ELSEVIER

Agricultural and Forest Meteorology 81 (1996) 79–93

AGRICULTURAL AND FOREST METEOROLOGY

Effects of trellising on the energy balance of a vineyard

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Received 13 January 1995; accepted 20 September 1995

Abstract

Field experiments were conducted in 1992 and 1993 in a commercial vineyard near Lamesa, TX, to evaluate soil and canopy energy balances. In 1992, grapevines were wrapped tightly to trellis wires, creating compact hedgerows that were 3 m apart, 1.6 m high and 0.4 m wide with little foliage below 1 m above the soil surface. In 1993, vines were allowed to grow outward and downward from the trellis because of concerns that excess shading of vines and fruit had occurred the previous year. This change in trellising created wider, less dense hedgerows that increased sunlit leaf area and reduced sunlit soil area from the previous year. Leaf area was also 55% larger in 1993. We examined how the change in trellising affected soil and canopy energy balances. 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 values were combined with measurements of soil net irradiance to partition the vineyard energy balance into soil and canopy components. The change in trellising in 1993 had little effect on vineyard net irradiance (R_n) and λE, but did alter the partitioning of R_n and λE into soil and canopy components. Canopy R_n and λE were substantially higher for the open hedgerows in 1993 whereas soil R_n and λE were lower than for the dense hedgerows in 1992. Both trellising and leaf area contributed to changes in the energy balance. A comparison of λE_c per unit land area with λE_c per unit leaf area suggested that roughly 60% of the difference in λE_c between years was caused by the change in trellising.

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SSDI 0168-1923(95)02312-7

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 create 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 surface water balance. Lascano et al. (1992) found that soil evaporation over a 100 day period in a vineyard of 3-year old Chardonnay plants in West Texas was 77% of evapotranspiration (ET). Exposed soil is a source and sink of radiation and sensible heat which may affect energy and water balances of the plants. Hicks (1973) speculated that sensible heat generated at the soil surface contributed to vineyard ET. However, Oliver and Sene (1992) concluded that soil and vines can be treated as independent systems with little interaction between them.

Vineyard geometry has an impact on air flow within and above the canopy which affects the energy balance and water use. Hicks (1973) found that the drag coefficient doubled as wind moved from parallel to perpendicular to vineyard rows, and found a 10–20% difference in ET between parallel and perpendicular wind directions. Weiss and Allen (1976a) found that turbulent intensity was greatest when winds were perpendicular to vineyard rows. Weiss and Allen (1976b) identified 81 air circulation patterns in vineyard rows. Riou et al. (1987) showed that wind direction affected roughness length and zero-plane displacement in vineyards. Padro et al. (1994) found that the aerodynamic resistance above a vineyard was dependent on wind direction, while Sene (1994) found that friction velocity and roughness length increased with leaf growth in a vineyard.

Trellis design can affect vineyard microclimate and physiological response of grapevines (Morsi et al., 1992; Smart, 1988; Smart et al., 1982). Designs which cause excessive shading of foliage and fruit can adversely affect fruit quality and yield (Morsi et al., 1992). Trellis design may also alter the distribution of net irradiance in vineyards and affect canopy and soil energy balances.

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. Ham et al. (1991) and Ham and Heilman (1991) showed that separate determination of plant and soil energy balances could be obtained by combining heat balance measurements of transpiration with Bowen ratio measurements of the surface energy balance. In 1992, we used their procedures to measure soil and canopy energy balances in a commercial vineyard in West Texas (Heilman et al., 1994). Grapevines were wrapped tightly on trellis wires, creating narrow, dense hedgerows. This was done to increase penetration of solar radiation to the lower part of the canopy. The narrow hedgerows and wide row spacing created high soil net irradiance, and an unusual diurnal pattern of canopy net irradiance having midmorning and midafternoon peaks, and a low midday plateau. Soil-generated sensible heat was transferred to the canopy, producing values of latent heat flux that were greater than net irradiance. In 1993, the trellising was changed because of concerns that excess shading of leaves and fruit had occurred in the dense hedgerows the previous year (W.N. Lipe, personal communication, 1993). Grapevines were allowed to grow outward and downward from the trellis which produced wider and less dense hedgerows. Energy balance experiments conducted the previous year were repeated. In this paper, we show how the change in trellising affected soil and canopy energy balances.

2. Materials and methods

Experiments were conducted between 31 May (Day 152) and 7 June (Day 159) 1992, and between 4 June (Day 155) and 12 June (Day 163) 1993, in a 183 m by 274 m vineyard of Chardonnay plants on the Delaney Vineyards located near Lamesa, TX (33.5° N, 102° W). Grapevines were 6 years old in 1992, and grown in North–South rows on vertical, bilateral cordon trellises with cordon wires at 1.0 m, and catch wires at 1.25 and 1.5 m above the soil. Row and plant spacings were 3 m and 1.7 m, respectively, and row azimuth was 160° from North. In 1992, vines were wrapped tightly on the wires, creating narrow, dense hedgerows that were 1.6 m high and 0.4 m wide with little foliage below the cordon wire (Fig. 1). In 1993, vines were allowed to extend outward and downward from the trellis, creating less dense hedgerows with plant widths averaging 1.5 m (Fig. 1). Plant height in 1993 was the same as in 1992, but leaf area was higher. North and south edges of the Chardonnay block were bordered by bare soil. Pasture was east of the block, and a similar size vineyard of Cabernet Sauvignon plants was to the West. The soil in the vineyard is classified in the Amarillo series (fine-loamy, mixed, thermic Aridic Paleustalf) with a fine sandy-loam surface. In the fall of 1991 and 1992, six rows of winter wheat at 0.2 m row spacings were planted midway

(a)


Fig. 1. South-facing view of the vineyard showing the hedgerows created by the trellising. (a) In 1992 vines were wrapped tightly to trellis wires, creating narrow, dense hedgerows. (b) In 1993 vines were allowed to grow outward and downward away from the trellis, creating more open hedgerows.

Fig. 1 (continued).

between every row of vines to control wind erosion. The winter wheat was mowed and disked in the spring prior to experiments. The vineyard was equipped with a drip irrigation system with an emitter adjacent to the trunk of each plant at an elevation of 0.5 m above the soil. Detailed descriptions of instrumentation and measurement procedures are given by Heilman et al. (1994). Following is an abbreviated discussion of methodology.

2.1. Energy balance measurements

The energy balance of the vineyard was determined using the Bowen ratio method (Tanner, 1960) using four measurement systems designed by Gay and Greenberg (1985). Each Bowen ratio system contained two exchanging wet and dry bulb psychrometers, a net radiometer and soil heat flux plates. The systems were positioned near the north edge of the field, producing a fetch-to-height ratio of 73:1 for the prevailing southerly winds. Psychrometers on each system were separated by a vertical distance of 1 m, and the bottom psychrometer was 2.6 m above the soil, 1.0 m above the plants. Two sets of psychrometers were positioned above the plants, and two positioned midway between rows. Net radiometers were mounted 3.2 m above the soil with two radiometers positioned directly over the plants and two midway between rows. Soil heat flux was determined by the combination method (Kimball and Jackson, 1979) using heat flux plates 0.05 m below the soil surface and measurements of soil temperature in the 0–0.05 m layer. Soil heat flux plates for each system were spaced 0.5 m apart in an East–West line between rows. Twelve-minute averages of the energy balance were obtained from each system, and then the energy balance components from each system were averaged to compute the vineyard energy balance.

Canopy latent heat flux density λE_c was obtained from heat balance measurements of sap flow (Sakuratani, 1981; Baker and Van Bavel, 1987). Sap-flow gauges (Model SGA 25, Dynamax, Inc., Houston, TX) were attached to 10 plants upwind of the Bowen ratio systems. Gauges were sampled every 15 s using a Model CR7X data logger (Campbell Scientific, Logan, UT) and 12-min averages recorded. Sap-flow measurements were converted to latent heat flux per unit land area by normalizing the measurements on a plant population basis. Soil latent heat flux density (λE_s) was calculated as

$$\lambda E_s = \lambda E - \lambda E_c \tag{1}$$

where λE is total latent heat flux of the vineyard as measured by the Bowen ratio method.

Soil net irradiance (R_{ns}) was measured by three net radiometers at a height of 0.5 m above the soil surface. 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}. Based on discussions by Ham et al. (1991), canopy net irradiance (R_{nc}) was calculated as

$$R_{nc} = R_n - R_{ns} \tag{2}$$

where R_n is net irradiance of the vineyard as measured by the above-canopy net radiometers. Sensible heat flux density from the soil (H_s) and the canopy (H_c) were computed as residuals from the energy balance of each surface by the equations

$$H_s = -(R_{ns} + \lambda E_s + G) \tag{3}$$

and

$$H_c = -(R_{nc} + \lambda E_c) \tag{4}$$

where G is soil heat flux density. In Eq. (3) and Eq. (4), flux densities toward the surface are positive, while those away from the surface are negative. An error analysis of this methodology was presented by Ham et al. (1990). Daytime totals of vineyard, soil and canopy energy balances were used in the analysis to minimize sampling errors associated with diurnal variations of soil and canopy net irradiance.

2.2. Additional measurements

Within- and above-canopy wind speed was measured with a combination of Model 1210D photo-chopped and Model 12102 d.c. generator cup anemometers (R.M. Young, Traverse City, MI). In 1992, anemometers were positioned midway between rows at heights of 0.4, 0.7, 1.1, 1.4, 1.9, 2.6, 3.5 and 4.7 m above the soil, and directly above the row at 1.7, 1.9, 2.1, 2.4, 2.8, 3.3, 3.9 and 4.7 m above the soil. In 1993, anemometers were positioned midway between rows at heights of 0.4, 0.8, 1.1, 1.5, 1.9, 2.4 and 4.2 m above the soil, and directly above the rows at 1.9, 2.1, 2.4, 2.8, 3.2, 3.7, 4.2 and 4.7 m above the soil. In addition, in 1993 a cup anemometer was positioned beneath the row at a height of 0.4 m above the soil. In both years, air temperature and humidity were measured with miniature wet- and dry-bulb psychrometers at the same heights as the between-row anemometers. All anemometers and psychrometers were sampled every 5 s with a Model CR7X data logger, and 12-min averages recorded. Drag coefficients (C_D) were calculated as

$$C_D = 2(U^*/V_h)^2 \quad (5)$$

where U^* is the friction velocity determined from wind profiles using the solution procedure of McInnes et al. (1990) and V_h is mean horizontal wind speed.

In 1993, *uvw* components of wind speed were measured at elevations of 0.4, 1.4, 2.0 and 2.9 m above the soil surface using Model 27106 bidirectional 15 pulse per revolution propeller anemometers (R.M. Young, Traverse City, MI). Propellers measuring *u* and *v* components were pointed South, parallel to rows, and East, perpendicular to rows, respectively, and were placed midway between rows. Outputs from the anemometers were sampled at 5 Hz by a Model CR7X datalogger (Campbell Scientific, Inc., Logan, UT), and the variance and average wind speed over 12-min periods were computed. Horizontal and vertical turbulent intensity were calculated from propeller anemometer measurements as

$$\mathrm{TI}_h = \sigma_h/V_h \quad (6)$$

and

$$\mathrm{TI}_v = \sigma_v/V_h \quad (7)$$

where σ_h and σ_v are standard deviations of horizontal and vertical wind speed, respectively.

Soil surface and canopy temperatures were measured with 4° field-of-view infrared radiometers (Model 4000A, Everest Interscience, Tustin, CA). Three radiometers were pointed at the soil surface, while two radiometers were aimed at east and west sides of trellises to obtain an average canopy temperature. Leaf areas of plants with sap flow gauges were determined from measurements of leaf length and width following the procedure of Lascano et al. (1992). Other measurements included global irradiance and rainfall.

3. Results and discussion

Environmental conditions during the 1992 and 1993 measurement periods are summarized in Table 1. Skies were generally partly cloudy during both periods. The vineyard was not irrigated during the 1992 study, but rainfall occurred on several days, mostly in the evening and early morning. On Days 153–155 of 1992, 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 $\boldsymbol{\lambda E}$ and $\boldsymbol{H}$, and therefore, $\boldsymbol{\lambda E_s}$ and $\boldsymbol{H_s}$ from Eq. (1) and Eq. (3). No rainfall occurred during the 1993 study, but the vineyard was drip-irrigated on Day 159 and 160. The amount of irrigation water applied was not

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, 1992, and 155–163, 1993. Temperatures and wind speed were measured 1 m above the canopy

Day	R_s ($MJ m^{-2}$)	T_{air} (°C) Maximum	T_{air} (°C) Minimum	T_{dew} (°C) Maximum	T_{dew} (°C) Minimum	U ($m s^{-1}$)	P (mm)
1992							
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	14.0	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
1993							
155	28.1	30.0	17.3	13.7	11.1	2.6	0
156	14.1	31.8	17.4	19.8	12.1	3.5	0
157	20.2	22.7	22.0	20.9	16.5	4.2	0
158	26.8	24.9	22.9	20.4	−6.4	3.6	0
159	29.7	33.2	17.6	16.7	−6.3	2.4	0
161	22.7	27.3	12.7	16.1	11.9	1.6	0
162	29.2	29.9	12.7	18.0	12.1	2.3	0
163	27.7	30.9	16.1	18.1	13.6	2.7	0

measured, but less than 2% of the soil surface was wet following irrigation. Energy balance measurements were not collected on Day 160, 1993 due to heavy cloud cover associated with a cold front.

Average leaf area on plants with sap flow gauges was 4.7 m^2 in 1992, and 7.1 m^2 in 1993, and corresponding leaf area indices were 0.9 and 1.4, respectively. Stomatal resistance on sunlit leaves was generally less than 75 $s m^{-1}$ during both measurement periods, indicating that plants were not water stressed.

Daytime energy balances of the vineyard with narrow and dense, widely-space hedgerows in 1992, and with wider, less dense (open) hedgerows in 1993 are given in Table 2. In 1992, R_n for the dense hedgerows ranged from 12.5 to 18.9 $MJ m^{-2}$, of which 82–89% was soil net irradiance (Table 3). Unstable conditions predominated above the vineyard, with H accounting for 17–28% of R_n, and G 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 of water loss), and accounted for 46–61% of R_n.

In 1993, R_n for the open hedgerows ranged from 10.0 to 19.1 $MJ m^{-2}$, of which 50–60% was soil net irradiance. On days with global irradiance comparable to that measured in 1992, R_n of the open hedgerows was similar to that of the dense hedgerows (Tables 1 and 2), consistent with observations of Baldocchi (1994) which showed that canopy closure had a minor effect on net irradiance. Unstable conditions again predominated, with H accounting for 13–37% of R_n. Soil heat flux was lower for the open

Table 2
Daylight (sunrise to sunset) energy balance components of the vineyard for dense hedgerows in 1992, and open hedgerows in 1993; included are net irradiance (R_n), soil heat flux (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})	$-G/R_n$	$-H/R_n$	$-\lambda E/R_n$
1992							
152	13.3	−3.2	−3.3	−6.8	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
1993							
155	17.9	−2.6	−6.6	−8.7	0.14	0.37	0.49
156	10.0	−1.5	−2.3	−6.2	0.15	0.23	0.62
157	13.1	−2.1	−1.7	−9.3	0.16	0.13	0.71
158	17.1	−2.2	−3.4	−11.5	0.13	0.20	0.67
159	17.8	−1.9	−3.4	−12.5	0.11	0.19	0.70
161	15.4	−2.1	−4.3	−9.0	0.14	0.28	0.58
162	18.2	−2.7	−5.3	−10.2	0.15	0.29	0.56
163	19.1	−2.7	−5.4	−11.0	0.14	0.37	0.49

Negative values indicate fluxes away from the surface. Values of H and λE on Days 153–155, 1992, were excluded because of inadequate fetch when winds were from the North. Energy balance measurements were not collected on Day 160, 1993, because of heavy overcast.

hedgerows, accounting for 11–16% of R_n, while λE ranged from 6.2 to 12.5 MJ m^{-2} (2.5–5.1 mm of water loss), and accounted for 49–70% of R_n.

Daytime energy balances of the soil surface are listed in Table 4. Soil net irradiance for the dense hedgerows 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 44–68% of vineyard λE (Table 3). 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. For the open hedgerows, H_s accounted for more than 50% of R_{ns}, with the remainder partitioned almost equally between G and λE_s. Soil latent heat flux ranged from 1.1 to 2.5 MJ m^{-2} (0.4–1.0 mm), and accounted for 16–22% of vineyard λE. Sensible heat was again generated at the soil surface, with soil surface temperatures exceeding air temperature at canopy height by as much as 20°C.

Daytime energy balances of the canopy are shown in Table 5. In 1992, canopy net irradiance per unit land area was low (1.4–3.0 MJ m^{-2}) because of the narrow hedgerows and widely spaced rows. Canopy λE exceeded R_{nc} on all days, and ranged from 2.1 to 3.8 MJ m^{-2} (0.8–1.6 mm). Positive H_c, and negative H_s and H indicate that the canopy absorbed sensible heat that was generated at the soil surface. This

Table 3
Ratios of daylight (sunrise to sunset) totals of soil and canopy net irradiance, sensible heat flux and latent heat flux to net irradiance, sensible heat flux and latent heat flux of the vineyard for dense hedgerows in 1992, and open hedgerows in 1993

Day	R_{ns}/R_n	R_{nc}/R_n	H_s/H	H_c/H	$\lambda E_s/\lambda E$	$\lambda E_c/\lambda E$
1992						
152	0.89	0.11	1.24	−0.24	0.68	0.32
153	0.89	0.11	–	–	–	–
154	0.82	0.18	–	–	–	–
155	0.87	0.13	–	–	–	–
156	0.84	0.16	1.40	−0.40	0.59	0.41
157	0.83	0.17	1.14	−0.14	0.55	0.45
158	0.87	0.13	1.68	−0.68	0.44	0.56
159	0.83	0.17	1.24	−0.24	0.64	0.36
1993						
155	0.55	0.45	0.88	0.12	0.17	0.83
156	0.52	0.48	1.13	−0.13	0.18	0.82
157	0.50	0.50	1.59	−0.59	0.19	0.81
158	0.60	0.40	1.67	−0.67	0.18	0.82
159	0.60	0.40	1.91	−0.91	0.18	0.82
161	0.51	0.49	0.98	0.02	0.17	0.83
162	0.57	0.43	1.11	−0.11	0.18	0.82
163	0.58	0.42	1.22	−0.22	0.16	0.84

Values of H and λE on Days 153–155, 1992, were excluded because of inadequate fetch when winds were from the North. Energy balance measurements were not collected on Day 160, 1993, because of heavy overcast.

within-row advection accounted for 17–60% of λE_c, and occurred mainly in the afternoon. Canopy temperatures were usually higher than air temperature at canopy height during the morning, but were as much as 5°C lower during the afternoon.

Canopy R_n for the open hedgerows was substantially higher than for the dense hedgerows, ranging from 4.8 to 8.0 MJ m^{-2}. Canopy λE ranged from 5.1 to 10.3 MJ m^{-2} (2.1–4.2 mm), and exceeded R_{nc} on all but two days due to within-row advection. Soil-generated H accounted for 1–30% of λE_c. On Days 155 and 161, canopy temperatures were higher than air temperature at canopy height throughout the day. On the other days, canopy temperatures were higher than air temperature during the morning, and lower in the afternoon by as much as 4°C.

Within- and above-canopy air temperature profiles showed that lapse conditions existed in the boundary layer during throughout the daytime on every day that energy balance measurements were made. The soil surface was considerably warmer than the air during most of the day, resulting in substantial sensible heat transport from the soil. Although the canopy was cooler than the air during the afternoon on all but two days, it was not a large enough sink for sensible heat to produce stable conditions above the canopy.

Soil and canopy energy balances were affected by wind speed and direction. McInnes et al. (1996) measured aerodynamic conductances at the soil surface in the vineyard

Table 4
Daylight (sunrise to sunset) energy balance components of the soil surface for dense hedgerows in 1992, and open hedgerows in 1993; 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 (MJ m^{-2})	H_s (MJ m^{-2})	λE_s (MJ m^{-2})	$-G/R_{ns}$	$-H_s/R_{ns}$	$-\lambda E_s/R_{ns}$
1992							
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	–	–	0.26	–	–
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
1993							
155	9.9	−2.6	−5.8	−1.5	0.26	0.59	0.15
156	5.2	−1.5	−2.6	−1.1	0.29	0.50	0.21
157	6.6	−2.1	−2.7	−1.8	0.32	0.41	0.27
158	10.4	−2.2	−5.7	−2.5	0.21	0.55	0.24
159	10.6	−1.9	−6.5	−2.2	0.18	0.61	0.21
161	7.8	−2.1	−4.2	−1.5	0.27	0.54	0.19
162	10.4	−2.7	−5.9	−1.8	0.26	0.57	0.17
163	11.1	−2.7	−6.6	−1.8	0.24	0.60	0.16

Negative values indicate fluxes away from the surface. Values of H_s and λE_s on Days 153–155, 1992, were excluded because of inadequate fetch when winds were from the North which affected their calculation via Eq. (1) and Eq. (3). Energy balance measurements were not collected on Day 160, 1993, because of heavy overcast.

concurrent with the energy balance measurements for the open hedgerows in 1993, and found that the spatial distribution of conductance varied with wind direction. For wind direction perpendicular to rows (cross-row wind), conductance beneath rows was higher than between rows, whereas for wind direction parallel to rows (down-row wind), the opposite was true. They also found that spatial mean values of conductance normalized to the square root of wind speed were 17% higher for down-row wind than for cross-row wind.

During the 1992 measurement period, we found evidence of downward penetration of turbulent eddies from above the canopy when wind direction was perpendicular to rows (Heilman et al., 1994), similar to observations made by McAneney and Judd (1990) in multiple windbreaks. Fig. 2 shows wind speeds at 0.4 m above the soil measured beneath and between rows of the open hedgerows in 1993. For cross-row wind, wind speed beneath rows was as much as 0.3 m s^{-1} higher than between rows, whereas for down-row wind, it was as much as 0.2 m s^{-1} lower. Data in Fig. 2 suggest that downward-moving air was channeled beneath rows and accelerated. Although wind speed beneath rows was not measured in the dense hedgerows, it is likely that spatial variability in wind speed and conductance for dense hedgerows was greater for

Table 5
Daylight (sunrise to sunset) energy balance components of the canopy for dense hedgerows in 1992, and open hedgerows in 1993; 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}. Also shown is the total daytime evaporative flux from the canopy on a unit leaf area basis (E_c)

Day	R_{nc} (MJ m^{-2})	H_c (MJ m^{-2})	λE_c (MJ m^{-2})	$-H_c/R_{nc}$	$-\lambda E_c/R_{nc}$	E_c (kg m^{-2})
1992						
152	1.4	0.8	−2.2	−0.57	1.57	1.0
153	1.5	0.6	−2.1	−0.40	1.40	0.9
154	3.0	0.8	−3.8	−0.27	1.27	1.7
155	2.5	0.5	−3.0	−0.20	1.20	1.3
156	2.5	1.0	−3.5	−0.40	1.40	1.6
157	2.9	0.6	−3.5	−0.20	1.20	1.6
158	1.6	2.4	−4.0	−1.50	2.50	1.8
159	2.8	0.8	−3.6	−0.29	1.29	1.6
1993						
155	8.0	−0.8	−7.2	0.10	0.90	2.1
156	4.8	0.3	−5.1	−0.06	1.06	1.5
157	6.5	1.0	−7.5	−0.15	1.15	2.2
158	6.7	2.3	−9.0	−0.34	1.34	2.6
159	7.2	3.1	−10.3	−0.43	1.43	3.0
161	7.6	−0.1	−7.5	0.01	0.99	2.2
162	7.8	0.6	−8.4	−0.08	1.08	2.5
163	8.0	1.2	−9.2	−0.15	1.15	2.7

Negative values indicate fluxes away from the surface. Energy balance measurements were not collected on Day 160, 1993, because of heavy overcast and light rain.

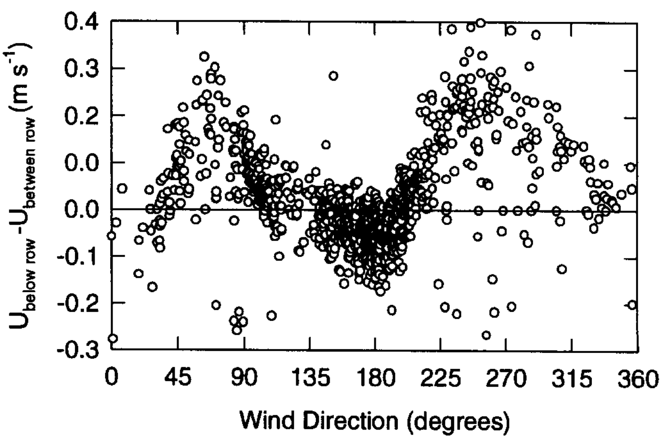

Fig. 2. The difference between wind speed measured below rows and between rows as a function of wind direction for open hedgerows in 1993. Wind speeds were measured at 0.4 m above the soil surface.

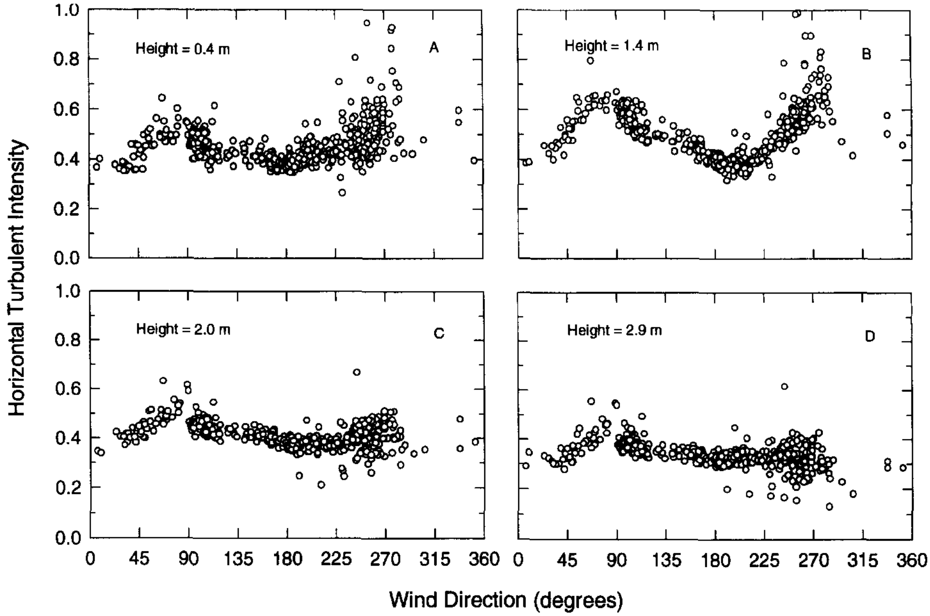

Fig. 3. Horizontal turbulent intensity measured midway between rows of the open hedgerows in 1993, as a function of wind direction. The height of the canopy was 1.6 m.

cross-row wind and lower for down-row wind because there was little foliage below the cordon wire at 1 m above the soil, in contrast to the open hedgerows.

Ham and Heilman (1991) found that wind speed by itself was not sufficient to characterize aerodynamic conductance at the soil surface in sparse crops, and suggested that turbulent intensity (TI) be used along with wind speed to quantify conductance under the assumption that conductance would be directly proportional to TI. However, variation of TI with wind direction was opposite that of aerodynamic conductance measured by McInnes et al. (1996). The TI measured midway between rows was highest for cross-row wind, and lowest for down-row wind (Figs. 3 and 4). Turbulent intensity was higher within the vineyard than above, and it decreased with elevation above vineyard rows.

We did not find any consistent dependence of drag coefficient on wind direction for either dense or open hedgerows. Drag coefficients were slightly higher for the open hedgerows than for the dense hedgerows, with mean values of 0.0542 and 0.0516 at 3 m above the soil, respectively, but were not significantly different at the 10% confidence level.

Our results show that canopy architecture had a substantial effect on soil and canopy energy balances, mainly by changing the partitioning of vineyard net irradiance into its soil and canopy components. The trellising procedure used in 1992 created narrow, widely-spaced hedgerows that decreased sunlit leaf area and increased sunlit soil area. As a result, canopy net irradiance and latent heat flux were reduced, and soil net

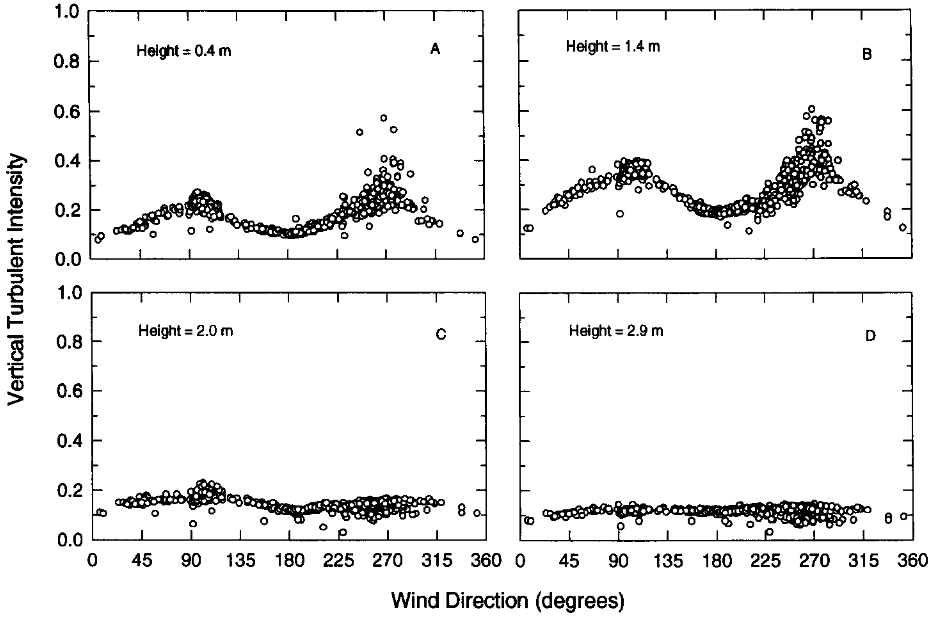

Fig. 4. Vertical turbulent intensity measured midway between rows of the open hedgerows in 1993, as a function of wind direction. The height of the canopy was 1.6 m.

irradiance, latent and soil heat fluxes were increased. Allowing the vines to grow outward and downward from the trellis in 1993 created more open hedgerows which increased sunlit leaf area and reduced sunlit soil area, resulting in increased canopy net irradiance and latent heat flux, and reduced soil net irradiance, latent and soil heat fluxes. Sensible heat generated at the soil surface was a major contributor to the energy balance of the canopy for both dense and open hedgerows.

On high-flux days with similar global irradiance, λE_c per unit land area was, on average, 150% higher for the open hedgerows than for the dense hedgerows, whereas LAI of the open hedgerows was only 55% higher. Canopy λE per unit leaf area was 63% higher than for the open hedgerows, which suggests that roughly 60% of the difference in λE_c was due to trellising.

Leaf area contributed to the energy balance differences we observed. However, if the vines in 1993 had been wrapped as tightly to the trellis as in 1992, it is likely that energy balances would have been similar, in spite of the higher leaf area.

In our experiments, we used spatially averaged parameters to describe the soil energy balance, and did not examine positional variation. Because of periodic shading, and variations in wind speed, aerodynamic conductance and surface 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 vineyard energy balances. Thus, any attempt to describe aerodynamic transport in vineyards must include wind direction.

Acknowledgements

Support for this research was provided by USDA-CSRS Grant No. 91-37101-6757. We thank Jerry Delaney, and Ronnie and Justin Wilson of Delaney Vineyards for their cooperation and assistance in providing and maintaining the research site for this study. Technical Article TA-31765 from the Texas Agricultural Experiment Station, College Station, TX 77843, USA.

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