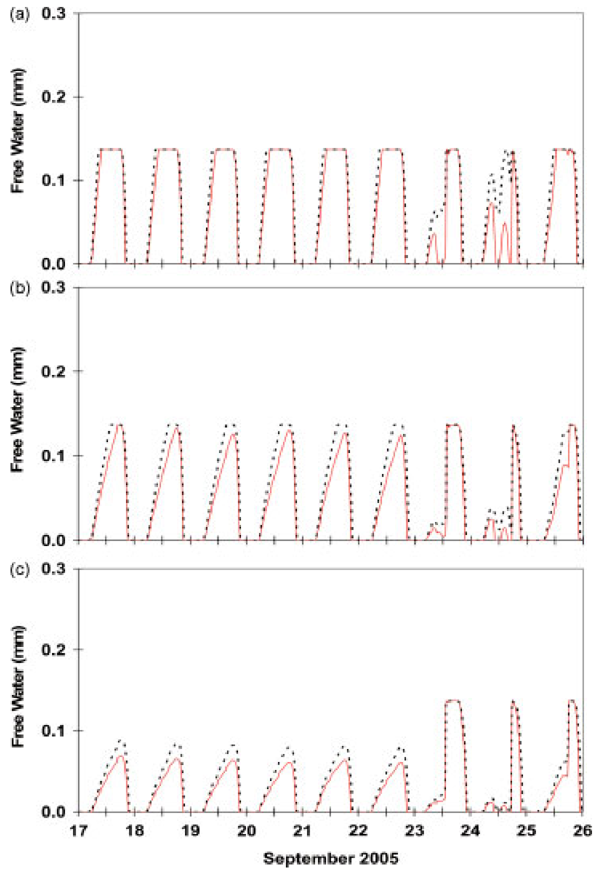

Figure 6. The course of the total accumulated free water amounts and the amounts *per* layer between 17 and 26 September 2005, for the top (a), centre (b) and bottom (c) layers calculated with the real net radiation above the crop and calculated with a reduced net radiation of 30% (all day) and a reduced wind speed at crop height of 50%. Solid line: sheltered crop, dotted line: unsheltered crop. This figure is available in colour online at www.interscience.wiley.com/ma

the sheltered case since the night-time radiative cooling is reduced. The start time of dew formation remains unchanged, which is to be expected because the sign of the net radiation remains unchanged and the start of dew formation begins after a negative net radiation. Only in the total wetness period was there a difference. In the presented simulation the wetness period for pure dew nights (no rain events) is longer, with a time difference ranging between 20 (top layer) and 40 min (bottom layer). For nights with rain events, the sheltered case also shows a longer wetness period, which ranges between 20 (top layer) and 50 min (bottom layer). It appears that wind sheltering has hardly any effect on the start time of the wetness period as well as on the total wetness period.

Under sheltered conditions, a more realistic night-time estimate for the net radiation is to assume that the sheltered canopy receives an extra amount of long wave radiation of, for example, 35 W m^{-2}. Next, it is assumed that all other assumptions remain the same as in the foregoing simulation. The results in this case are displayed in Figure 7. The impact on the amount of dew as well as on the starting wetness period and on the drying time is much larger. In this simulation, the starting wetness period for the sheltered case is somewhat delayed with a period ranging between 10 and 20 min for the pure dew events. The total wetness period during pure dew nights is always shorter for the sheltered case and it appears in this simulation that the shortening of the wetness period ranges between 20 (top layer) and 50 min (bottom layer). Thus, in this more realistic simulation, sheltering reduces the wetness period, which is opposite to the foregoing simulation. For rain events, however, the sheltered case shows a longer wetness period ranging between 20 (top layer) and 40 min (bottom layer). In particular, during daytime rain events, it must be expected that the unsheltered wet crop will dry faster since then the net radiation is higher. In general, it can be concluded that sheltering reduces the wetness period for pure dew events. In practice, this means that sheltering reduces the leaf wetness period. Consequently for practical applications, radiation sheltering reduces the infection risk of fungal spores, which require free water. Example are spores of fungal foliar pathogens such as *Phytophthora infestans* on potato and *Botrytis elleptica*

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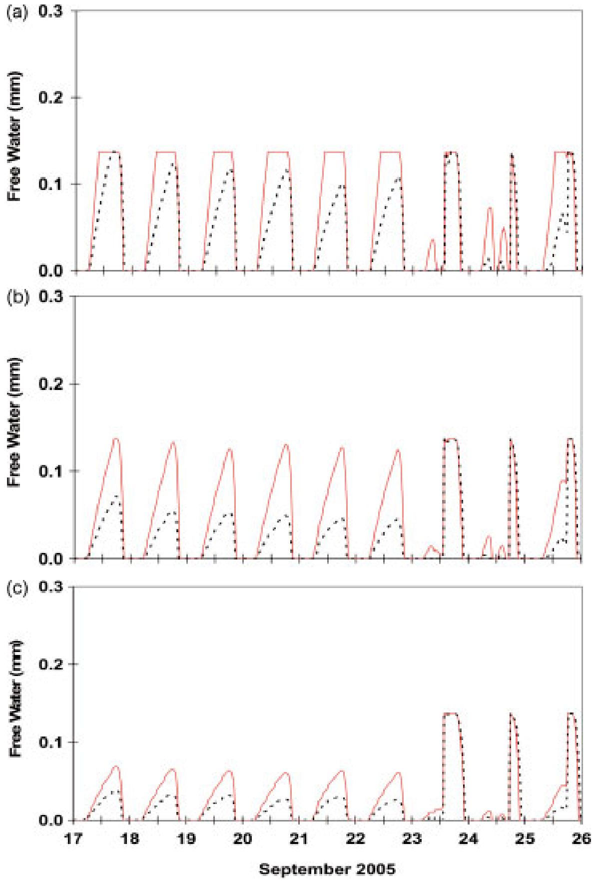

Figure 7. The course of the total accumulated free water amounts and the amounts *per* layer between 17 and 26 September 2005, for the top (a), centre (b) and bottom (c) layers calculated with the real net radiation above the crop and calculated with a reduced daytime net radiation of 30% and at night-time an extra incoming net radiation of 35 W m^{-2} from the shelters and an all day reduced wind speed at crop height of 50%. Solid line: sheltered crop, dotted line: unsheltered crop. This figure is available in colour online at www.interscience.wiley.com/ma

on lily. For rain events, particularly during daytime, the unsheltered crop shows the shortest wetness period.

It is found that wind sheltering has hardly any effect on the maximum dew amount as well as on leaf wetness duration. It must be noted, however, that wind reduction lowers the transport distance of spores to other nearby crop canopies and consequently reduces the influx of viable pathogen inoculum to these nearby canopies (Skelsey *et al*., 2008).

A lower radiative loss during night-time also affects the air temperature within the canopy crop. In the sheltered canopy the air temperature will be somewhat higher than in the unsheltered case. In the present simulation, the effect of air temperature differences has not been taken into account.

To obtain a better overview of the foregoing sensitivity study, the main results are contained in Table I. For the selected period, only days with no rain events have been displayed. The effect of reduction of the *LAI*, wind speed, U, and net radiation, Q^*, on the mean maximum amount of free water (*MFW*) and the mean leaf wetness

Table I. The effect of reduction of Leaf Area Index (LAI), wind speed (U) and net radiation (Q^*) on the mean maximum amount of free water (MFW) within the three canopy layers and the mean leaf wetness duration (LWD) between 17 and 26 September 2005. Only results without rain events are provided.

	ΔMFW (mm)	ΔLWD (min)
$\Delta LAI = -1$ ($LAI = 4 \rightarrow LAI = 3$)	−0.06 (top) −0.00 (centre) +0.01 (bottom)	≈0 (top) ≈0 (centre) +10 (bottom)
$\Delta Q^* = -30\%$ (daytime) $\Delta Q^* = +30\%$ (night-time) $\Delta U = -50\%$ (all day)	+0.02 (top) +0.06 (centre) +0.03 (bottom)	+20 (top) +30 (centre) +40 (bottom)
$\Delta Q^* = -30\%$ (daytime) $\Delta Q^* = +35$ W m^{-2} (night-time) $\Delta U = -50\%$ (all day)	−0.0 (top) −1.5 (centre) −2.0 (bottom)	−20 (top) −30 (centre) −40 (bottom)

duration (*LWD*) within the various layers of the canopy are indicated.

5. Conclusions

In this paper the leaf wetness duration and weather variables within and above a potato crop are quantified for a canopy located in the centre of the Netherlands about 4 km north of the River Rhine. Dew model calculations were compared to measured leaf wetness to better understand the physical mechanisms that control the exchange mechanism of water vapour to and from the plant canopy. The model distinguishes three leaf layers in the canopy (top, centre and bottom) and is extended with a precipitation interception module. The effect of inhomogeneity of some main weather variables and parameters on the leaf wetness period was assessed. The following conclusions can be drawn from the study;

1. The leaf wetness duration in all three leaf layers is well represented by the multi-layer model. The simulated wetness duration agrees with the measured wetness duration within 10 min (the data averaging time).
2. The agreement between model results and observations is valid for periods where dew is the only wetting process as well as for periods in which heavy precipitation events occurred.
3. The deeper the air layer within a crop canopy, the longer the wetness period.
4. The model results suggest that the leaf wetness period first begins at the top of the canopy and then penetrates into the crop canopy. The same sequence is found for the drying process within the canopy.
5. The leaf area index slightly affects the free water amount: in the top canopy the free water amounts tend to decline with decreasing *LAI*, while in the

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bottom layer the amount of free water tends to increase with decreasing *LAI*.

6. The start time of free water formation as well as the end time of the leaf wetness period is barely dependent on the leaf area index.
7. Net radiation measurements from a nearby observatory, in addition to a limited number of net radiation measurements above a crop, can be used for an accurate estimate of the above crop net radiation. Thus the net radiation measurements from a nearby observatory are very useful if no local measurements above the crop of interest are available.
8. Wind sheltering has hardly any impact on the start time of the wetness period as well as on the total wetness period. However, for practical use, wind sheltering reduces the chance of viable pathogen inoculum to other nearby crop canopies.
9. Radiation sheltering reduces the amount of free water in all crop layers and considerably reduces the leaf wetness period in all crop layers. Consequently for practical applications, radiation sheltering reduces the infection risk of fungal spores which require free water. Examples are spores of fungal foliar pathogens such as Phytophthora *infestans* on potato and *Botrytis elleptica* on lily.
10. Sheltering enhances leaf wetness duration during rain events, particularly during daytime.

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Appendix A. Derivation Dew Model

The dew part of the model used in the present study is an extension of the model presented earlier by Pedro and Gillespie (1982a, 1982b). The main difference is that Pedro and Gillespie's model was derived for the top layer of a crop, while our model can be applied to every layer within a canopy. If an arbitrary layer within a canopy is taken, the energy budget of that layer is:

$$\Delta Q_1^* + \Delta H_1 + \Delta\lambda_v E_1 = 0 \tag{A.1}$$

where ΔQ_1^* is the absorbed net radiation within this layer, ΔH_1 is the released sensible heat, and $\Delta\lambda_v E_1$ is the released evaporation within that layer. For simplicity the energy storage and metabolic energy terms within this layer have been neglected since most of the time these terms are relatively small (Jacobs and Nieveen, 1995).

The model assumes the net radiation, Q^*, available, either by measurement or by estimation for example as proposed by Pedro and Gillespie (1982a, 1982b). Within the canopy the net radiation flux is attenuated and it is assumed this extinction follows the relationship proposed by Lowry and Lowry (1989):

$$Q_1^*(L(z)) = Q^* e^{-(0.622L - 0.055L^2)} \tag{A.2}$$

where $L(z)$ is the integrated leaf area from the top, h, of the canopy to height, z, within the canopy. The absorbed net radiation, ΔQ_1^*, within the layer is:

$$\Delta Q_1^* = \Delta Q_1^*(L_t) - \Delta Q_1^*(L_b) \tag{A.3}$$

where L_t and L_b are the integrated leaf area from the top of the canopy to the top and the bottom of that layer, respectively.

The released sensible heat, ΔH_1, in the layer is simulated as:

$$\Delta H_1 = -2\alpha(T_1 - T_a)(L_b - L_t) \tag{A.4}$$

with T_1 the mean leaf temperature in that layer, T_a the mean ambient air temperature of that layer, and α is the convective heat transfer coefficient of a one-sided leaf in this layer. A factor 2 in Equation (A.4) 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 (Gates, 1980):

$$Nu = \frac{\alpha D}{\lambda} = 0.664 Pr^{0.333} Re^{0.5} \tag{A.5}$$

where D is a characteristic leaf diameter, λ is the molecular heat conductivity of still air, *Pr* is the Prandtl number and *Re* is the Reynolds number defined as (Gates, 1980):

$$Pr = \frac{\nu}{a} \text{ and } Re = \frac{UD}{\nu} \tag{A.6}$$

where U is mean wind speed, ν is the kinematic viscosity and a is the thermal diffusivity of air.

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

$$Nu = \frac{\alpha D}{\lambda} = 0.50 Gr^{0.25} \tag{A.7}$$

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

$$Gr = \frac{g\beta(T_1 - T_a)D^3}{\nu^2} \tag{A.8}$$

where g is gravity and β the coefficient of thermal expansion. For a gas, $\beta = 1/T_{abs}$ where T_{abs}, is the absolute air temperature. Forced convection is taken when $Gr < 0.1\ Re^2$ (Gates, 1980). In the present model distinction has been made between forced and free convection since under light wind conditions free convection can occur very frequently.

The released latent heat, ΔLE_l, in the layer is simulated as (Pedro and Gillespie, 1982a):

$$\Delta LE_l = -2\frac{0.622}{p}\rho\lambda_v\alpha'(e_{sl} - e_a)(L_b - L_t) \qquad (A.9)$$

where p is air pressure, ρ is density air, λ_v is latent heat of vapourization, α' is the convective mass exchange coefficient, e_{sl} is the saturated vapour pressure at leaf level and e_a is the vapour pressure of the ambient air. From similarity analogy between heat and mass it can be shown that (Gates, 1980):

$$\frac{\alpha}{\alpha'} = \left(\frac{a}{D_i}\right)^{0.667} = Le^{0.667} = 0.93 \qquad (A.10)$$

with D_i is molecular mass diffusivity and Le is the Lewis number.

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

$$U(L) = U_c \exp\left(-M\frac{L}{LAI}\right) \qquad (A.11)$$

where U_c 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 momentum depending on the canopy architecture. For most agricultural crops with planophile leaves, M has a value of about 0.3 (Goudriaan, 1977).

During the night, and around sunrise and sunset, the top of the canopy cools down due to radiative cooling at the top of the canopy. In addition, at the floor of the canopy there is a soil heat towards the canopy. Both processes cause a free convective layer within the canopy, which results in a within-canopy temperature profile that is more or less constant with height (Jacobs *et al.*, 1992, 1994). In the present study the air temperature at two heights within the canopy is measured and the within-canopy air temperature is simulated by a linear profile.

Combining Equations (A.1), (A.4) and (A.9), and using Penman's elimination procedure (Garratt, 1992) results in

$$e_{sl} - e_a = (e_{sa} - e_a) + s(T_l - T_a) \qquad (A.12)$$

where s is the slope of the saturation vapour pressure curve, and gives the temperature difference between leaf and ambient air, $\Delta T = T_l - T_a$, which equals the equation:

$$\Delta T = \frac{\Delta Q_l - 2\frac{0.622}{p}\alpha'(e_{sa} - e_a)(L_b - L_t)}{2\alpha(L_b - L_t) + 2s\frac{0.622}{p}\alpha(L_b - L_t)} \qquad (A.13)$$

Following Pedro and Gillespie (1982a), dew is accumulated when $e_a > e_{sl}$ and the amount of dew is calculated using Equation (A.9). The ending of dew occurs when all accumulated free water is evaporated.

Appendix B. Derivation Interception Model

The interception part of the model is a combination of the models of Rutter (1975), Mahfouf and Jacquemin (1989) and Norman and Cambell (1983). The free water budget within a crop canopy is (Rutter, 1975):

$$\frac{\partial W}{\partial t} = P_i - E_i - D \text{ if } 0 \le W \le W_{max} \qquad (B.1)$$

with W the interception reservoir, P_i the intercepted precipitation, E_i the evaporation of intercepted water, and D the drainage and dripping effect. W_{max} is the maximum possible interception and can be written as:

$$W_{max} = veg\ LAI\ h' \qquad (B.2)$$

with *LAI* the one-sided leaf area index, h' the maximum water density on leaves and *veg* the horizontal vegetation density. It must be noted that this maximum is also used in the maximum possible dew amount on the leaves. In the literature, the numerical value for h' ranges between 0.05 and 0.2 mm, depending on the leaf architecture. Because a potato crop tends to have an arched and a more or less planophile leaf architecture, a value of 1.5 mm was assumed in the present model (Rutter, 1975). For the horizontal density, *veg,* the following relation is assumed (Norman and Campbell, 1983):

$$veg = 1 - e^{-0.8LAI} \qquad (B.3)$$

The intercepted precipitation can be written (Mahfouf and Jacqumin, 1989):

$$P_i = P - T \qquad (B.4)$$

with P the above canopy precipitation and T the throughfall that follows the relation (Noilhan and Planton, 1989):

$$T = P\ e^{-0.5LAI} \qquad (B.5)$$

Corrections are carried out for drainage and dripping effects. Here we followed Rutter (1975) for the combined drainage and dripping by taking:

$$D = D_s e^{b(W - W_{max})} \qquad (B.6)$$

where D_s is the maximum drainage, taken as 1.67×10^{-5} (mm s^{-1}) in the present study, and b is a drainage constant taken as 3.7 mm^{-1} (Rutter, 1975). The evaporation of the free water caused by interception is worked out in the same way as for free water evaporation of the dew (see Equation (A.9)).

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After precipitation there will be a certain intercepted water distribution within the crop, depending on the type of precipitation (rain or shower) and the amount. During a light rain episode, most of the water is concentrated in the upper region of the canopy, and after a long rain episode the water is more or less equally distributed over all the leaves. In the present model, an equal interception has been assumed for all precipitation episodes.

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