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A three-source SVAT modeling of evaporation: Application to the seasonal dynamics of a grassed vineyard

Carlo Montes[a,*], Jean-Paul Lhomme[a], Jérôme Demarty[b], Laurent Prévot[c], Frédéric Jacob[a]

[a] Institut de Recherche pour le Développement, UMR LISAH, 34060 Montpellier, France
[b] Institut de Recherche pour le Développement, UMR HSM, 34095 Montpellier, France
[c] Institut National de la Recherche Agronomique, UMR LISAH, 34060 Montpellier, France

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ABSTRACT

A parsimonious and versatile Soil–Vegetation–Atmosphere Transfer (SVAT) model is proposed for three component vineyards, which includes vine foliage, grassed soil and bare soil. A three-source energy balance approach describes the energy and mass transfer between the soil–plant continuum and the lower atmosphere with an hourly time step. It is coupled with a soil water balance module running with a daily time step. The model makes use of standard meteorological data together with parameters describing foliage development, grass and soil characteristics. The model is calibrated by means of the Multi-objective Calibration Iterative Process (MCIP) algorithm and next validated for evaporation and soil moisture over a dataset collected in a Southern France grassed vineyard. The validation exercise is twofold. It focuses first on the daily course of evaporation derived from the surface energy balance module only, forced with meteorological variables, net radiation and soil moisture. The comparison against Eddy Covariance measurements shows a good agreement ($R^2 = 0.96$ and RMSE = 14.0 W m^{-2}). Next, a simulation coupling the surface energy balance module with the soil water balance module is validated over Eddy Covariance and soil moisture measurements. Simulations throughout two contrasting growing seasons provide good estimates of daily evaporation ($R^2 = 0.90$ and RMSE = 0.43 mm d^{-1}) and soil water content ($R^2 = 0.98$ and RMSE = 6.95 mm). Model inaccuracies arise mainly under conditions of strong surface runoff. Results also suggest that the parameterizations relating the surface-atmosphere module with the soil module (i.e. stomatal resistance) should be carefully examined under water stress conditions. Finally, the model versatility is addressed through a set of simulations. It appears that the modeling approach allows assessing the seasonal water balance of vineyards with different structure (grass fraction or distance between rows) and that it could be applied to similar cropping systems.

1. Introduction

Progress in theoretical and applied research aiming at accurately assessing crop water consumption in both rain-fed and irrigated conditions is an essential issue for agricultural water management. Since evaporation measurements are scarce, operational formulations to estimate water consumption at field scale are necessary (Trambouze et al., 1998; Spano et al., 2009). For viticulture regions in Mediterranean and semi-arid environments, actual evaporation represents a major component of surface water balance, reaching up to 70% of the yearly precipitation (Moussa et al., 2007). Knowledge of actual evaporation is also of interest in viticulture, in order to assess and handle the influence of soil water deficit on grapevine yields and berry composition (Vaudour, 2003; Pellegrino et al., 2005). Nevertheless, the physical representation of the soil–plant–atmosphere system in grapevines is a complex issue, because the sparse structure of vineyards imposes to consider both the foliage and the understory, which requires multi-source modeling.

The most frequently used multi-source evaporation model is the one first developed by Shuttleworth and Wallace (1985) (S–W model) and extended by Choudhury and Monteith (1988) and Shuttleworth and Gurney (1990). This model corresponds to an extension of the big-leaf model of Penman–Monteith (Monteith, 1965) into two interacting evaporative layers: the main foliage and the underlying substrate. Subsequently, the S–W model was upgraded by Brenner and Incoll (1997) ("clumped" model) to

* Corresponding author at: UMR LISAH, 2 place Pierre Viala, 34060 Montpellier, France. Tel.: +33 07 85 40 83 26.
E-mail address: ccmontesv@gmail.com (C. Montes).

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A_i	available energy for each component *vs* and *bs* (W m^{-2})
A_f	available energy for the main foliage (W m^{-2})
c	radiation extinction coefficient by canopy
c_p	specific heat of air at constant pressure (J kg^{-1} K^{-1})
CR_3	capillary rise into reservoir (3) (mm)
d	displacement height (m)
D_1	drainage from reservoir (1) to (3) (mm)
D_2	drainage from reservoir (2) to (3) (mm)
D_3	deep percolation from reservoir (3) (mm)
D_a	vapor pressure deficit at reference height (Pa)
D_m	vapor pressure deficit at mean canopy source height (Pa)
e_a	vapor pressure at reference height (Pa)
$e^*(T_i)$	saturated vapor pressure at temperature T_i ($i = f, vs, bs$) (Pa)
F_{bs}	fraction of bare soil (=1 − F_{vs})
F_{vs}	fraction of vegetated soil
F_1	F_{bs}
F_2	F_{vs}
G_{vs}	soil heat flux of vegetated soil (W m^{-2})
G_{bs}	soil heat flux of bare soil (W m^{-2})
I_{vs}	infiltration term for vegetated soil (mm)
I_{bs}	infiltration term for bare soil (mm)
$K(z_h)$	turbulent diffusivity at canopy height (m^2 s^{-1})
L	Monin-Obukhov length (m)
LAI_f	leaf area index of main foliage (m^2 m^{-2})
$CLAI_{vs}$	clumped leaf area index of vegetated soil (m^2 m^{-2})
n	parameter with value of 1 for amphistomatous and 2 for hypostomatous foliage
r_a	aerodynamic resistance between the mean source height (z_m) and the reference height (z_r) (s m^{-1})
$r_{a,i}$	aerodynamic resistance between the evaporative source ($i = vs, bs$) and mean source height (z_m, s m^{-1})
$r_{a,f,h}$	bulk boundary-layer resistance of the foliage for sensible heat (s m^{-1})
$r_{s,i}$	surface resistance (stomatal or soil surface) for each source ($i = f, vs, bs$) (s m^{-1})
R_n	net radiation of the whole canopy (W m^{-2})
u_a	wind speed at reference height (m s^{-1})
z_h	height of the main foliage (m)
z_m	mean source height (m)
z_r	reference height (m)
z_0	roughness length for momentum of main foliage (m)
z_0^i	roughness length for momentum of vegetated ($i = vs$) or bare soil ($i = bs$) (m)
z_1	depth of soil reservoir (1) (m)
z_2	depth of soil reservoir (2) (m)
z_R	vines rooting depth (m)
z_G	water table depth (m)
γ	psychrometric constant (Pa K^{-1})
λ	latent heat of vaporization (J kg^{-1})
Δ	slope of the saturated vapor pressure curve at air temperature (Pa K^{-1})
ρ	air density (kg m^{-3})
ϕ_s	solar zenith angle (radians)

account for three sources of evaporation after dividing the understory into a bare soil fraction and a soil fraction below the main foliage, and also by Verhoef and Allen (2000) to account for four sources of evaporation. The two- and three-source formalisms were revisited by Lhomme et al. (2012) to propose more concise and accurate formulations and to account for foliage morphological characteristics (amphistomatous versus hypostomatous leaves). All these models are based on the diffusion theory (*K*-theory) for energy and mass transfer within the lower atmosphere. More complex models based on higher order Lagrangian and Eulerian dispersion processes can be found in the literature: they allow a better representation of vegetation–atmosphere turbulent transfers (Raupach, 1989; Yi, 2008), but their complexity and data requirement make them difficult to use in a practical modeling framework. It has been shown, further, that the diffusion theory is appropriate to represent the microclimate at canopy scale in comparison with Lagrangian representations (Van den Hurk and McNaughton, 1995; Wu et al., 2001).

One of the first models to estimate vineyard evaporation is the one proposed by Riou et al. (1989, 1994). It is not a multi-source model: vineyard evaporation under unstressed conditions is expressed as a simple function of potential evaporation and solar radiation intercepted by the canopy. This model was extended later by Trambouze and Voltz (2001), who derived a bilinear relationship relating the ratio between vineyard actual and maximum transpiration to the average soil water storage. Subsequently, several authors have applied the multi-source resistance-based formulations to assess vineyard evaporation. First, we have to mention the work by Rana and Katerji (2008), where a simple single-source model (Penman–Monteith) was applied to vineyards trained on overhead system. In an earlier work by Sene (1994), the more complex S–W model was applied with the purpose of interpreting energy balance measurements over a sparse vineyard in southern Spain. More recently, an appropriate representation of total latent heat flux from a drip-irrigated vineyard in central Chile was obtained by Ortega-Farias et al. (2007) by applying the same S–W model. In addition, Poblete-Echeverria and Ortega-Farias (2009) adapted the so-called "clumped" model to drip irrigation over the same region of Chile by dividing the substrate (bare soil) into a dry and a wet (irrigated) portion. Zhang et al. (2008) compared these two models (S–W and clumped) against Bowen ratio estimates in a semi-arid vineyard of China: they concluded that the clumped model was more suitable to estimate total vineyard evaporation than the S-W model. On the same basis, Zhang et al. (2009) elaborated a multi-source S–W type model to simulate the evaporation from a vineyard under partial root-zone irrigation, taking into consideration different patches of soil.

All these vineyard evaporation models, however, do not take into account the common practice of maintaining a permanent or semi-permanent grass cover. This consists in a seeded or natural grass cover in between vine rows, maintaining bare soil on the rows. This practice is increasingly used because it has several positive impacts, such as the reduction in rainfall erosive potential and surface runoff, the reduction in nutrient lixiviation, the decrease in vine vigor and grape production (which improves grapes quality) and the improvements in soil structure and trafficability after rainfall events (Pradel and Pieri, 2000; Morlat and Jacquet, 2003; Celette et al., 2005, 2008; Gaudin et al., 2010). As compared with the traditional bare soil grapevine cultivation, the grass cover affects energy and water balance since surface albedo, net radiation partitioning, water consumption and infiltration are modified (Rodriguez-Iturbe, 2000; Zhang and Schilling, 2006; Centinari et al., 2012). For instance, in a recent work by Holland et al. (2013) on grassed vineyard, significant differences were found between grassed and bare soil energy partitioning. Therefore, this grass cover component should be considered into a modeling formulation.

In addition, most of the vineyard evaporation models mentioned above only consider above-ground processes (i.e. vegetation and soil surface), which interact with soil water through the parameterization of a stomatal or substrate resistance to evaporation, in the best case. Thus, they do not allow the temporal dynamics of vineyard evaporation to be adequately simulated throughout