

# Evapotranspiration from cranberry compared with the equilibrium rate<sup>1</sup>

Clay P.L. Vanderleest and William L. Bland

**Abstract:** The rate of evapotranspiration from a mature cranberry bed in Wisconsin was measured using infrared thermometry. Values ranged from 0.8 to 6.2 mm d<sup>-1</sup>, which were on average 1.05 of the equilibrium evaporation rate. These results are in good agreement with those measured earlier in Wisconsin by the Bowen-ratio technique. Estimates of stomatal conductance were extracted from the data, yielding values of at least 0.2–0.3 mol m<sup>-2</sup> s<sup>-1</sup>, substantially higher than earlier reports for cranberry but typical of uncultivated plants. Our results give us good confidence that cranberry evapotranspiration in the continental climate of Wisconsin, at least, can be estimated from the equilibrium evaporation rate, i.e., the Priestley–Taylor potential rate, with  $\alpha = 1.05$ .

**Key words:** *Vaccinium macrocarpon* Ait., evapotranspiration, water use, equilibrium evaporation, stomatal conductance.

**Résumé :** Les auteurs ont mesuré le taux d'évapotranspiration d'un lit de canneberge mature par thermométrie infrarouge, au Wisconsin. Les valeurs fluctuaient de 0,8 à 6,2 mm d<sup>-1</sup>, ce qui correspond en moyenne à 1,05 fois le taux d'évaporation au point d'équilibre. Ces résultats concordent bien avec ceux établis antérieurement au Wisconsin avec la technique du rapport de Bowen. Les données ont servi à estimer la conductance des stomates, qui s'est établie à au moins 0,2–0,3 mol m<sup>-2</sup> s<sup>-1</sup>, soit nettement au-dessus de ce qui a déjà été rapporté pour la canneberge, mais une valeur typique pour des plantes sauvages. Ces résultats permettent aux auteurs d'affirmer avec confiance qu'il est possible d'estimer le taux d'évapotranspiration de la canneberge, du moins dans le climat continental du Wisconsin, à partir du taux d'évaporation au point d'équilibre, à savoir l'évaporation potentielle de Priestley–Taylor, avec  $\alpha = 1,05$ . [Traduit par la Rédaction]

**Mots-clés :** *Vaccinium macrocarpon* Ait., évapotranspiration, utilisation de l'eau, évaporation au point d'équilibre, conductance des stomates.

## Introduction

The current water appropriation by agriculture and the future demands of this economic sector are of increasing interest as projections indicate shortfalls to meet food demand (Godfray et al. 2010). One facet of this is estimating the “water footprint” of food products. These estimates are then used as the food sector studies its water-related vulnerabilities (Roberts and Barton 2015). New regulatory regimes surrounding water use include requirements to report consumptive use by crop and livestock producers (e.g., the Great Lakes Compact, and Wisconsin State statutes 281.343(4d) and

281.346(2c). Cranberry production is recognized as “water dependent” within the context of the United States’ Clean Water Act (USACE 1995), requiring best management practices. Detailed analyses of crop water usage for sustainability assessments and regulatory compliance depend on estimates of evapotranspiration (ET, (H<sub>2</sub>O depth time<sup>-1</sup>)) losses.

Few experiments have measured ET from cranberry. Hattendorf and Davenport (1996), working in coastal Washington state, found cranberry ET from near 0 to about 4 mm d<sup>-1</sup>. In Wisconsin, Bland et al. (1996) observed cranberry ET rates between 0.7 and 6.3 mm d<sup>-1</sup>.

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**Abbreviations:** ET, evapotranspiration rate (water depth flux density);  $E_{eq}$ , equilibrium evaporation rate (molar flux density);  $E_{imp}$ , imposed evaporation rate (molar flux density);  $R_n$ , net radiation;  $H$ , sensible heat flux;  $G$ , soil heat flux;  $\lambda$ , latent heat of vaporization;  $\gamma$ , psychrometer constant;  $s$ , slope of saturation vapor pressure vs temperature;  $\alpha$ , Priestley–Taylor coefficient;  $\Omega$ , coupling coefficient;  $c_p$ , heat capacity of dry air;  $D$ , water vapor saturation deficit;  $g_c$ , canopy conductance;  $g_s$ , leaf-level stomatal conductance.

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**Table 1.** Variables required for the double-delta-T method. Environmental variables were directly measured in the field at 30 min intervals.

Parameter	Average (range)	Unit
<b>Measured</b>		
Net radiation ( $R_n$ )	315.92 (−44.17 to 782)	$W m^{-2}$
Soil heat flux ( $G$ )	18.60 (−54.24 to 71.79)	$W m^{-2}$
Canopy temperature	25.79 (13.32–37.34)	$^{\circ}C$
Air temperature	23.19 (13.02–30.46)	$^{\circ}C$
Soil temperature	19.80 (14.57–23.75)	$^{\circ}C$
Wind speed	2.15 (0–5.57)	$m s^{-1}$
Canopy height	0.15	m
Leaf area index (LAI)	3.8 (3.3–4.3)	
<b>Estimated</b>		
Fraction of canopy that is green	1	
Displacement height ( $d_o$ )	0.12	m
Momentum transport roughness length ( $Z_{om}$ )	0.0075	m
Heat transport roughness length ( $Z_{oh}$ )	0.0075	m
Priestley–Taylor coefficient ( $\alpha_{PT}$ )	1.26	

The Washington ET values were about 55% of the Priestley–Taylor potential ET (Priestley and Taylor 1972), while the Wisconsin values were about 83% of this widely used standard. Assuming a reasonable average potential ET during the main growing season of  $5.0 \text{ mm d}^{-1}$ , the substantial difference between the two estimates of cranberry ET (i.e., reasonable season-long averages of 2.8 and  $4.2 \text{ mm d}^{-1}$ ) suggests that additional research is warranted in understanding how to estimate cranberry water requirements.

The two research groups used very different measurement techniques in the 1996 work. Hattendorf and Davenport (1996) used ground-based thermal remote sensing (Maes and Steppe 2012) of the canopy temperature to estimate the sensible heat flux component of the surface energy budget:

$$R_n = H + G + \lambda ET \quad (1)$$

where  $R_n$  = net radiation,  $H$  = sensible heat flux,  $G$  = soil heat flux, all in ( $Wm^{-2}$ ), and  $\lambda$  = latent heat of vaporization ( $J m^{-3}$ ). Direct measurements of  $R_n$  and  $G$  combined with the temperature-based estimation of  $H$  allowed solution for  $\lambda ET$ .

The Wisconsin group used the Bowen-ratio energy budget method (Irmak et al. 2014). In this approach, the gradients of temperature and vapor pressure are measured above the evaporating surface, and their ratio used to partition ( $R_n - G$ ) between  $H$  and  $\lambda ET$ , yielding ET.

In comparison with the earlier Washington work, in this research we applied thermal remote sensing of canopy temperature with a more recent analysis strategy (Norman and Kustas 1999; Norman et al. 2000) and newer radiometers to revisit cranberry ET in Wisconsin. We further analyzed our new measurements using the “coupling” framework of Jarvis and McNaughton (1986) to gain insight into the role of stomatal control in observed cranberry ET.

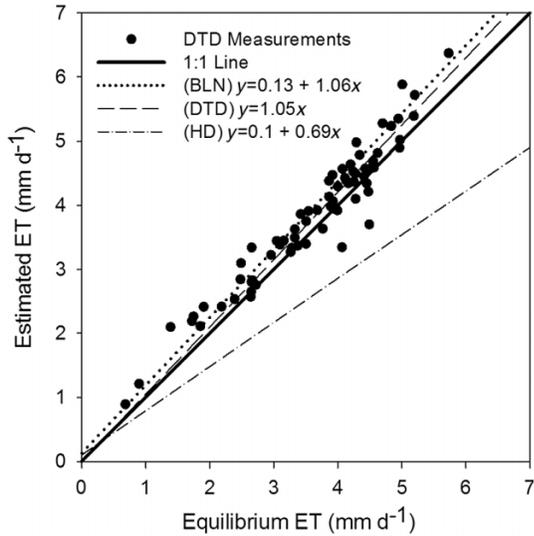
## Materials and Methods

The 1 ha area study site was a commercial bed located near Warrens, Wisconsin (44.087926 N, −90.477031 E). The soil was 1 m of fine sand relocated from nearby sand dunes. Cranberry plants were ‘Grygleski Hybrid 1’ (GH1) planted in 2002. Drain tiles were located at a depth of 500 mm, 4 m apart, running the length of the bed.

Crop ET was estimated using ground-based thermal remote sensing of the energy budget. Canopy temperature was measured using infrared radiometers (model SI-111, Apogee Instruments Inc., Logan, UT, USA), installed at 1 m above the canopy, at two locations about 30 m apart. Soil heat flux ( $G$ ) was measured at each site using soil heat flux plates (model HFT 1.1, Radiation and Energy Balance Systems, Inc., Seattle, WA, USA) installed at 50 mm depth. Heat storage above the flux plate was based on temperature recorded by thermocouples installed at 25 mm and assumed heat capacity of sandy soil. Net radiation was recorded using a four-component net-radiation sensor (model NR01, Hukseflux Thermal Sensors, Manorsville, NY, USA) installed at 1 m above the canopy. Air temperature and relative humidity were measured (model HMP 60, Campbell Scientific, Logan, UT, USA) at 1 m above the canopy. Wind speed was recorded using a cup anemometer (model 014, Met One Instruments, Grant Pass, OR, USA). All measurements were recorded at 30 min intervals using either a CR23X data logger or a CR1000 data logger (Campbell Scientific, Logan, UT, USA). Leaf area index (LAI) was measured using a plant canopy analyzer (model LAI-2000, Li-Cor, Lincoln, NE, USA). Reported observations were made between days of year 155 and 247, 2014.

Infrared temperatures were interpreted using the “double-delta-T” method described by Norman et al. (Norman and Kustas 1999; Norman et al. 2000) (Table 1). This method is based on interpreting the infrared

**Fig. 1.** Cranberry evapotranspiration (ET) versus equilibrium evapotranspiration for three experiments. Data points and dashed line are the present study (DTD), the dotted line (BLN) shows the relationship obtained by Bland et al. (1996), and the dashed-dotted line (HD) shows approximately the relationship obtained by Hattendorf and Davenport (1996), assuming an  $\alpha$  value of 1.26.



temperature of the crop and soil in terms of  $H$ , as did Hattendorf and Davenport (1996). The double-delta-T method also adds explicit separation of leaf and soil (a two-source model) and compares changes of both air and canopy temperatures through the day, rather than just their difference. The values of canopy height, transport resistances, and LAI were assumed constant because of the relatively static nature of the cranberry canopy through the season and lack of sensitivity of the analysis across the range observed (see Results and Discussion).

### Results and Discussion

Daily values of ET by the double-delta-T method were similar to those obtained earlier (Bland et al. 1996) using the Bowen-ratio method (Fig. 1). In Fig. 1, we compare the observed ET values to the “equilibrium” ET rate (Jarvis and McNaughton 1986; Moene and van Dam 2014):

$$\lambda ET_{eq} = (s/(s + \gamma))(R_n - G) \quad (2)$$

where  $s$  = slope of the saturation vapor pressure versus temperature ( $\text{kPa K}^{-1}$ ) and  $\gamma$  = psychrometer constant ( $\text{kPa K}^{-1}$ ). The equilibrium rate is the theoretical value of evaporation from a wet surface into a saturated atmosphere. Water loss is sustained because the evaporating surface is also supplying sensible heat to the overlying air, steadily increasing the saturation vapor pressure. The well-known Priestley–Taylor potential evaporation rate is the equilibrium rate multiplied by  $\alpha$ , a value between 1.1 and 1.4, most commonly cited as 1.26, as originally proposed by Priestley and Taylor

(1972). The opportunity for  $\alpha > 1$  occurs because of entrainment of dry air into the planetary boundary layer as the day progresses (Moene and van Dam 2014).

We found that the double-delta-T calculation reduced to the method essentially used by Hattendorf and Davenport (1996). This occurs because the LAI of crop was sufficiently high and nongreen fraction low, so that there was little soil or nontranspiring tissue in the infrared radiometer’s view. Additionally, air temperature was consistently close to canopy temperature at the start of each day, so the differencing of temperature changes in the double-delta-T method had no impact. A consequence of this is that the calculation we did was not appreciably sensitive to input values of LAI, green fraction, and the Priestley–Taylor  $\alpha$ . Varying the values of LAI, green fraction, and  $\alpha$  by  $\pm 20\%$  changed the daily values of evapotranspiration by  $\pm 9\%$ .

Comparing our results with those of Hattendorf and Davenport (1996) is complicated by two issues. First, they chose to not include those hours of the early morning during which dew was present. We reanalyzed our data excluding hours before 1000 and found that it reduced daily ET by 10.6%, enough to explain 32% of the difference between the locations (Fig. 1). Second, Hattendorf and Davenport (1996) altered  $\alpha$  daily by multiplying it by the vapor pressure deficient (kPa). To convert their published results, we assumed that their  $\alpha = 1.26$ , but this assumption should be acceptable given that  $D$  is typically near 1.0. Before returning to the question of why our results differed from the Washington values, we wish to explore the question raised by Hattendorf and Davenport (1996): Why are the observed values so far below the Priestley–Taylor potential ET? They concluded that cranberry had quite low stomatal conductance, and that this was a possible explanation.

Jarvis and McNaughton (1986) analyzed the factors controlling ET by introducing the coupling coefficient  $\Omega$ , which expresses how well the surfaces of individual leaves are coupled to the surrounding free air:

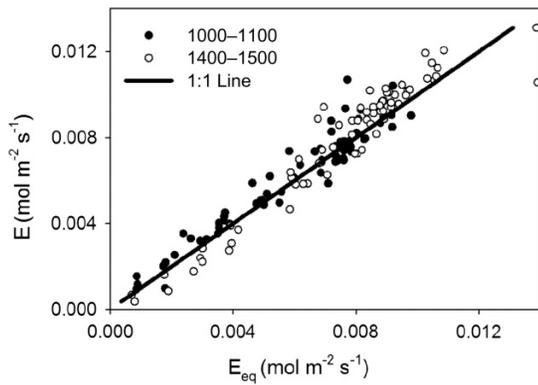
$$E = \Omega E_{eq} + (1 - \Omega)E_{imp} \quad (3)$$

where (shifting to flux densities in units of  $\text{mol m}^{-2} \text{s}^{-1}$ )  $E$  is total evaporation rate,  $E_{eq}$  is the equilibrium evaporation rate as defined in eq. 2 (with appropriate unit conversions), and  $E_{imp}$  is the “imposed” evaporation rate defined as

$$E_{imp} = (c_p/\gamma)g_c D \quad (4)$$

where  $c_p$  = heat capacity of dry air ( $\text{J mol}^{-1} \text{K}^{-1}$ ),  $g_c$  = canopy conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ ), and  $D$  = water vapor saturation deficit (kPa). Thus, both  $ET_{eq}$  (eq. 2) and  $E_{eq}$  (eq. 3) refer to the water loss rate (taking evapotranspiration and evaporation as both referring to total water loss from the soil-crop system) from a canopy into a saturated atmosphere but expressed in different units (to maintain consistency with various other authors).

**Fig. 2.** Mid-morning (1000–1100) and mid-afternoon (1400–1500) values of estimated evaporation versus equilibrium evaporation.

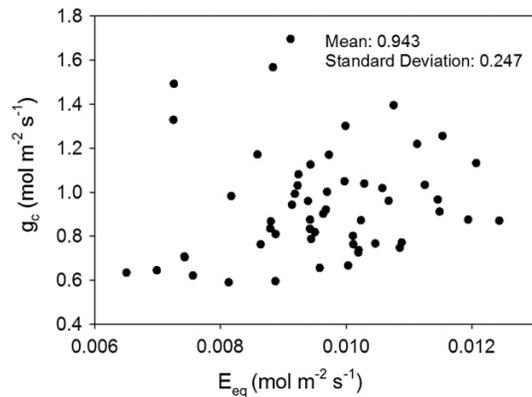


These limiting rates of evaporation arise from the well-known Penman–Monteith equation:  $E_{eq}$  is the case of leaf boundary layer conductance becoming very small, effectively uncoupling the leaf from the surrounding air, while  $E_{imp}$  is the opposite case of very high leaf boundary layer conductance, leading to control of the water loss rates becoming some function of  $g_c$  and  $D$ . When  $\Omega = 1$ , the leaf or canopy is effectively uncoupled (perhaps a better term for  $\Omega$ ) from the ambient air-stream, so  $E$  is controlled by available energy. In practice,  $E$  over any given time interval is some combination of both terms of eq. 3, i.e.,  $\Omega$  is never 1 or 0. Jarvis and McNaughton (1986) compiled a table of estimated  $\Omega$  values; alfalfa was highest at  $\Omega = 0.9$ , while pine trees had a  $\Omega$  of 0.1. Heathland dominated by *Calluna vulgaris* (L.) Hull, which like cranberry is a member of the *Ericaceae* family, had a  $\Omega$  of 0.34 (Miranda et al. 1984). Explanations of this analysis approach are available in Jarvis and McNaughton (1986) and Monson and Baldocchi (2014).

We tested for  $\Omega < 1$  by plotting mid-morning and mid-afternoon values of estimated  $E$  against  $E_{eq}$  (Fig. 2). We selected the mid-morning period to capture the situation after any dew has evaporated and before heat or water stresses are likely to have set in. The mid-afternoon times were assumed to be periods of typically ample energy and when heat or water stress, if any, may have developed. When  $E = E_{eq}$  (on the 1:1 line of Fig. 2), it is not possible to learn anything about  $\Omega$  because these values can arise from various combinations of the terms in eq. 3. For those points not on the 1:1 line, we can know that  $\Omega$  is  $< 1$ . Furthermore, if  $E > E_{eq}$ , we can assume that  $E_{imp} > E_{eq}$ , and vice versa.

The morning measurements generally fall along the 1:1 line and so yield no insight into the terms of eq. 3. However, the afternoon measurements on high evaporation days tend to lie above  $E_{eq}$ , implying that  $\Omega$  is  $< 1$  and  $E_{imp}$  during that time is frequently greater than  $E_{eq}$ . We cannot separate the value of  $\Omega$  from  $E_{imp}$  for these

**Fig. 3.** Lower boundary of canopy conductance for mid-afternoon evaporation measurements on high evaporation days.



observations, but because we know that  $E_{imp} > E_{eq}$ , we can estimate a value of  $g_c$  that must have been exceeded:

$$g_c > E_{eq} / (c_p D / \gamma) \quad (5)$$

We found the lower boundary of  $g_c$  to range approximately 0.6–1.6  $\text{mol m}^{-2} \text{s}^{-1}$  (Fig. 3) in the range  $0.006 < E_{eq} < 0.013$ . Actual  $g_c$  values had to exceed those in Fig. 3, in proportion to  $\Omega$ , e.g., if  $\Omega$  is relatively small  $E_{imp}$  exerts a large influence on  $E$  and so  $g_c$  values need to only be slightly larger than those we calculated. From this general range of  $g_c$ , we can further go on to roughly estimate  $g_s$ , the leaf-level stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ ). Kelliher et al. (1995) found that for LAI values of 2–4, the ratio  $g_c$  to maximum values of  $g_s$  (stomata at maximum aperture) was between 2 and 3. This suggests that for our cranberry beds,  $g_s$  was at least 0.2–0.3  $\text{mol m}^{-2} \text{s}^{-1}$  (assuming stomata were at maximum aperture).

Our estimated range of  $g_s$  is consistent with predictions made by Maes and Steppe (2012) in an extensive modeling exercise of leaf and canopy temperatures. Our mid-afternoon canopy temperature measurements ranged 0–10 °C above air temperature, with half of them between 4 and 8 °C (data not shown). Their modeling estimates for a crop with hypostomatous leaves (as is cranberry, Sawyer 1932), 0.25 m tall, in a 2  $\text{m s}^{-1}$  wind, at air temperature = 25 °C, and relative humidity = 50%, indicated that the canopy temperature elevation increased from 4 °C with  $g_s = 0.4 \text{ mol m}^{-2} \text{s}^{-1}$  to 8 °C at  $g_s = 0.2 \text{ mol m}^{-2} \text{s}^{-1}$  (see figure 6b in Maes and Steppe 2012).

This range is higher than other reports for cranberry  $g_s$  (here converted from  $\text{mm s}^{-1}$  to molar flux density by multiplying by 0.041, Campbell and Norman 1998). Hattendorf and Davenport (1996) measured a  $g_s$  of 0.04  $\text{mol m}^{-2} \text{s}^{-1}$  in one of their beds under overcast conditions. Croft et al. (1993) observed a range of 0.008–0.031  $\text{mol m}^{-2} \text{s}^{-1}$  near Chatsworth, New Jersey.

Using current porometry technology, [Pelletier et al. \(2016\)](#) found  $g_s$  to be as high as  $0.24 \text{ mol m}^{-2} \text{ s}^{-1}$  in growth chamber-grown cranberry plants. [Palmroth et al. \(2014\)](#) measured  $g_s$  in other *Vaccinium* species, *V. myrtilus*, and *V. vitis-idaea*, growing as boreal forest understory in northern Sweden. For *V. myrtilus*,  $g_s$  ranged from 0.05 to  $0.08 \text{ mol m}^{-2} \text{ s}^{-1}$  while *V. vitis-idaea* observations ranged from 0.08 to  $0.14 \text{ mol m}^{-2} \text{ s}^{-1}$ . The *Calluna vulgaris* (L.) Hull heathland data in [Miranda et al. \(1984\)](#) yielded a  $g_s$  value of about  $0.2 \text{ mol m}^{-2} \text{ s}^{-1}$  ([Kelliher et al. 1995](#)). In a compilation of field observations of assimilation and stomatal conductance, [Hetherington and Woodward \(2003\)](#) found  $g_s$  values well distributed from near 0 to  $1.2 \text{ mol m}^{-2} \text{ s}^{-1}$ . [Kelliher et al. \(1995\)](#) propose that uncultivated plants will have a maximum  $g_s$  of about  $0.25 \text{ mol m}^{-2} \text{ s}^{-1}$  and that of crop plants will be about  $0.45 \text{ mol m}^{-2} \text{ s}^{-1}$  (at LAI approaching 4). Stomatal conductance might be reduced in natural vegetation, compared with cultivated crops, given lower  $N$  availability in the former ([Schulze et al. 1994](#)) and, perhaps, selection and breeding for productivity in the latter. Thus, our estimations of  $g_s$  are in line with broad compilations of this parameter but are comparable to or higher than limited reports for cranberry and two understory *Vaccinium* species.

Our results combined with those of [Bland et al. \(1996\)](#) suggest that under Wisconsin growing conditions,  $\Omega$ ,  $D$ , and  $g_s$  interact in a conservative way such that cranberry ET is about 1.05 the equilibrium value or 83% of the nominal Priestley–Taylor potential value. That the same result was obtained years apart from two different beds, as measured by two techniques, lends confidence to this assertion. The smaller values reported by [Hattendorf and Davenport \(1996\)](#) are consistent with the low  $g_s$  values they measured. It may be that under their conditions,  $\Omega$ ,  $D$ , and  $g_s$  differed from ours, leading to  $E_{\text{imp}} < E_{\text{eq}}$ . The higher Wisconsin water use is consistent with the relatively high yields observed in the state. Yields were not reported in the cranberry studies cited above, but the bed on which we made the ET measurements reported here yielded about  $38\,000 \text{ kg ha}^{-1}$  in 2013 and  $27\,000 \text{ kg ha}^{-1}$  in 2014, both comparable to the Wisconsin state averages of  $32\,000$  and  $28\,000 \text{ kg ha}^{-1}$  for 2013 and 2014, respectively ([National Agricultural Statistics Service 2015](#)). Additional measurements are required in diverse growing environments to understand the controls over cranberry ET.

## Conclusions

We made canopy temperature-based measurements of cranberry ET and found the same relationship with the equilibrium ET rate as had [Bland et al. \(1996\)](#) using the Bowen-ratio method. Applying the [Jarvis and McNaughton \(1986\)](#) coupling concept, we found that  $\Omega$  was  $<1$  in our experiment during high evaporation periods, and  $g_s$  was likely in the range of  $0.2\text{--}0.3 \text{ mol m}^{-2} \text{ s}^{-1}$ . This places cranberry  $g_s$  below that of cultivated crops in general but perhaps at the higher end of that to be

expected for “natural” vegetation. It appears that for the Wisconsin growing environment, ET estimations are possible based on the equilibrium ET rate. The partitioning of total evaporation into equilibrium and imposed components offers a way forward to resolving the differences between the Wisconsin measurements and those from coastal Washington.

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## References

- Bland, W.L., Loew, J.T., and Norman, J.M. 1996. Evaporation from cranberry. *Agric. For. Meteorol.* **81**: 1–12. doi:[10.1016/0168-1923\(95\)02304-6](#).
- Campbell, G.S., and Norman, J.M. 1998. An introduction to environmental biophysics. 2nd ed. Springer, New York, NY.
- Croft, P.J., Shulman, M.D., and Avissar, R. 1993. Cranberry stomatal conductivity. *HortScience*. **28**(11): 1114–1116.
- Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., and Toulmin, C.; American Association for the Advancement of Science. 2010. Food security: The challenge of feeding 9 billion people. *Science*. **327**(5967): 812–818. doi:[10.1126/science.1185383](#). PMID:[20110467](#).
- Hattendorf, M., and Davenport, J.; American Society for Horticultural Science. 1996. Cranberry evapotranspiration. *HortScience*. **31**(3): 334–337.
- Hetherington, A.M., and Woodward, F.I. 2003. The role of stomata in sensing and driving environmental change. *Nature*. **424**: 901–908. doi:[10.1038/nature01843](#). PMID:[12931178](#).
- Irmak, S., Skaggs, K.E., and Chatterjee, S. 2014. A review of the Bowen ratio surface energy balance method for quantifying evapotranspiration and other energy fluxes. *Trans. ASABE* **57**(6): 1657–1674. doi:[10.13031/trans.57.10686](#).
- Jarvis, P.G., and McNaughton, K.G. 1986. Stomatal control of transpiration: Scaling up from leaf to region. Pages 1–49 in A. Macfayden and E.D. Ford, eds. *Advances in ecological research*. Elsevier, New York, NY.
- Kelliher, F.M., Leuning, R., Raupach, M.R., and Schulze, E.D. 1995. Maximum conductances for evaporation from global vegetation types. *Agric. For. Meteorol.* **73**: 1–16. doi:[10.1016/0168-1923\(94\)02178-M](#).
- Maes, W.H., and Steppe, K. 2012. Estimating evapotranspiration and drought stress with ground-based thermal remote sensing in agriculture: A review. *J. Exp. Bot.* **63**(13): 4671–4712. doi:[10.1093/jxb/ers165](#).
- Miranda, A.C., Jarvis, P.G., and Grace, J. 1984. Transpiration and evaporation from heather moorland. *Bound.-Lay. Meteorol.* **28**: 227–243. doi:[10.1007/BF00121306](#).
- Moene, A.F., and van Dam, J.C. 2014. *Transport in the atmosphere–vegetation–soil continuum*. Academic Press, New York, NY.

- Monson, R.K., and Baldocchi, D.D. 2014. Terrestrial biosphere-atmosphere fluxes. Cambridge University Press, New York, NY.
- National Agricultural Statistics Service. 2015. Noncitrus fruits and nuts. 2014 Summary. United States Department of Agriculture. July 2015: 49.
- Norman, J.M., and Kustas, W.P. 1999. Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover. *Agric. For. Meteorol.* **94**(1): 13–29. doi:[10.1016/S0168-1923\(99\)00005-2](https://doi.org/10.1016/S0168-1923(99)00005-2).
- Norman, J.M., Prueger, J.H., Diak, G.R., and Kustas, W.P. 2000. Surface flux estimation using radiometric temperature: A dual-temperature-difference method to minimize measurement errors. *Water Resour. Res.* **36**(8): 2263–2274. doi:[10.1029/2000WR900033](https://doi.org/10.1029/2000WR900033).
- Palmroth, S., Holm Bach, L., Nordin, A., and Palmqvist, K. 2014. Nitrogen-addition effects on leaf traits and photosynthetic carbon gain of boreal forest understory shrubs. *Oecologia*. **175**(2): 457–470. doi:[10.1007/s00442-014-2923-9](https://doi.org/10.1007/s00442-014-2923-9).
- Pelletier, V., Pepin, S., Gallichand, J., and Caron, J. 2016. Reducing cranberry heat stress and midday depression with evaporative cooling. *Sci Hort.* **198**: 445–453. doi:[10.1016/j.scienta.2015.12.028](https://doi.org/10.1016/j.scienta.2015.12.028).
- Priestley, C.H.B., and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Weather Rev.* **100**(2): 81–92. doi:[10.1175/1520-0493\(1972\)100<0081:OTAOSH>2.3.CO;2](https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2).
- Roberts, E., and Barton, B. 2015. Feeding ourselves thirsty: How the food sector is managing global water risks. Ceres, Boston, MA.
- Sawyer, W.H. 1932. Stomatal apparatus of the cultivated cranberry *Vaccinium macrocarpon*. *Amer. J. Bot.* **19**(6): 508–513.
- Schulze, E.D., Kelliher, F.M., Korner, C., Lloyd, J., and Leuning, R. 1994. Relationships among maximum stomatal conductance, ecosystem surface conductance, carbon assimilation rate, and plant nitrogen nutrition — A global ecology scaling exercise. *Annu. Rev. Ecol. Evol. Syst.* **25**(1): 629–660. doi:[10.1146/annurev.es.25.110194.003213](https://doi.org/10.1146/annurev.es.25.110194.003213).
- USACE (United States Army Corps of Engineers). 1995. St. Paul District Analysis Regarding Section 404 review of Commercial Cranberry Operations. [Online] Available: <http://dnr.wi.gov/topic/waterways/documents/CranberryAnalysis-RedBook-1995.pdf>.