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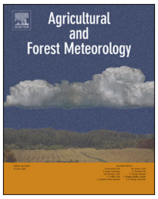

Short communication

Evaluation of soil resistance formulations for estimates of sensible heat flux in a desert vineyard

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ABSTRACT

For irrigated vineyards, accurate estimates of the sensible heat flux from the soil surface (H_s) is essential for determining the contribution of soil evaporation (E) to evapotranspiration (ET) using thermal-based energy balance approaches. A key to an accurate estimate of H_s is a robust physically-based soil resistance formulation. Here we compare the performance of two soil resistance formulations: a conventional resistance model (r_{KN}) derived from field and laboratory studies which has been extensively implemented in the thermal-based Two-Source Energy Balance (TSEB) model, and a recently developed physically-based soil resistance formulation (r_{HO}) that explicitly accounts for near-surface interactions affecting scalar fluxes at the soil surface in the presence of bluff-body roughness elements. Estimates of H_s using the two resistance formulations were evaluated using in-situ observations from a drip-irrigated vineyard in the arid central Negev Highlands of Israel. The results indicate that the soil resistance model r_{HO} outperforms the r_{KN} formulation using standard model coefficients and provides robust estimates of H_s independent of model calibration or parameter tuning. This offers an opportunity to advance the utility of TSEB model when applied to sparsely vegetated areas where ground-based calibration data are not available for adjusting coefficients in the r_{KN} formulation, and potentially improves its practical applications to heterogeneous landscapes by obviating its reliance on semi-empirical coefficients.

1. Introduction

Vineyards are economically important horticultural crops grown in many arid regions and are characterized by clumped vegetation with large row spacing, where bare soil can make up the largest part of vineyard surface area (Williams and Ayars, 2005; Kool et al., 2016). Compared with traditional rain-fed vineyards, irrigated vineyards are becoming increasingly common (Ortega-Farías et al., 2010). Precise water management is critical for irrigated vineyards since water supply strongly affects grape production and wine quality (Trambouze et al., 1998; Poblete-Echeverría et al., 2014). Mild stress can lead to improvements of grape quality, whereas severe stress can reduce quality (Van Leeuwen et al., 2009). Evapotranspiration (ET), the sum of transpiration (T) from plants and evaporation (E) from soil, accounts for > 95% of the water budget in arid regions (Kool et al., 2014b; Wilcox et al., 2003). For row crops, T is associated with plant production, while E is generally regarded as water loss from soil surface that does not directly contribute to plant growth (Kool et al., 2014a). To optimize grape production and vine quality and improve the water use efficiency (WUE), accurate ET, E, and T are needed to inform water management decisions in irrigated vineyards.

Over the last few decades, several methods have been developed for determining ET, which can be divided into two major categories: (1) measurements of ET using instrumentation, such as lysimeters, eddy covariance (EC), and the Bowen ratio energy balance (BREB) systems; (2) estimated ET based on models, such as surface conductance-based models, land surface temperature - vegetation index ($T_s - VI$) contextual-scaling methods, and surface energy balance (SEB) models (Wang and Dickinson, 2012). In addition, studies on ET partitioning also have been conducted, which include observing E using microlysimeters, estimating T from sap flow, and E/ET partitioning from isotopic analyses (see Kool et al., 2014a). Other ET partitioning

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approaches include the flux variance similarity partitioning method based on correlation analyses of high-frequency EC data (Scanlon and Sahu, 2008; Scanlon and Kustas, 2010, 2012), using multiyear EC carbon dioxide and water vapor fluxes (Scott and Biederman, 2017) and indirect methods using models (e.g. Kustas and Norman, 1999; Poblete-Echeverría et al., 2014; Zhao et al., 2018).

Poblete-Echeverría et al. (2014) indicated that most measurement methods for determining ET, E and T require complex, expensive instrumentation and complicated data processing algorithms and interpretation. Additionally, these measurements represent only a small area of the landscape. However, Anderson et al. (2012) showed great potential in using remote sensing for mapping the surface energy balance over the landscape with relatively simple yet fairly robust methods for estimating net radiation (R_n) and surface soil heat flux (G), and solving for the latent heat flux (LE) as residual of the surface energy balance equation (e.g. $LE = \lambda ET = R_n - G - H$, where λ is the latent heat of vaporization and H is the sensible heat flux). Moreover, E and T can be estimated by considering surface energy budgets for soil and vegetation separately (e.g. $LE_s = R_{ns} - H_s - G$ and $LE_c = R_{nc} - H_c$, where subscripts s and c represent soil and vegetation components, respectively). With this approach, sensible heat flux from soil, H_s, and vegetation, H_c, are the most difficult components of surface energy balance to estimate, which are usually calculated based on the "two-source" formulation using the soil and canopy temperatures (T_s and T_c) and modeling the soil and canopy heat exchange with the surrounding air (e.g. Kustas and Norman, 1999),

$$H_s = \rho c_P \frac{T_s - T_{ac}}{r_s} \tag{1}$$

$$H_c = \rho c_P \frac{T_c - T_{ac}}{r_x} \tag{2}$$

where ρc_p ($J/(m^3 \cdot K)$) is the volumetric heat capacity of air. T_{ac} (K) is the temperature in the canopy-air space. r_s (s/m) is the resistance to heat flow in the boundary layer immediately above the soil surface. r_x (s/m) is the boundary layer resistance associated with the complete canopy of leaves. The values of r_s and r_x are critical for accurate estimation of H_s and H_c. This two-source approach has been a robust method when applied to partially vegetated surfaces since r_s and r_x explicitly account for the difference in the efficiency in aerodynamic heat exchange from the soil and canopy surfaces, which not only affect the turbulent transport but also the radiometric surface temperature. As a result, the two-source formulation with radiometric surface temperature has provided reliable heat fluxes over a wide variety of landscapes (Kustas and Anderson, 2009).

This study focuses on evaluating the performance of different soil resistance formulations for sensible heat flux from soil surface (H_s) in a desert vineyard. The soil resistance formulation proposed by Kustas and Norman (1999) has been used to compute land surface turbulence fluxes and ET over a wide range of land cover types and soil moisture conditions as part of the Two-source Energy Balance (TSEB) model (e.g. Kustas et al., 2013; Li et al., 2005; Song et al., 2016; Xia et al., 2016). In these previous studies, the performance of TSEB with soil resistance formulation proposed by Kustas and Norman (1999) (hereinafter referred to as r_{KN}) has been evaluated by comparing modeled H and LE with observations from EC systems, highlighting that TSEB with standard r_{KN} can provide reliable H over a range of landscapes from irrigated cropland to drylands (Kustas and Anderson, 2009). From a previous study conducted by Xia et al. (2016), it appears that TSEB with r_{KN} could produce reliable fluxes in drip-irrigated vineyards. Nevertheless, Kustas et al. (2016) emphasized the need for detailed local observations in order to adjust the coefficients in the soil resistance formulation to achieve robust H estimates for sparsely vegetated arid and semiarid landscapes. Additionally, Kool et al. (2016) indicated that r_{KN} may not be suitable in general for vineyards since the influence of the unique vineyard architecture (i.e. strongly clumped row crop with leaf area concentrated in the upper half of the canopy) on the below canopy wind profile is not considered.

Recently, a new soil resistance formulation was proposed and verified by Haghighi and Or (2015b) (hereinafter referred to as r_{HO}) using laboratory wind tunnel data, which has been regarded as an improved soil resistance scheme for drying surfaces covered by bluff-body obstacles. For example, Decker et al. (2017) demonstrated that incorporating a previous version of r_{HO} (Haghighi et al., 2013; Haghighi and Or, 2015a) into the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model resulted in reduced errors in daily sensible heat flux and ET during spring. Moreover, Haghighi and Kirchner (2017) have successfully integrated r_{HO} into a new physically based ET model to provide theoretical estimates of turbulent heat fluxes and their partitioning over sparsely vegetated semiarid surfaces. Considering the positive results obtained by Haghighi and Kirchner (2017) and Decker et al. (2017), the objective of this study is to assess r_{HO} for a vineyard dataset used to evaluate r_{KN} in a prior study (Kool et al., 2016). To evaluate the performance of r_{KN} and r_{HO}, the estimates of H_s based on r_{KN} and r_{HO} are compared with "observed" H_s below the vine and in the midrow derived by Kool et al. (2016) from interrow energy balance and evapotranspiration partitioning observations.

2. Materials and methods

2.1. Study site and observations

Data used in this study were collected from a large experiment conducted over a drip-irrigated commercial vineyard in the arid central Negev highlands of Israel in 2012. The 10-year-old Cabernet-Sauvignon vineyard has an area of about 10 ha surrounded by desert. The vines were trained on a vertical shoot-position system with 1 m cordon height and were planted 1.5 m apart with 3 m distance between rows. Vine height and width reach 1.8 m and 0.5 m at maturity, respectively. Vineyard row orientation was approximately north-south. Average annual precipitation in this area is less than 100 mm, and usually occurs from November to April. No rainfall occurred during the growing season of 2012, which started with bud break on 1 April and ended with harvest in early August. For a more detailed description of study site, please refer to Kool et al. (2014b).

A number of meteorological and land surface fluxes observations were measured during the experiment. The measurements used for this study include wind speed, air temperature and soil surface temperature in the midrow and below the vine, and net radiation and soil heat flux in the midrow. Wind speed at 3.3 m height was derived from a sonic anemometer (CSAT 3-D sonic anemometer, Campbell Scientific Inc, USA). Air temperature above the midrow bare soil surface was obtained indirectly, using eddy-covariance and soil surface temperature data (Kool et al., 2016). Air temperature below the vine was measured by a shielded Beta-Thermal thermistor at 0.06 m height. Two infrared thermometers (IRTs, Apogee IRTS-P, Campbell Scientific Inc, USA) were installed, one below the vine at 0.3 m height and one above the midrow at 2.5 m height, to measure the soil surface temperature below the vine and in the midrow, respectively. Net radiation in the midrow was measured by a Q*7 net radiometer (Radiation and Energy Balance Systems, USA). Two soil heat flux plates (HFT1.1, Radiation and Energy Balance Systems, USA) were buried in the midrow at a depth of 0.06 m. The surface soil heat flux was derived by adding the heat storage above the plate determined from soil water content and temperature profiles to measurements of the flux plate (Sauer, 2002; Kool et al., 2014b, 2016, 2018). All meteorological and flux data were recorded as 15 min averages. In addition, vegetation parameters including leaf area index (LAI), vine height and width were measured about once a week. LAI was measured using LAI-2000 (Li-Cor Bioscience Inc, USA). The vegetation cover fraction (f_c) was defined as the ratio of vine width to row width (Kool et al., 2016).

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