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Soil and canopy energy balances in a west Texas vineyard

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Abstract

Water use in vineyards is controlled by energy absorbed by plants and the soil surface. An 8 day field experiment was conducted in a commercial vineyard near Lamesa, TX, to evaluate soil and canopy energy balances, and to examine energy exchange between canopy and soil. Grapevines in the vineyard were wrapped tightly to trellis wires, creating compact hedgerows that were 3 m apart and of 1.6 m height and 0.4 m width, with little foliage below 1 m above the soil surface. The Bowen ratio method was used to measure the vineyard energy balance including total latent heat flux (λE). Latent heat flux from the canopy (λE_c) was determined from sap flow measurements of transpiration. Soil latent heat flux (λE_s) was calculated as the difference between λE and λE_c. These measurements were combined with measurements of soil net irradiance to partition the vineyard energy balance into soil and canopy components. During the study, λE_s accounted for 44–68% of λE. Unstable conditions predominated during the study, with the soil generating sensible heat that was transferred to the canopy, producing values of λE_c that were greater than canopy net irradiance. Within-row advection of sensible heat was 17–36% of λE_c. Although the canopy was cooler than within- and above-canopy air, it was not a strong enough sink for sensible heat to produce stable conditions above the canopy. The narrow hedgerows created an unusual diurnal pattern of canopy net irradiance, having midmorning and midafternoon peaks, and a low midday plateau. Morning and afternoon peaks occurred during times of maximum direct beam irradiance on east and west sides of the hedgerows. Results also showed that within-canopy wind speed and air temperature were affected by wind direction.

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1. Introduction

Water use in vineyards is a complex function of water and energy balances of the plant canopy and the soil surface. Vineyards usually contain tall plants and widely spaced rows that produce large diurnal changes in exposure of plants and soil to solar radiation. Wide row spacing in vineyards increases the contribution of soil evaporation to the vineyard water balance. Lascano et al. (1992) found that soil evaporation over a 100 day period in a flood-irrigated vineyard of 3-year-old Chardonnay plants in west Texas was 77% of evapotranspiration (ET). Water use of the vines on a unit land area basis over that period was only 124 mm. Oliver and Sene (1992) reported similar water use rates in a vineyard in southern Spain, in which the vines were planted in a grid at a spacing of 2.5 m, and found that sensible heat flux from the vineyard was twice that of latent heat flux.

Exposed soil represents an important source and sink of radiation and sensible heat which may affect energy and water balances of the plants. Hicks (1973) speculated that sensible heat transport from the soil surface in vineyards contributed to vineyard ET. However, Oliver and Sene (1992) concluded that grapevines and soil can be treated as independent systems with little interaction between them. Hanks et al. (1971) found that in wide-row sorghum, as much as 21% of transpiration was the result of sensible heat flux from the soil surface. Ham et al. (1991) found that a cotton canopy simultaneously absorbed sensible heat from the soil and the above-canopy air when the soil surface was dry. They also showed that longwave irradiance from the soil significantly increased net irradiance of the canopy during the middle of the day.

Vineyard geometry has an impact on air flow within and above the canopy which may affect the energy balance and water use. Hicks (1973) found from eddy correlation measurements in a vineyard that the drag coefficient doubled as wind moved from parallel to perpendicular to rows, and found a 10–20% difference in ET between parallel and perpendicular wind directions. Weiss and Allen (1976a) identified 81 air circulation patterns in vineyard rows, with intermittent vortices the size of the row spacing predominating. These vortices lasted about 2 s when wind speed 0.3 m above the row was about 3 m s^{-1}. Weiss and Allen (1976b) were unable to find a constant momentum flux layer above a vineyard, in contrast to the findings of Graetz (1972). Riou et al. (1987) showed that wind direction affected roughness length and zero-plane displacement in vineyards.

Although aerodynamic behavior of vineyards has been studied in some detail, research on energy balance interactions has been limited because of the difficulty of obtaining separate measurements of plant and soil energy balances. Recently, Ham and Heilman (1991) and Ham et al. (1991) showed that separate determination of plant and soil energy balances could be obtained by combining sap flow measurements of transpiration with Bowen ratio measurements of the surface energy balance. We used their procedures to evaluate, in detail, soil and canopy energy balances in a vineyard, and to examine how vineyard evapotranspiration is affected by energy transfer between the soil, canopy and atmosphere. A better understanding of these transfer processes could lead to improved models for simulating soil and canopy energy balances.

Fig. 1. South-facing view of the vineyard showing the compact hedgerows created by the trellising. Solar elevation and azimuth angles were 40° and 87°, respectively, at the time of the photograph. The dark band, of 1 m width, between rows is shadow.

2. Materials and methods

2.1. Experimental site

We conducted an experiment between 31 May (Day 152) and 7 June (Day 159) 1992, in a 183 m by 274 m vineyard of 6-year-old Chardonnay plants on the Delaney Vineyards located at Lamesa, TX (33.5°N, 102°W). Vines were grown in rows on vertical, bilateral cordon trellises with cordon wires 1.0 m above the soil surface, and catch wires 1.25 and 1.5 m above the soil. Vines were wrapped tightly on the wires, creating compact hedgerows with plants of 1.6 m height and 0.4 m width, with little foliage below the cordon wire (Fig. 1). Row and plant spacings were 3 m and 1.7 m, respectively, and row azimuth was 160° from north. The north edge of the Chardonnay block was bordered by a field containing cotton at the seedling stage. Pasture was east of the block, and bare soil to the south. A vineyard of similar size, of 6-year-old Cabernet Sauvignon plants, was immediately to the west. The soil at the vineyard is classified in the Amarillo series (fine loamy, mixed, thermic Aridic Paleustalf) with a fine sandy-loam surface texture. In autumn 1991, six rows of winter wheat at 0.2 m row spacings were planted midway between every row of vines to control wind erosion. The winter wheat was mowed and disked before the experiment.

2.2. Energy balance measurements

The surface energy balance of the vineyard (plants and soil) can be written as

$$R_n + \lambda E + H + G = 0 \tag{1}$$

where R_n is the net irradiance, and λE, H, and G are the flux densities of latent, sensible and soil heat, respectively (all in units of W m^{-2}). In Eq. (1), flux densities toward the surface are positive, and those away from the surface are negative. Energy storage in the canopy was neglected because it was less than 2% of R_n. The surface energy balance was measured by the Bowen ratio method (Tanner, 1960) using four independent systems designed by Gay and Greenberg (1985). Each Bowen ratio system contained two exchanging ceramic wick wet- and dry-bulb psychrometers separated by a vertical distance of 1 m, and a net radiometer (Model Q6, Radiation Energy Balance Systems (REBS), Seattle, WA). Two of the systems used six soil heat flux plates (model HFT-1, REBS) per system wired in series, and the other two used three plates wired in series. Masts were positioned 10 m from the north edge of the vineyard. Systems 1 and 2 were 30 m and 37 m, respectively, from the east edge of the vineyard, and Systems 3 and 4 were 61 m and 67 m, respectively, from the east edge. Psychrometers in Systems 1 and 3 were positioned above the plants, and those in Systems 2 and 4 were positioned midway between rows. The bottom psychrometer on each mast was 2.6 m above the soil, 1.0 m above the plants. This configuration produced a fetch-to-height ratio of 73:1 for the prevailing southerly winds, well above the minimum of 20:1 for Bowen ratio measurements found by Heilman et al. (1989).

Dry- and wet-bulb temperatures were measured during a 3 min period followed by a 3 min period during which psychrometers exchanged and equilibrated with the environment. This procedure eliminated sensor bias and allowed the Bowen ratio to be determined every 12 min. Net radiometers were mounted 3.2 m above the soil, with radiometers in Systems 1 and 3 positioned directly above the plants, and those in Systems 2 and 4 positioned midway between rows. Soil heat flux was determined using the combination method (Kimball and Jackson, 1979). Heat flux plates were placed 0.05 m below the soil surface, and the change in heat content above the plates was determined from measurements of soil temperature in the 0–0.05 m layer and an estimate of the heat capacity (DeVries, 1963). Soil temperatures in the 0–0.05 m layer were measured with integrating thermocouple temperature probes constructed in our laboratory. The six heat flux plates in Systems 1 and 2 and corresponding temperature probes were spaced 0.5 m apart in an east–west line between rows. The three heat flux plates and temperature probes of System 3 were spaced 0.5 m apart covering the east half of the interrow distance, and plates and probes on System 4 were spaced 0.5 m apart over the west half of the interrow distance.

Energy balances at Bowen ratio Systems 1 and 2 were determined independently from measurements of the Bowen ratio, R_n and G at each mast. For Systems 3 and 4, independent measurements of Bowen ratio and R_n from each system were used together with the average G for the two systems to determine energy balances.

Energy balance terms (Eq. (1)) from the four systems were then averaged to compute the vineyard energy balance.

2.3. Determination of canopy and soil latent heat flux

Canopy latent heat flux density (λE_c) was obtained from heat balance measurements of transpiration (Sakuratani, 1981; Baker and Van Bavel, 1987). Lascano et al. (1992) found that heat balance measurements of transpiration in grapevines were within 10% of gravimetric measurements of transpiration. Sap flow gauges (Model SGA 25, Dynamax, Inc., Houston, TX) were attached to the trunks of 10 plants located an average distance of 43 m south of the Bowen ratio systems. Trunk diameters at gauge locations ranged from 28 to 31 mm. Approximately 0.5 W of power was applied to the trunks by gauge heaters. Insulation was placed above and below the gauges to reduce effects of the environment on trunk heat balance. Gauges were sampled every 15 s using a Model CR7X data-logger (Campbell Scientific, Logan, UT) and 12 min averages were computed. Four of the gauges had intermittent problems during periods of high flow rate (Ham and Heilman, 1990), and data from these gauges were excluded from analysis during these periods.

Sap flow measurements were converted to latent heat flux per unit land area by normalizing the measurements on a plant population basis. Mean λE_c (W m^{-2}) was calculated as

$$\lambda E_c = \lambda \sum (f_i \rho)/n \tag{2}$$

for $i = 1, 2, \ldots, n$, where λ is the latent heat of vaporization (J kg^{-1}), f_i is the sap flow (kg s^{-1}) of plant i, ρ is the plant density (plants m^{-2}) and n is the number of plants measured. Soil latent heat flux density (λE_s) was calculated as

$$\lambda E_s = \lambda E - \lambda E_c \tag{3}$$

where λE is the total latent heat flux density of the vineyard as measured by the Bowen ratio method. Ham et al. (1990) used the above procedure to partition λE from a cotton canopy at partial cover, and found that values of λE_s calculated with Eq. (3) were within 11% of microlysimeter measurements.

2.4. Determination of canopy and soil energy balances

The energy balance of the soil surface can be written as

$$R_{ns} + \lambda E_s + H_s + G = 0 \tag{4}$$

where R_{ns} is the soil net irradiance and H_s is the sensible heat flux from the soil. The soil heat flux (G) was measured as described above, and λE_s was calculated with Eq. (3). The soil net irradiance was measured by three Model Q6 net radiometers (REBS) at a height of 0.5 m above the soil surface. The net radiometers were positioned 0.5 m east and 0.5 m west of rows, and midway between rows to obtain an average value of R_{ns}. Net radiometers were sampled every 15 s with a CR7X data-logger, and 12 min averages were computed. The sensible heat flux (H_s) was calculated by rearranging

Eq. (4) to yield

$$H_s = -(R_{ns} + \lambda E_s + G) \tag{5}$$

The surface energy balance of the grapevine canopy can be written as

$$R_{nc} + \lambda E_c + H_c = 0 \tag{6}$$

where R_{nc} is the net irradiance of the canopy, and λE_c and H_c are the latent and sensible heat flux densities, respectively, from the canopy. Based on discussions by Ham et al. (1991), the canopy net irradiance was calculated as the difference between the above- and below-canopy net irradiance:

$$R_{nc} = R_n - R_{ns} \tag{7}$$

where R_n and R_{ns} were measured as described above. Fuchs (1972) and Kanemasu and Arkin (1974) used a similar approach to evaluate canopy–soil radiation relationships. The canopy sensible heat flux (H_c) was calculated by rearranging Eq. (6) as

$$H_c = -(R_{nc} + \lambda E_c) \tag{8}$$

2.5. Additional measurements

Soil surface and canopy temperatures were measured with 4° field-of-view IR radiometers (Model 4000A, Everest Interscience, Tustin, CA). Three radiometers at a height of 0.7 m above the soil surface and a view angle of 20° from the horizontal were pointed at the soil surface to obtain an average surface temperature, and two radiometers were aimed at east and west sides of trellises to obtain an average canopy temperature. Soil and canopy temperatures were corrected for emissivity and long-wave sky irradiance. Soil emissivity was measured using a procedure similar to that of Fuchs and Tanner (1966), and canopy emissivity was assumed to be 0.97. Radiometers were sampled every 15 s by a Model CR7X data-logger, and 12 min averages were computed.

Above-canopy air temperature and humidity profiles were measured with miniature wet- and dry-bulb psychrometers constructed with copper–constantan thermocouples of 0.076 mm diameter. Wet-bulb junctions were inserted into cotton thread connected to hypodermic syringes used as water reservoirs. Psychrometers were positioned directly above the row at heights of 1.70, 1.88, 2.14, 2.44, 2.82, 3.30, 3.91 and 4.70 m above the soil surface. Within-canopy air temperature and humidity at heights of 0.45, 0.80, 1.15 and 1.5 m above the soil surface were measured with 32 miniature wet- and dry-bulb psychrometers. Eight psychrometers were used per height, and were spaced 0.35 m apart between rows. All psychrometers were sampled every 5 s with a Model CR7X data-logger, and 12 min averages were computed.

Within-canopy wind speed was measured with 32 heat transport anemometers (Kanemasu and Tanner, 1968), with axes of anemometers held vertically at the same heights and spacings as the within-canopy psychrometers. Within- and above-canopy wind speed was also measured with a combination of Model 1210D photo-

Table 1
Daily values of global irradiance (R_s), maximum and minimum air (T_{air}) and dewpoint (T_{dew}) temperatures, average wind speed (U) and precipitation (P) on Days 152–159

Day	R_s (MJ m^{-2})	T_{air} (°C)		T_{dew} (°C)		U (m s^{-1})	P (mm)
		Maximum	Minimum	Maximum	Minimum		
152	20.0	25.4	12.9	16.8	12.8	2.3	0
153	19.7	22.3	12.5	17.1	12.1	2.9	1.0
154	26.5	23.4	12.2	15.2	9.0	2.6	8.1
155	28.9	27.1	12.5	15.7	10.3	1.5	0.2
156	24.5	31.1	16.6	17.1	14.1	2.6	0
157	27.8	33.3	17.5	17.6	12.3	2.7	0
158	19.7	27.6	18.3	18.2	11.4	2.8	8.4
159	25.0	27.9	16.8	19.2	13.2	1.9	4.1

Temperatures and wind speed were measured 1 m above the canopy

chopped and Model 12102 d.c. generator cup anemometers (R.M. Young, Traverse City, MI). Cup anemometers were positioned midway between rows at heights of 0.35, 0.70, 1.05, 1.40, 1.9, 2.6, 3.5 and 4.7 m above the soil. Cup anemometers were also placed directly above the row at the same heights as the above-canopy psychrometers. Wind direction was measured with a Model 12005 wind vane (R.M. Young). Data sampling and logging were as for the psychrometers.

Microlysimeters of 0.13 m length and 0.074 m diameter were used to measure daily soil evaporation (Lascano and Van Bavel, 1986). Three groups of six lysimeters spaced 0.5 m apart between rows were used to obtain an average evaporation rate. Lysimeters were weighed at sunrise and sunset. However, frequent rainfall during the study period limited the lysimeter measurements. Gravimetric soil samples in the 0–0.05 m layer were collected daily to determine volumetric soil water content. Leaf areas of plants with sap flow gauges were determined twice during the experiment from measurements of leaf length and width, by the procedure of Lascano et al. (1992). Stomatal resistance was measured at selected periods with a steady-state porometer (Model LI-1600, Li-Cor, Lincoln, NE). Additional measurements included global irradiance and rainfall.

3. Results and discussion

Environmental conditions during the study are summarized in Table 1. Skies were mostly clear on Days 155 and 157, and partly cloudy on the other days. The vineyard was not irrigated during the study period, but rainfall occurred on several days, mostly in the evening and early morning. On Days 153–155, winds were from the north rather than from the prevailing southerly direction, which limited the fetch for Bowen ratio measurements. Therefore, energy balance measurements for the vineyard and soil surface for these days were excluded from analysis because of the inability to obtain accurate measurements of λE and H, and therefore, λE_s and H_s

Table 2
Daylight (sunrise to sunset) energy balance of the vineyard on Days 152–159; included are net irradiance (R_n), soil heat (G), sensible heat flux (H) and latent heat flux (λE), together with ratios of G, H and λE to R_n

Day	R_n (MJ m^{-2})	G (MJ m^{-2})	H (MJ m^{-2})	λE (MJ m^{-2})	$-G/R_n$	$-H/R_n$	$-\lambda E/R_n$
152	13.3	−3.2	−3.3	−3.3	0.24	0.25	0.51
153	14.0	−1.6	–	–	0.11	–	–
154	16.7	−3.5	–	–	0.21	–	–
155	18.9	−3.5	–	–	0.19	–	–
156	15.4	−4.5	−2.6	−8.3	0.29	0.17	0.54
157	17.1	−5.0	−4.3	−7.8	0.29	0.25	0.46
158	12.5	−1.8	−3.5	−7.2	0.14	0.28	0.58
159	16.6	−3.2	−3.3	−10.1	0.19	0.20	0.61

Negative values indicate fluxes away from the surface. Values of H and λE on Days 153–155 were excluded because of inadequate fetch when winds were from the north.

from Eqs. (3) and (5). Leaf area on plants with sap flow gauges ranged from 2.83 to 4.42 m^2 per plant on Day 151 and from 4.19 to 7.39 m^2 per plant on Day 160. Leaf area index (LAI) increased from 0.7 on Day 151 to 1.1 on Day 160.

Daytime energy balances for the vineyard are given in Table 2. Net irradiance of the vineyard ranged from 12.5 to 18.9 MJ m^{-2}, of which 82–89% was soil net irradiance. Unstable conditions predominated above the vineyard, with H accounting for 17–28% of R_n, and soil heat flux accounted for as much as 29% of R_n. Latent heat flux ranged from 6.8 to 10.1 MJ m^{-2} (2.8–4.1 mm water loss), and accounted for 46–61% of R_n.

Daytime energy balances of the soil surface are listed in Table 3. Soil net irradiance was partitioned almost equally among λE_s, H_s and G. Soil latent heat flux ranged from 3.2 to 6.5 MJ m^{-2} (1.3–2.7 mm), and accounted for 29–47% of R_{ns}. Soil λE

Table 3
Daylight (sunrise to sunset) energy balance of the soil surface on Days 152–159; included are net irradiance (R_{ns}), soil heat flux (G), sensible heat flux (H_s) and latent heat flux (λE_s), together with ratios of G, H_s and λE_s to R_{ns}

Day	R_{ns} (MJ m^{-2})	G_s (MJ m^{-2})	H_s (MJ m^{-2})	λE_s (MJ m^{-2})	$-G/R_{ns}$	$-H_s/R_{ns}$	$-\lambda E_s/R_{ns}$
152	11.9	−3.2	−4.1	−4.6	0.27	0.34	0.39
153	12.5	−1.6	–	–	0.13	–	–
154	13.7	−3.5	–	–	0.26	–	–
155	16.4	−3.5	–	–	0.21	–	–
156	12.9	−4.5	−3.6	−4.8	0.35	0.28	0.37
157	14.2	−5.0	−4.9	−4.3	0.35	0.35	0.30
158	10.9	−1.8	−5.9	−3.2	0.17	0.54	0.29
159	13.8	−3.2	−4.1	−6.5	0.23	0.30	0.47

Negative values indicate fluxes away from the surface. Values of H_s and λE_s on Days 153–155 were excluded because of inadequate fetch which affected their calculation via Eqs. (3) and (5).

Table 4

Daylight (sunrise to sunset) energy balance of the canopy on Days 152–159; included are net irradiance (R_{nc}), sensible heat flux (H_c) and latent heat flux (λE_c), together with ratios of H_c and λE_c to R_{nc}

Day	R_{nc} (MJ m^{-2})	H_c (MJ m^{-2})	λE_c (MJ m^{-2})	$-H_c/R_{nc}$	$-\lambda E_c/R_{nc}$
152	1.4	0.8	−2.2	−0.57	1.57
153	1.5	0.6	−2.1	−0.40	1.40
154	3.0	0.8	−3.8	−0.27	1.27
155	2.5	0.5	−3.0	−0.20	1.20
156	2.5	1.0	−3.5	−0.40	1.40
157	2.9	0.6	−3.5	−0.20	1.20
158	1.6	2.4	−4.0	−1.50	2.50
159	2.8	0.8	−3.6	−0.29	1.29

Negative values indicate fluxes away from the canopy

accounted for 44–68% of vineyard λE. On Day 157, the only day on which microlysimter measurements were obtained, daytime soil evaporation as measured by microlysimeters was 1.5 ± 0.5 mm (standard deviation), compared with 1.7 ± 0.3 mm as calculated from the Bowen ratio and sap flow measurements. Sensible heat flux was negative on all days, indicating convective transport of heat away from the soil surface. Soil surface temperature exceeded air temperature at canopy height by as much as 17°C.

Daytime energy balances of the canopy are shown in Table 4. Canopy net irradiance on a unit land area basis was low (1.4–3.0 MJ m^{-2}) because of the narrow hedgerows and widely spaced rows. Canopy λE ranged from 2.1 to 3.8 MJ m^{-2} (0.8–1.6 mm), and exceeded R_{nc} on all days. Positive values of H_c, and negative values of H and H_s, indicated that the canopy was absorbing sensible heat that was generated at the soil surface. This within-row advection occurred mainly in the afternoon, and was 17–36% of λE_c. Canopy temperatures were generally higher than air temperature at canopy height during the morning, and were as much as 5°C lower than air temperature during the afternoon. Stomatal resistance of sunlit leaves was generally less than 50 s m^{-1}, indicating that the plants were not water stressed.

Comparisons of vineyard, soil and canopy energy balances indicate that the soil had a major impact on canopy and vineyard energy balances. Diurnal energy balance measurements for Day 157 will be presented, so that canopy–soil energy balance interactions can be examined in greater detail. Day 157 was selected because skies on that day were generally clear, in contrast to the other days, and winds were from the south and west, producing both down-row and cross-row flow.

On Day 157, the soil surface was dry, air temperatures were high and wind speed at 1 m above the canopy averaged 2.7 m s^{-1}. Vineyard energy balance measurements (Fig. 2) indicated that lapse conditions existed throughout most of the day, with H reaching −192 W m^{-2} at 11:24 h (Fig. 2(A)) . The maximum value of R_n was 620 W m^{-2}, and G and λE reached −263 W m^{-2} and −321 W m^{-2}, respectively. Soil net irradiance generally followed the diurnal course of R_n, and reached 588 W m^{-2} near

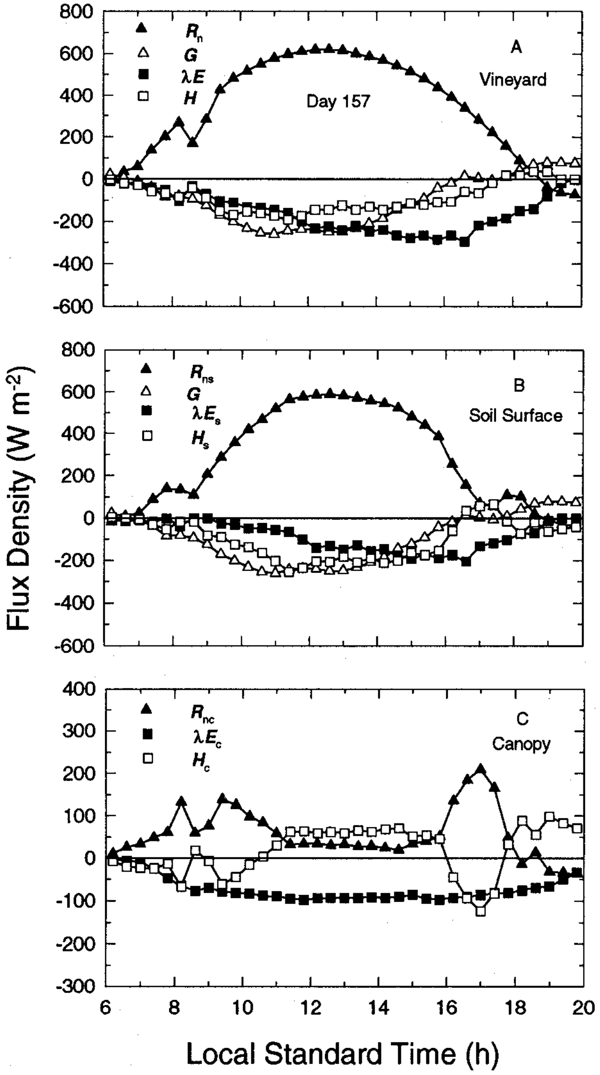

Fig. 2. Energy balances of the vineyard (A), soil surface (B) and canopy (C) on Day 157.

solar noon, with secondary peaks occurring at 08:00 h and 17:48 h, when solar elevation angles were low (Fig. 2(B)). The soil was fully illuminated at low solar elevation angles because the canopy was devoid of foliage below 1.0 m, the height of the cordon wire. Soil H_s and λE_s reached maximum values of -254 W m^{-2} and -205 W m^{-2}, respectively. Latent heat flux from the soil was 55% of λE.

The photograph of the vineyard (Fig. 1) illustrates the soil illumination created by the trellising. At the time of the photograph (09:06 h), solar elevation and azimuth angles were 40° and 87°, respectively. At these angles, the soil beneath the rows was

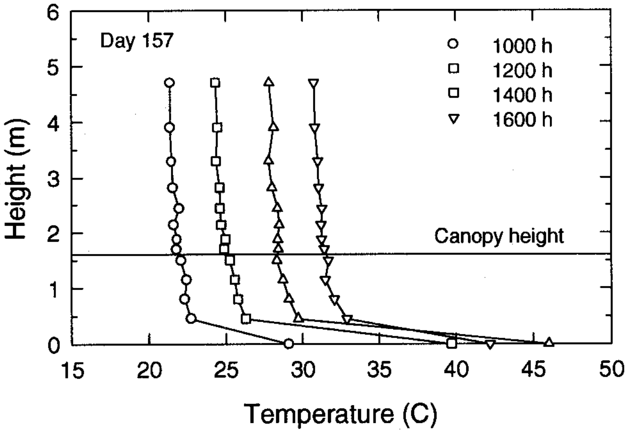

Fig. 3. Air temperature profiles within and above the vineyard at 10:00, 12:00, 14:00 and 16:00 h on Day 157. Canopy radiative temperatures at these times were 23.7°C, 25.6°C, 27.7°C and 28.9°C, respectively.

sunlit because there was no foliage below 1 m, whereas a band of shadow of 1 m width occurred midway between rows.

Whereas R_{ns} followed the diurnal course of net irradiance above the canopy, R_{nc} did not (Fig. 2(C)). Canopy net irradiance had morning and afternoon peaks of 139 W m^{-2} and 209 W m^{-2}, respectively, corresponding to times when direct beam irradiance on the east and west walls of the hedgerow was at a maximum. The morning peak was lower because of clouds. Between the peaks was a midday plateau near 40 W m^{-2}. Canopy sensible heat flux was negative in the morning and positive in the afternoon. Between 11:00 and 15:48 h, the canopy absorbed soil-generated sensible heat which amounted to between 33 and 78% of λE_c. The direction of H_c coincided with the canopy–air temperature difference except between 16:00 and 18:00 h, when flow apparently was counter to the temperature gradient.

The discrepancy between flow direction and the temperature gradient may have been due to an accumulation of errors in the residual calculation of H_c, or to actual counter-gradient transport. Denmead and Bradley (1985) reported that sensible heat flux within canopies is often counter-gradient or zero-gradient. They found that 70% of their sensible heat flux measurements in a forest were counter- or zero-gradient below mid-canopy. Likewise, Graser et al. (1987) observed counter-gradient flow in sorghum canopies. As pointed out by Raupauch (1989), vertical transport in canopies is maintained by eddies with length scales of the order of canopy height, so that vertical mixing is not necessarily controlled by within-canopy temperature gradients.

Air temperature profiles within and above the canopy provided further evidence that the soil strongly affected canopy and vineyard energy balances. The soil was considerably warmer than the air during most of the day, and the resulting transport of sensible heat from the soil produced lapse conditions in the boundary layer (Fig. 3). Although the canopy was cooler than the air during the afternoon, it was not a large enough sink for sensible heat to produce stable conditions above the canopy.

We found that wind and air temperature profiles within and above the canopy were

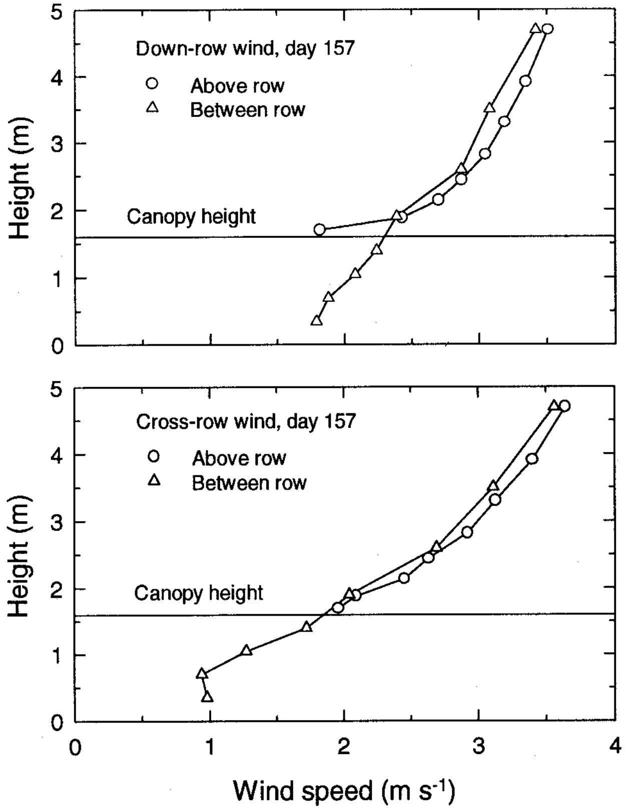

Fig. 4. Comparison of wind profiles measured above and between rows on Day 157. Down-row profiles were measured at 14:12 h when wind direction was 160°, and cross-row profiles were measured at 16:48 h when wind direction was 222°. Row azimuth was 160° from north.

affected by wind direction. Fig. 4 shows examples of wind profiles measured above and between the rows for down-row and cross-row winds. Down-row wind profiles in Fig. 4 were measured at 14:12 h, when the wind direction was 160°, whereas cross-row profiles were measured at 16:48 h, when the direction was 222°. Wind speed at 4.7 m, the elevation of the highest anemometers, was nearly identical at those times. For down-row wind, profiles measured between and above the row diverged near the top of the canopy, whereas for cross-row wind, the two profiles were similar, suggesting greater turbulence and mixing near the top of the canopy when wind direction was perpendicular to rows. Wind speed gradients were greater for cross-row flow. Hicks (1973) and Weiss and Allen (1976b) found that drag coefficients were higher for cross-row flow than for down-row flow in vineyards. Weiss and Allen (1976b) also found that turbulent intensity above the canopy was higher for cross-row flow than for down-row flow. Within-canopy wind speed was higher for down-row wind, but wind speed within the canopy was still relatively high for cross-row wind because the canopy was porous below 1 m.

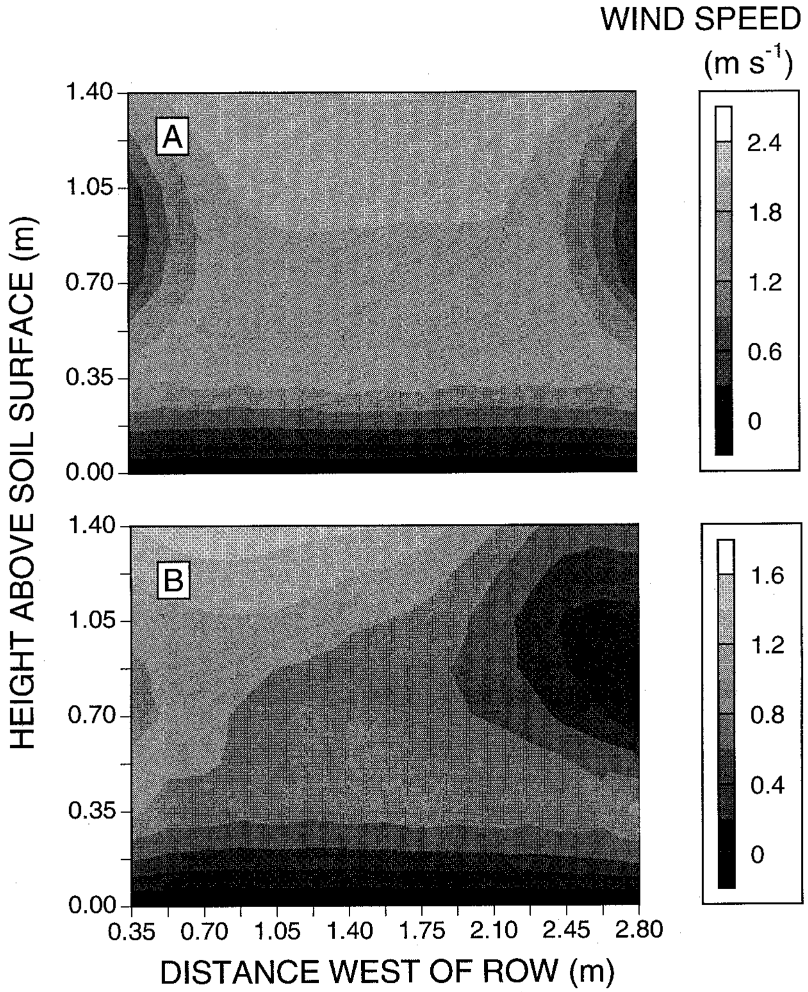

Fig. 5. Contour plots of within-canopy wind speed at 14:12 h (A) and 16:48 h (B) on Day 157. Respective wind directions were 160° and 222°. Row azimuth was 160° from north.

Contour plots of within-canopy wind speed at 14:12 and 16:48 h are shown in Fig. 5. For down-row flow, there was little horizontal variation in wind speed between rows, except adjacent to the hedgerow, where wind speed decreased. The down-row contour (Fig. 5(A)) was symmetrical about the midpoint of the interrow distance. For cross-row flow, wind speed increased from leeward to windward sides of the hedgerow (Fig. 5(B)). The cross-row contour plot suggested possible penetration of turbulent eddies from above the canopy that may have contributed to counter-gradient flow. Weiss and Allen (1976a) found evidence of such eddy penetration in the vineyards they studied.

Corresponding contour plots of within-canopy air temperature are shown in

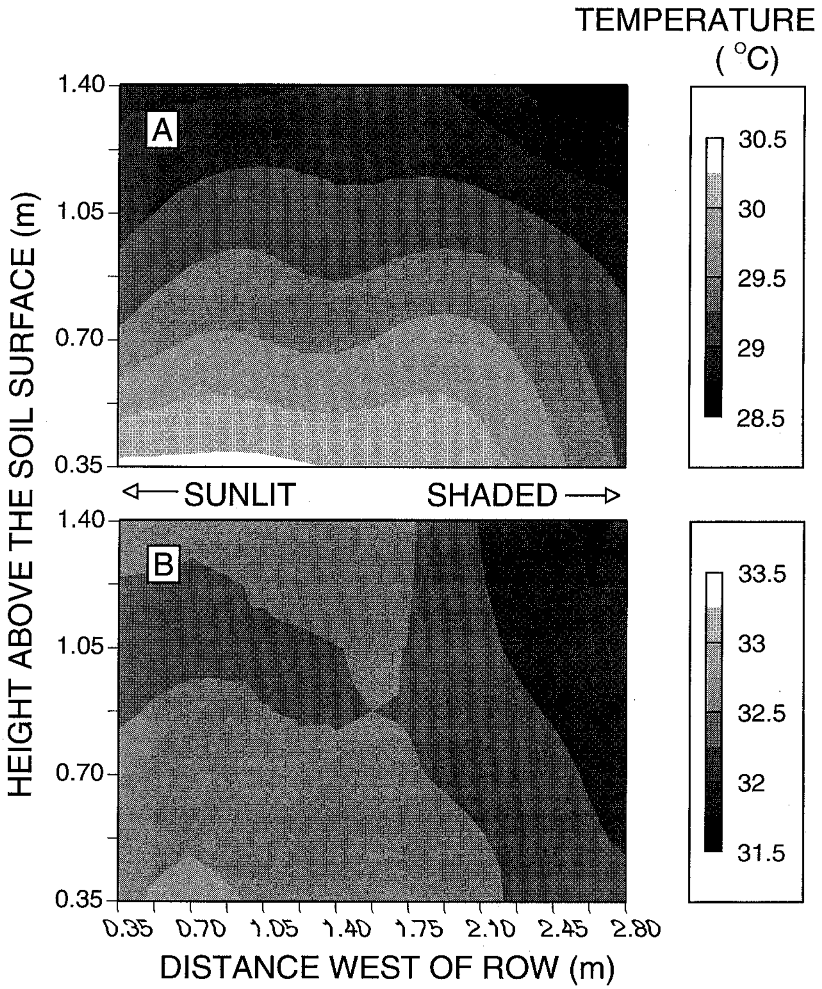

Fig. 6. Contour plots of within-canopy air temperature at 14:12 h (A) and 16:48 h (B) on Day 157. Respective wind directions were 160° and 222°. Row azimuth was 160° from north.

Fig. 6. When flow was down-row, air temperature decreased with elevation (Fig. 6(A)). Air temperature was higher between rows than adjacent to hedgerows, and was higher next to the sunlit side of the hedgerow than to the shaded side. Average radiative temperatures of sunlit and shaded sides of the hedgerow were 29.2°C and 26.0°C, respectively; and the average soil surface temperature was 44.0°C. For cross-row flow, there was not a clearly defined vertical temperature gradient (Fig. 6(B)). Temperature generally increased from the leeward, shaded side of the hedgerow to the windward, sunlit side. Sunlit hedgerow, shaded hedgerow and soil surface temperatures were 31.5°C, 27.1° and 38.7°C, respectively.

4. Conclusions

Results from our study clearly show that the soil has a major role in determining canopy and vineyard energy balances. Sensible heat generated at the soil surface can be a major contributor to the energy balance and transpiration of the vines. Thus, the soil and canopy cannot be treated as independent systems. In our experiment, we used spatially averaged parameters to describe the soil surface energy balance, and did not examine positional variation. Because of periodic shading, and variations in within-canopy wind speed and temperature, it is likely that large variations in the soil energy balance occurred as a function of position between rows (Ham and Kluitenberg, 1993). Our results also show that wind direction has an important role in heat transfer within and above vineyards. Thus, any attempt to describe aerodynamic transport in vineyards must include wind direction.

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