Simulation of surface wetness with a water budget and energy balance approach

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Abstract

Surface wetness plays an important role in environmental studies. In particular, it is a major variable for plant disease prediction. Surface wetness is commonly measured with electronic sensors but simulation with a surface wetness model is an alternative. Recently, the increased use of interpolation procedures and atmospheric models to produce site-specific weather products has created a greater need for reliable surface wetness models. However, surface wetness models have not been widely used operationally because they are often highly complex, do not simulate both dews and rain or do not adapt well to a new spatial scale or crop. Other models estimate surface wetness in units that are cumbersome to observe in the field. In addition, few models have been calibrated to observed surface wetness over a wide range of atmospheric variables and plant leaf properties under controlled environmental conditions. The objective of this study was to develop a surface wetness model that would be appropriate for operational use in site-specific weather products for grapes. For this purpose, we developed the surface wetness energy balance (SWEB) model based on a ‘big leaf’. The SWEB model consists of four sub-modules describing: (i) surface water distribution based on an observed wet fraction; (ii) canopy water budget; (iii) energy balance module based on a combination equation developed by Tanner and Fuchs; (iv) a transfer function based on Bird et al.’s generic transfer coefficient that was previously calibrated to surface wetness under controlled conditions. The SWEB model can be adapted to the physical characteristics of a particular crop by adjusting four plant parameters: leaf area index (LAI), maximum fraction of canopy allowed as wet surface area ($W_{\text{max}}$), crop height and maximum water storage. The SWEB model is most sensitive to LAI and $W_{\text{max}}$. The SWEB model is close to the required criteria for a suitable surface wetness model including simplicity, utility, scalability, easily observable output units and in addition, it has been calibrated under controlled conditions. The SWEB model was validated in a vineyard and in a companion study, compared to a widely used sensor. The overall objective of these studies was to develop a theoretical standard for surface wetness measurement.

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1. Introduction

In the past, many site-specific applications that require agricultural weather data have relied upon an on-site automated weather station. However, there are considerable costs, including user’s time associated with purchasing, maintaining, downloading and processing data from these stations (Magarey et al., 2001). More recently,
several meteorological companies have been offering site-specific weather products created from interpolation procedures or from high-resolution atmospheric models (Russo, 2000). This new method of supplying users with weather data has caused us to look afresh at surface wetness.

Surface wetness is important for many agricultural and environmental applications including plant disease management, the deposition of atmospheric pollutants and the survival of some arthropods (Weiss, 1990). Since surface wetness influences fungal infection and sporulation, it is important for plant disease forecasting (Huber and Gillespie, 1992). Surface wetness is commonly measured with electronic sensors (Sutton et al., 1984) but an on-site automated weather station is required. In addition, sensors measure surface wetness indirectly and there has been no accepted measurement standard (Anonymous, 1990). Sensors often have poorly defined accuracy and precision, and because of different measurement protocols, data may require additional interpretation (Magarey et al., 2005b). Consequently, surface wetness data for agricultural applications is often lacking in either quality or quantity and an alternative to measurement is desirable.

The simulation of surface wetness is an accepted alternative to measurement (Pedro and Gillespie, 1982; Huber and Gillespie, 1992; Hoppmann and Wittich, 1997). One literature review listed at least 16 models capable of simulating surface wetness (Huber and Gillespie, 1992) and others have been developed since then. Although many models have been developed, relatively few are used operationally and most surface wetness data is obtained from measurements (Magarey et al., 2005b). Many reasons can be given for the failure of surface wetness models including a user bias in favor of measurement, the absence of canopy scale input data, the absence of a standard method or model for surface wetness simulation, and the failure of national or international agencies to adopt the simulation approach. It is also possible to identify reasons more directly related to model design. We believe that surface wetness models have not been widely accepted because few or no models fulfill six basic criteria for adoption. These criteria are simplicity, utility, easily scalable, easily observable output units, ease of adaptation to other crops or sites, and calibration under controlled conditions. In this study, we used these criteria to guide the development of a surface wetness model designed for grapes.

The model we developed, the surface wetness energy balance (SWEB) model, is based on the combination formula developed by Tanner and Fuchs (1968) and uses a simple transfer coefficient (Bird et al., 1960). Appropriate values of the transfer coefficient that describe the drying of drops and films were identified under controlled conditions for a range of atmospheric variables and plant properties (Magarey et al., 2005a). The SWEB model can be adapted to the physical characteristics of a particular crop or cultivar by adjusting four plant parameters: leaf area index (LAI), maximum fraction of canopy allowed as wet surface area (Wmax), crop height (Zmax) and maximum water storage per unit area (Coi). In this study, the theoretical basis for SWEB is described. Simulations of surface wetness duration were made to determine the sensitivity of the model to the four input plant parameters. Finally, we discuss the rationale for each of the six criteria and evaluate the success of SWEB in fulfilling these criteria. Validation of SWEB in a vineyard has been examined in other studies (Magarey et al., unpublished data; Seem et al., 2000; Dalla Marta et al., 2005).

2. Theory

2.1. Model overview

In its simplest terms, the SWEB model is a canopy water budget. Our research project focused on grapes, which are a suitable choice for several reasons. Grapes are a widely cultivated and high value horticultural crop. Surface wetness data are required for forecasting several important grape diseases including Plasmopara viticola (downy mildew) and Phomopsis (Pearson and Goheen, 1988). Consequently, automated weather stations and sensors are commonly deployed in grape canopies.

Three assumptions are made in constructing the model. Since our research program focused only on grapes, the assumptions are directed at a grape canopy. The first assumption considers the grape canopy as one big leaf at the average height of the crop. The big leaf model is the simplest approach, whereas a multilayer approach would require serious modification each time it is moved to a new crop type. A multilayer model may have a slight advantage over a big leaf model for estimation of evaporation (Greenspan and Matthews, 1996) but this improvement is probably mostly due to the inclusion of the soil energy budget (Heilman et al., 1994). However, the SWEB model may also be scaled to also represent a layer in the crop canopy by adjusting the input parameters, with the exception that it cannot represent sunlit portions of the canopy due to the third assumption (below). Second, we assume that the inputs to the model are temperature and relative humidity at canopy height, precipitation and wind speed collected.
above the canopy and the net radiative flux for the canopy. Third, net radiation is only used to calculate condensation during the night and is ignored by the model during the day. Leaves or grape clusters inside the canopy are the slowest to dry and therefore the most important to plant disease studies. This last assumption is based upon the fact that the first sunlit leaf layer in a grape canopy absorbs 94% of the incoming solar radiation (Smart and Robinson, 1991). Since net radiation is included during the night, the model can also simulate longer wetness durations caused by dew at the top of canopies.

The SWEB model is composed of four modules: (i) surface water distribution; (ii) canopy water budget; (iii) energy balance module; (iv) transfer coefficient calibrated to surface wetness. The model calculation sequence (Table 1) and the definitions of the most important model inputs, variables and constants (Table 2) are also given.

2.2. Water distribution module

The surface wetness (SW) is estimated from the index of the fraction of canopy wet surface area, \( W_{\text{ind}} \), during a given time interval as shown in Eqs. (1) and (2):

\[
SW = \begin{cases} 
1, & \text{for } W_{\text{ind}} > W_{\text{th}} \\
0, & \text{for } W_{\text{ind}} < W_{\text{th}}
\end{cases}
\]  

(1)

\[
SW = \begin{cases} 
1, & \text{for } W_{\text{ind}} > W_{\text{th}} \\
0, & \text{for } W_{\text{ind}} < W_{\text{th}}
\end{cases}
\]  

(2)

where \( SW = \) surface wetness, \( W_{\text{ind}} = \) index of fraction of canopy wet surface area, and \( W_{\text{th}} = \) surface wetness threshold.

Since small traces of water may persist in the canopy for extended periods, it is useful to include a surface wetness threshold, \( W_{\text{th}} \), below which the canopy is considered to be dry. In our studies, a value of 0.1 of leaves or other plant units was chosen to represent this threshold.

The index of the fraction of canopy wet surface area, \( W_{\text{ind}} \), is estimated from: (i) the relative volume of water stored in the canopy and (ii) the change in surface area to volume ratio during drying. Wet surface area decreases in a non-linear fashion as the water stored in a canopy decreases due to the volume-to-area argument. That is, the water volume changes as a cubic power, while the wet area changes as a square (Deardorff, 1978). These relationships are shown in Eq. (3) below:

\[
W_{\text{ind}} = \left( \frac{S}{C} \right)^{0.67}
\]  

(3)

where \( S = \) canopy water storage (cm) and \( C = \) maximum canopy water storage (cm).

Although \( W_{\text{ind}} \) is useful to describe canopy wetness, it is necessary to know the actual fraction of canopy wet surface area, \( W \), for estimating the water budget and

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### Table 1

Calculation steps in the SWEB model

<table>
<thead>
<tr>
<th>Order</th>
<th>Equation</th>
<th>Calculation</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(6)</td>
<td>Max water storage (C)</td>
<td>LAI, C</td>
</tr>
<tr>
<td>2</td>
<td>(5)</td>
<td>Max wet area (W_{\text{max}})</td>
<td>W_{\text{d}}, W_{\text{f}}, p</td>
</tr>
<tr>
<td>3</td>
<td>(8)</td>
<td>Interception (I)</td>
<td>LAI, P</td>
</tr>
<tr>
<td>4</td>
<td>(12)</td>
<td>Potential condensation (D_{p})</td>
<td>R_{nc}, T_{c}</td>
</tr>
<tr>
<td>5</td>
<td>(7)</td>
<td>Initial canopy water budget (S_{i})</td>
<td>C, I, D_{pr}, S_{r-1}</td>
</tr>
<tr>
<td>6</td>
<td>(3) and (4)</td>
<td>Wet area (W_{\text{ind}} - W)</td>
<td>S_{i}, C, W_{max}</td>
</tr>
<tr>
<td>7</td>
<td>(15)</td>
<td>Canopy wind speed (U_{c})</td>
<td>U_{Z}, Z_{c}</td>
</tr>
<tr>
<td>8</td>
<td>(13) and (14)</td>
<td>Transfer (h, c)</td>
<td>U_{c}, W_{c}, c_{t}, c_{l}</td>
</tr>
<tr>
<td>9</td>
<td>(10) and (11)</td>
<td>Evaporation (E)</td>
<td>T_{c}, RH_{c}, h, W</td>
</tr>
<tr>
<td>10</td>
<td>(7)</td>
<td>Canopy water budget (S)</td>
<td>S_{i}, E, C</td>
</tr>
<tr>
<td>11</td>
<td>(3)</td>
<td>Canopy wet surface area</td>
<td>S, C</td>
</tr>
<tr>
<td>12</td>
<td>(1) and (2)</td>
<td>Surface wetness (SW)</td>
<td>W_{\text{ind}}, W_{\text{th}}</td>
</tr>
</tbody>
</table>

### Table 2

Main inputs, variables and constants used in the SWEB model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Variable/constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Max water storage. C (cm)</td>
</tr>
<tr>
<td>C_{i}</td>
<td>Max water storage per leaf area (cm)</td>
</tr>
<tr>
<td>c</td>
<td>Shape scale variable (cm^{0.5} min^{-0.5})</td>
</tr>
<tr>
<td>c_{a}</td>
<td>Shape scale constant for drops (cm^{0.5} min^{-0.5})</td>
</tr>
<tr>
<td>c_{t}</td>
<td>Shape scale constant for film (cm^{0.5} min^{-0.5})</td>
</tr>
<tr>
<td>D_{p}</td>
<td>Potential condensation (cm min^{-1})</td>
</tr>
<tr>
<td>E</td>
<td>Evaporation (cm min^{-1})</td>
</tr>
<tr>
<td>h</td>
<td>Transfer coefficient (cm min^{-1})</td>
</tr>
<tr>
<td>I</td>
<td>Interception (cm)</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf area index</td>
</tr>
<tr>
<td>P</td>
<td>Precipitation (cm)</td>
</tr>
<tr>
<td>p</td>
<td>Fraction of wettable leaves to total leaves in canopy</td>
</tr>
<tr>
<td>RH_{c}</td>
<td>Canopy relative humidity (%)</td>
</tr>
<tr>
<td>R_{nc}</td>
<td>Canopy net radiant flux (J min^{-1} cm^{-2})</td>
</tr>
<tr>
<td>S</td>
<td>Canopy water budget (cm)</td>
</tr>
<tr>
<td>S_{i}</td>
<td>Initial canopy water budget (cm)</td>
</tr>
<tr>
<td>SW</td>
<td>Surface wetness</td>
</tr>
<tr>
<td>T_{c}</td>
<td>Canopy air temperature (°C)</td>
</tr>
<tr>
<td>U_{c}</td>
<td>Canopy wind speed (cm min^{-1})</td>
</tr>
<tr>
<td>U_{Z}</td>
<td>Wind speed at reference height (cm min^{-1})</td>
</tr>
<tr>
<td>W</td>
<td>Actual fraction of wet area to total canopy surface area</td>
</tr>
<tr>
<td>W_{d}</td>
<td>Average fraction of wet area to total area of non-wettable leaves</td>
</tr>
<tr>
<td>W_{f}</td>
<td>Average fraction of wet area to total area of wettable leaves</td>
</tr>
<tr>
<td>W_{\text{ind}}</td>
<td>Index of fraction of canopy wet surface area</td>
</tr>
<tr>
<td>W_{\text{th}}</td>
<td>Wetness threshold</td>
</tr>
<tr>
<td>Z_{c}</td>
<td>Height of canopy (cm)</td>
</tr>
</tbody>
</table>
evaporation. In SWEB, we assume that \( W \) is dependant on \( W_{\text{ind}} \) and a factor that accounts for the relative wettability of the leaf:

\[
W = W_{\text{ind}} \times W_{\text{max}}
\]  

(4)

where \( W \) = actual fraction of wet area to total canopy surface area, \( W_{\text{max}} \) = maximum fraction of canopy allowed as wet surface area.

The factor \( W_{\text{max}} \) is assumed to be the same for both dew and rain. Although a dew may initially wet the entire leaf surface, individual microdrops usually coalesce into relatively larger drops. The factor \( W_{\text{max}} \) could be estimated by quantitative techniques, but we also suggest a simple method for approximation. When a leaf surface is wettable, it favors water distribution as a film. When a leaf surface is non-wettable, it favors water distribution as drops. A simple technique for determining \( W_{\text{max}} \) in terms of leaf wettability is to partition the canopy leaf area into wettable and non-wettable fractions and then assign a proportion of maximum wet area to each fraction:

\[
W_{\text{max}} = pW_t + (1 - p)W_d
\]  

(5)

where \( p \) = fraction of wettable leaves to total leaves in canopy, \( W_t \) = average fraction of wet area to total area of wettable leaves, \( (1 - p) \) = fraction of non-wettable leaves to total leaves in canopy, and \( W_d \) = average fraction of wet area to total area of non-wettable leaves.

The proportion of wettable and non-wettable leaves could be based on observed or estimated leaf age. Values of \( W_d \) and \( W_t \) could be determined by selecting representative wettable and non-wettable leaves and determining the fraction of wet surface area in the laboratory after simulated rain or dew. In our studies, we used a value of 0.5 for \( W_{\text{max}} \) since tests in the lab showed immature grape leaves are highly wettable and mature leaves are non-wettable.

2.3. Canopy water budget

In the construction of the canopy water budget, the maximum water storage is computed by multiplying the leaf area index (LAI) and the maximum water storage for a single leaf \( (C_1) \) having average properties of all leaves. This calculation is

\[
C = \text{LAI} \times C_1
\]  

(6)

where \( C \) = maximum water storage for a canopy (cm), LAI = leaf area index, and \( C_1 \) = maximum water storage for an average leaf (cm).

The LAI for a grape canopy can be either measured (Grantz and Williams, 1993) or estimated from a crop model. The maximum water storage for a leaf, \( C_p \), is a function of age and species (Hall et al., 1997), however, a commonly accepted value for \( C_1 \) is 0.02 cm (Noilhan and Planton, 1989).

With the maximum fraction of canopy allowed as wet surface area and maximum water storage determined for a canopy, the water budget can be computed in terms of intercepted precipitation, condensation and evaporation from a vegetative surface. The canopy water budget is

\[
S = (I + D_p - E), \text{ for } 0 < S < C
\]  

(7)

where \( S \) = water storage (cm), \( I \) = intercepted rain (cm), \( D_p \) = potential condensation of dew (cm), and \( E \) = evaporation (cm).

The canopy water budget changes over time. In the model time steps, interception and condensation add to the water budget. If the balance is positive then evaporation may subtract from the budget. The equation for the interception of precipitation, which is assumed to be rain, was derived from the work of Norman and Campbell (1983):

\[
I = (1 - \exp(-0.5\text{LAI}))P
\]  

(8)

where LAI = leaf area index and \( P \) = precipitation as rain (cm).

There are a large number of interception models in the literature (Huber and Gillespie, 1992). Many of these models are complex and rely on empirical drainage parameters that may change with canopy size and type. In comparison, the formulation of Norman and Campbell is simple; its only inputs are precipitation and leaf area index (LAI).

2.4. Energy balance module

The condensation and evaporation processes in the canopy water budget are based on a combination formulation developed by Tanner and Fuchs (1968) for evaporation and condensation from unsaturated surfaces:

\[
E_p = \frac{\Delta}{\lambda(\Delta + \delta)} \left\{ R_n + \rho C_p \left( \frac{h}{\Delta} (e_a' - e_a) \right) \right\}
\]  

(9)

where \( E_p \) = potential latent heat flux density (evaporation) (cm min\(^{-1}\)), \( \Delta \) = slope of the saturation vapor pressure curve (mbar C\(^{-1}\)), \( \lambda \) = latent heat of vaporization (J g\(^{-1}\)), \( \delta \) = psychrometric constant (mbar C\(^{-1}\)), \( R_n \) = net radiant flux density (J min\(^{-1}\) cm\(^{-2}\)), \( \rho \) = density of air (g cm\(^{-3}\)), \( C_p \) = specific heat of air (J g\(^{-1}\) C\(^{-1}\)), \( h \) = transfer coefficient for heat and vapor
from the surface to the atmosphere (cm min\(^{-1}\)), \(e_a\) = water vapor pressure of the atmosphere (mbar), and \(e_a^*\) = saturated water vapor pressure of the atmosphere (mbar).

According to the original assumptions of the model, daytime net radiation is assumed not to contribute to evaporation in a shaded grape canopy. Consequently, evaporation is calculated solely from the aerodynamic term of Eq. (9):

\[
E_p = \frac{\Delta}{\lambda(\Delta + \delta)} \left\{ \rho C_p \left( \frac{h}{\Delta} \right) (e_a^* - e_a) \right\}
\]

Eq. (10) represents a potential volume of water loss from a wet surface area. In order to compute the actual total moisture lost from the entire canopy, the evaporation, \(E\) must be multiplied by the actual fraction of canopy wet surface area, \(W\). This expression is represented as

\[
E = E_p W
\]

In addition to evaporation, at night the contribution of condensation must also be considered. Since the aerodynamic term cannot be negative, only the net radiation term makes a contribution to the potential condensation of dew, \(D_p\):

\[
D_p = \frac{\Delta}{\lambda(\Delta + \delta)} 0.5R_{nc}
\]

where \(D_p\) = the potential condensation of dew (cm min\(^{-1}\)) and \(R_{nc}\) = canopy net radiant flux density (J min\(^{-1}\) cm\(^{-2}\)).

The radiant flux at the average height of the canopy is assumed to be 50% of the total canopy flux. This is based upon the original assumption of the model that SWEB represents the canopy as a big leaf at the average height of the canopy. In summary, the energy and water balance is calculated from the aerodynamic term (Eqs. (10) and (11)) during the day and at night from both aerodynamic term and the potential condensation.

2.5. Transfer coefficient calibrated to surface wetness

The transfer coefficient in Eqs. (9) and (10), \(h\), was based on a generic transfer coefficient that accounted for the influence of wind speed and an object’s shape and size by Bird et al. (1960; Magarey et al., 2005a). The formulation is

\[
h = cU_c^{0.5}
\]

where \(h\) = transfer coefficient (cm min\(^{-1}\)), \(c\) = shape scale constant of an object (cm\(^{0.5}\) min\(^{-0.5}\)), and \(U_c\) = canopy wind speed (cm min\(^{-1}\)).

In the present study, the shape scale constant, \(c\), becomes a variable in the SWEB model. As a leaf surface becomes wetter, the moisture transfer increasingly behaves as if the water shape is a film. Conversely, as a leaf surface becomes drier, the moisture transfer behaves as if the water shape is a drop. To account for this change in behavior due to water shape, the shape scale variable, \(c\), is weighted between constants for drops, \(c_d\) and film, \(c_f\) according to the fraction of the leaf surface that is wet:

\[
c = Wc_f + (1 - W)c_d
\]

where \(c\) = shape scale variable (cm\(^{0.5}\) min\(^{-0.5}\)), \(W\) = actual fraction of canopy wet surface area in previous time step, \(c_f\) = shape scale constant for film (cm\(^{0.5}\) min\(^{-0.5}\)), and \(c_d\) = shape scale constant for drops (cm\(^{0.5}\) min\(^{-0.5}\)).

The values of \(c_d\) and \(c_f\) were determined from controlled laboratory tests of the drying of drops and films on an artificial leaf surface representing a typical hydrophobic leaf surface to be 8.7 and 2.0, respectively (Magarey et al., 2005a).

The canopy wind speed, \(U_c\) is affected by the height and density of a canopy. The canopy wind speed is computed from the logarithmic wind profile equation (Monteith and Unsworth, 1990) and an analytical wind speed profile (Landsberg and James, 1971). The equation is

\[
U_c = U_Z \left( \frac{\ln[(Z_c - D_Z)/Z_0]}{\ln[(Z - D_Z)/Z_0]} \right) \left[ 1 + \alpha \left( \frac{1 - Z_c}{Z} \right) \right]^{-2}
\]

where \(U_c\) = wind speed at average height of the canopy (cm min\(^{-1}\)), \(Z_c\) = height of canopy (cm), \(U_Z\) = wind speed (cm min\(^{-1}\)), at reference height, \(Z\), \(D_Z\) = zero plane displacement (assumed to be 2/3\(Z_c\)) (cm), \(Z_0\) = roughness length (assumed to be 1/10\(Z_c\)) (cm), \(Z\) = reference height (cm), and \(\alpha\) = 1.3.

The shape of the wind speed profile is dependent upon whether the wind is blowing parallel or perpendicular to the direction of the vine rows (Heilman et al., 1994), so an intermediate value of \(\alpha\) was chosen. The value of is also dependent upon crop type.

3. Sensitivity to input plant parameters

The SWEB model can be adapted to the physical characteristics of a particular crop or cultivar by adjusting
four plant parameters: leaf area index (LAI); maximum fraction of canopy allowed as wet surface area ($W_{\text{max}}$); crop height ($Z_{c}$); maximum water storage per unit area ($C_{l}$). A simulation study was done to determine the influence of the four plant parameters on the surface wetness duration. The model was run in 10 min time steps. The simulation was setup under the following environmental conditions: canopy air temperature ($T_{c}$) of 20 °C, canopy relative humidity (RH$_c$) of 75%; reference height wind speed ($U_{Z}$) of 1.5 m s$^{-1}$, with an initial rainfall of 2 mm in the first 10 min, after which no rain fell. Net radiation was set to zero, since net radiation does not contribute to evaporation. The surface wetness threshold, $W_{th}$ was set as 0.1.

The leaf area index and the maximum wet area had the greatest influence on surface wetness duration. Leaf area index was varied between 1 and 4 resulting in a change in the surface wetness duration between 130 and 650 min (Fig. 1A). The maximum wet surface area was varied between 0.2 and 1 resulting in a change in surface wetness duration between 670 and 110 min (Fig. 1B). At typical plant heights for grapevines (approximately 0.5 and 2 m), there was relatively little response to $Z_{c}$ (Fig. 1C). The response to the maximum water storage per unit leaf area, $C_{l}$, was relatively flat with the exception of values of $C_{l}$ less than 0.01 (Fig. 1D). One published study on grapes found that $C_{l}$ was 0.018 (Hoppmann and Wittich, 1997), our preliminary lab studies showed that a value of 0.02 was appropriate for grapes (Magarey, unpublished data).

4. Model validation

The SWEB model was validated with visual observations of surface wetness duration at 3-year-site combinations, two in Geneva, NY and one in Adelaide, Australia (Magarey et al., 2006). The validation at each site included visual observations of surface wetness of at least 4 h or more (2 h at the Australian site) during 14 dew, near-dew or rain periods. Wetness was observed visually by assessing the presence or absence of surface water on 15 tagged leaves on each of 3 vines. Three leaves were taken from each of five canopy positions corresponding to top, middle left side (north), middle right side (south), middle and bottom of the canopy (Magarey et al., 2006). In New York,

![Fig. 1. Influence of plant input parameters on simulated surface wetness duration: (A) leaf area index; (B) maximum fraction of canopy allowed as wet surface area, $W_{\text{max}}$; (C) crop height, $Z_{c}$ (m); (D) maximum water storage per unit surface area, $C_{l}$.](image-url)
a relatively humid site (mean wetness duration 5–6 h), the mean absolute error (MAE) of the model varied from 1.5 to 1.8 h (Table 3). The Australian site was relatively dry (mean wetness 1.2 h), the MAE of the model was 0.9 h. In the companion paper, the limitations of current validation techniques are discussed and the SWEB model is compared to a widely used electronic sensor (Magarey et al., 2002).

### 5. Discussion

The six criteria for a successful operation surface wetness model were developed from the perceived limitations associated with many current models. The rationale for these criteria will now be discussed and the success of the SWEB model in fulfilling these criteria.

The first criterion is simplicity. Many surface wetness models are quite complex, with many canopy parameters (Huber and Itier, 1990) or with complex drop geometries (Leclerc et al., 1985; Zhang and Gillespie, 1990). Complexity may retard the adoption of models by users (Magarey et al., 2001; Madeira et al., 2002; Papastamati et al., 2004) and may prohibit their operational use if processing times are too great (Magarey et al., 2002). One strength of the SWEB model is its moderate simplicity. It has neither the complex geometries found in many drop models (Leclerc et al., 1985) nor the complexity of a multilayer canopy scale model (Huber and Itier, 1990; Norman and Campbell, 1983).

The model should also have relatively simple inputs. One difficulty with SWEB and many other simulation models is that net radiation is not a commonly measured variable. Although there are simple techniques for its estimation, uncertainties of 5% or more may be expected (Oke, 1987). Commercial weather companies are now producing site-specific simulated observations or forecasts, which can produce weather data for remote sites (Russo, 2000; Magarey et al., 2001), including longwave radiation from which net radiation can be calculated.

The second criterion is utility (Papastamati et al., 2004). Unfortunately, some surface wetness models simulate dew and do not consider rain (Pedro and Gillespie, 1982) and vice versa (Barr and Gillespie, 1987). Wetness periods from rain may result in large drops of water on many crop plants whereas dews begin as a film that may coalesce into drops. The simple, water storage function of SWEB enables the models to simulate both dews and rain events.

Third, models should be easily scalable. Surface wetness models have been constructed at three spatial scales: drop, leaf and canopy scale (Huber and Gillespie, 1992). For example, models constructed at the leaf and drop scale may be hard to use at the canopy or field scale or vice versa. Drop models must be scaled either by following a population of drops (Brain and Butler, 1985) or by compromising and only following the largest population of drop sizes (Bass et al., 1991). Likewise, it may be difficult to adapt a complex multilayer canopy model to the scale of a leaf or fruit. In contrast, the relatively simple design of SWEB would make the adaptation to a new spatial scale relatively easy.

The fourth criterion concerns the choice of surface wetness simulation units. Many surface wetness models do not use units that are easily observed and quantifiable in the field. For example, most drop models use a remaining drop volume (Zhang and Gillespie, 1990) or drop number (Brain and Butler, 1985). A frequently referenced dew simulation model uses latent energy as the output units (Pedro and Gillespie, 1982), while other dew models use film thickness (Monteith and Butler, 1979). These types of units require tedious counting of drops, exact weighing or specialized equipment for field verification. Another option for simulated output is the fraction of canopy wet surface area, \( W \) which is used in many canopy or large scale simulation models (Huber and Itier, 1990; Deardorff, 1978). However, since the actual wet area cannot be easily measured it is more practical to use \( W_{\text{ind}} \) which is the index of the fraction of the maximum wet area \( W_{\text{max}} \). For field validation, it would be convenient to compare simulated values of \( W_{\text{ind}} \) with an observed value, which is easily estimated by sampling the presence or absence of moisture on leaves or other plant parts.

The fifth criterion is the ease of adaptation to a new site or crop. Although many of the statistical models for surface wetness can achieve good predictions for a given site or region, they can be difficult to adapt to new sites (Crowe et al., 1978; Francl and Panigrahi, 1997). For this reason the physical approach based on a water budget is to be preferred. The SWEB model can be

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean</th>
<th>Mean error</th>
<th>Mean absolute error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geneva, NY, 1997</td>
<td>6.3</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Geneva, NY, 1998</td>
<td>5.5</td>
<td>−0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Adelaide, Australia</td>
<td>1.2</td>
<td>0.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

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adapted to the physical characteristics of a particular crop by adjusting four plant parameters: crop height, LAI, maximum water storage per unit area $C_l$, and maximum fraction of canopy allowed as wet surface area, $W_{\text{max}}$. Crop height and LAI can be easily measured or their values can be estimated from a crop simulation model. Since $C$ is mostly dependent on LAI (Eq. (5)), larger canopies have greater surface wetness duration (Mahfouf and Jacquemin, 1989). The SWEB model is relatively insensitive to $C_l$, but if required, it can be easily determined in the lab (Barfield et al., 1973).

Attention should also be paid to fruit and other plant organs that may differ in water storage capacity from leaves (Huber and Gillespie, 1992).

Unfortunately, selection of an appropriate value of $W_{\text{max}}$ is more problematic. It is known that leaf wettability can make a difference of up to 8 h in drying time (Huber, 1988). The leaves of some species may have values of $W_{\text{max}}$ as low as 0.06–0.2 (Brain and Butler, 1985; Norman and Campbell, 1983) while other species may hold water like a film. However, a value of 0.5 for $W_{\text{max}}$ may be a good general approximation since immature leaves are highly wettable and mature leaves are often non-wettable (Hall et al., 1997). Another consideration is that biologically significant values of $W_{\text{th}}$ have not been defined. Another consideration is that the value of $W_{\text{max}}$ may differ for dew and rain.

Apart from input parameters, the formulation of SWEB may require modification for some crops. The soil may act as an important reservoir of moisture for row or field crops (Wilson et al., 1999). The need for a more complex interception formulation is probably not necessary for most crop types. The interception equation (Eq. (8)), shows that for a canopy with a LAI of 1.0, even a light rain of 0.5 mm will almost saturate the canopy. However, in dense multilayered canopies the distribution of intercepted water does influence surface wetness estimation (Sellers and Lockwood, 1981; Mahfouf and Jacquemin, 1989; Watanabe and Mizutani, 1996).

The sixth and final criterion is calibration under controlled conditions. Unfortunately, the field-testing of models is labor intensive and most models are validated for only a few sites. For this reason, models should be treated as a sensor and tested under controlled conditions before introduction in the field. Although controlled experiments are not a substitute for field-testing, they help determine the model’s performance over a wide range of atmospheric conditions and with diverse plant physical properties. The SWEB model will be validated in a grape canopy in a companion study (Magarey et al., 2006). Validation of a preliminary version of the model has been published elsewhere (Seem et al., 2000).

The modelling approach may also eventually make an important contribution to standardization. A theoretical standard offers many advantages including ease of dissemination and ability to use historical or forecast weather data. We propose, SWEB as one possible candidate for a theoretical standard, other candidates include the Hoppmann model (Hoppmann and Wittich, 1997) and the combination drop and dew model approach from the Gillespie team (Bass et al., 1991). We believe the next developmental step is to compare the candidate models with sensors and visual observations over a range of crop types and climates. Such a project would require the cooperation of many researchers and institutions. For this purpose, the SWEB model is available on request from the first author.

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References


