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NOTE

Estimating evaporation for low wind speeds at an eddy correlation site: potential for windbreak evaluation

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Abstract

Creating new windbreaks may reduce lee evaporation by reducing surface wind speed (*u*). However, applying theoretical models to anticipate the extent of evaporation reduction may be liable to error because the physical processes of windbreak evaporative impacts are not fully understood.

An alternative, statistical approach is proposed for sites where eddy correlation time series are available. For low wind speeds the Penman-Monteith equation indicates that recorded evaporation should be approximated as a linear function of *Rn*, neglecting ground heat flux. That is, air temperature and saturation vapour pressure become of lesser importance. Linear regression with *Rn* could then be applied as a simple means to anticipate the extent of site evaporation reduction that would occur if *u* could be sufficiently lowered.

Evaporation linearity with *Rn* may not always be achievable in the lee of actual constructed windbreaks. However, a linear model could still be useful to obtain an upper bound to evaporation reduction, aiding decisions as to whether to construct a windbreak. Preliminary analysis for an eddy correlation site in Canterbury (South Island, New Zealand) indicates that summer evaporation for wind speed around 1 ms^{-1} is well approximated as a linear function of *Rn*, in this case indicating up to 20% possible evaporation reduction. This assumes that consequential changes in other environmental variables can be neglected when wind speed is reduced. If confirmed by further work, the regression approach may find general application as a simple means to anticipate the maximum extent of evaporation reduction from a new windbreak.

Keywords

evaporation; wind speed; shelter belt; windbreak; evaporation reduction

Introduction

For a site where wind speed (*u*) is a significant contributing factor to evaporation from open agricultural land, the question arises as to whether to construct windbreaks to reduce surface wind speeds, and consequently reduce evaporation to increase available water. 'Windbreak' is used here as a collective term to include both constructed windbreaks and planted shelterbelts.

There remains a degree of uncertainty when anticipating the impact of new windbreaks on evaporation. In an early paper, van Bavel *et al.* (1967) noted that under certain conditions evaporation may actually increase if u is reduced. Subsequent contributors to the discussion include Seginer (1970), Skidmore and Hagen (1970), Cleugh (1998), Campi *et al.* (2012) and Davarzani *et al.* (2014), among many others.

In a recent review paper Baker *et al.* (2018) note that agricultural water conservation in windbreak-sheltered zones has been demonstrated in Australian and New Zealand studies. In a more theory-based study, Sugita (2018) cautions that there is still not a full physical understanding of windbreak influences on evaporation. That paper goes on to define mathematical conditions where the sign of the derivative of evaporation with changing u can be positive or negative.

Given the uncertainty of theoretical predictive models, we raise the possibility here of a data-based linear regression approach to estimate the extent of possible evaporation reduction from introducing a windbreak. This is only with respect to anticipating effects in windbreak-sheltered locations where net radiation (Rn) remains unchanged. It may happen that evaporation is actually enhanced further downwind under some conditions (Cleugh and Hughs, 2002). Also, we are not concerned with anticipating indirect evaporative effects of windbreaks, such as development of modified crop characteristics in the lee of windbreaks (McNaughton, 1983). Similarly, we do not attempt to estimate windbreak total water balance, which would need to include factors such as tree windbreak water use and windbreak restriction of irrigation spray drift.

Linear model

For wind speeds near zero and negligible ground heat flux, the Penman-Monteith equation simplifies to a linear function of Rn. There is, therefore, some theoretical justification in seeking a simple linear regression model as an approximation for evaporation with low wind speeds. Of course, simplification of Penman-Monteith for the low wind speed case could also be used directly as a theoretical linear predictive expression. However, our preference is for site data-based application with minimal model assumption other than approximate evaporation linearity with Rn, where linear regression coefficients are to be determined from fitting to data.

Confirming measured evaporation as a linear function of Rn under low wind speeds would provide a simple means by which to anticipate site evaporation reduction potentially achievable by reducing wind speeds. The reduction is noted here as 'potentially achievable' because the reference base is with respect to wind speeds sufficiently low for Rn to dominate as the causal variable in a linear association with evaporation. If high wind speeds are reduced by only a moderate amount then other variables will still contribute and evaporation may be unchanged because conditions of maximum turbulent mixing will still apply (Davarzani *et al.*, 2014). Also, the reference 'low' wind speeds may or may not be achievable in practice, depending on windbreak characteristics and the wind speed distribution.

Data quality control

Eddy correlation data provide the most direct form of evaporation measurement in real time. However, there are some data-related issues that have potential to introduce error into the regression model.

A common issue with eddy correlation data is that the energy terms do not sum to zero. That is, $Rn + LE + H + G \neq 0$, where LE is latent heat flux, H is sensible heat flux and G is ground heat flux. There is never perfect closure and it often happens that $Rn - G > LE + H$. If energy closure is significantly different from zero, one or more of the energy terms must have a degree of measurement error. No evaporation data were used in this study if the energy closure inequality was in excess of 100 Wm^{-2}, using an absolute measure in this case rather than a percentage.

A further issue particularly relevant for the present paper is the potential for eddy correlation data to under-estimate evaporation when wind speeds are low (Anderson and Wang, 2014). It is necessary, therefore, to avoid very low wind speeds to avoid this biasing effect. At the same time, it is necessary to find a reference wind speed that is sufficiently low for the linear relation of evaporation with *Rn* to hold as an approximation. For the purposes of this study, the selected 'low' wind speed data were defined to be within the narrow wind speed range 0.8–1.0 ms^{-1}, where 0.8 ms^{-1} still exceeds those lower *u* values that have been previously noted to be associated with bias effects (Barr *et al.*, 2013).

We used gap-filled data for this study, which creates a potential source of error. However, any significant error should be filtered out by the energy closure requirement.

Site

The eddy correlation site used to evaluate the linear approach is located on an irrigated dairy farm in the mid-Canterbury plains of the South Island, New Zealand. Site information and data is available as part of the OzFlux network (Laubach, 2016). Hunt *et al.* (2016) give details of data processing and filtering.

Site wind speeds were recorded at 1.8 metres above ground surface. The data include 30-minute means of wind speed, evaporation, latent heat flux, sensible heat flux, ground heat flux, and net radiation. Utilised data were restricted to the summer months of December, January and February, extending from December 2012 to February 2014. There were 180 days included in total.

This open site has only a small proportion of daytime wind speeds less than 1 ms^{-1} (Fig. 1). To help better define any linear function arising from a regression model, a Waikato region (North Island, New Zealand) eddy correlation site with lower mean wind speeds was also selected to provide some further low wind speed data. This was simply for data support and not with a view to consideration of windbreaks in the Waikato region. The same flux variables were available as for the Canterbury site, with utilised Waikato data being 30-minute means for January and February of 2012 and 2013, and December 2012. A site description is given by Pronger *et al.* (2016).

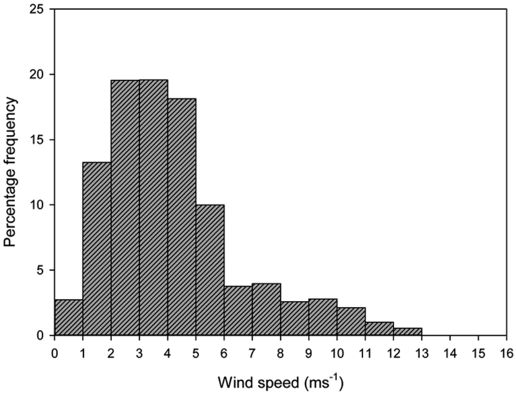

Figure 1 – Wind speed frequency distribution for *Rn* > 100 Wm^{-2} (30-minute means).

Data selection

The selected low wind speed data for the Canterbury site showed a consistent pattern of departure from energy closure (Fig. 2), which is common with eddy correlation data (Leuning *et al.*, 2012). To reduce possible biasing effects, the same field of energy closure was used to select the comparison set of higher wind speed half-hours. Specifically, wind speeds greater than 1 ms^{-1} were only utilised for evaporation comparison if their associated energy closure plotted within ± 30 Wm^{-2} of a regression line through the lower wind speed data. A final filtering process removed any data points with $Rn < 100\ Wm^{-2}$, giving approximate overlap with daylight hours.

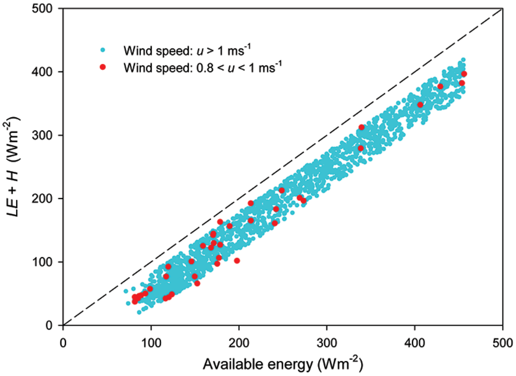

Figure 2 – Selected 30-minute flux means for the higher and lower wind speed data sets, showing overlap of the energy closure region. Dashed line is exact closure. Available energy is *Rn - G*.

Linear expression

The selection process defined above produced a data set of 30-minute flux means within the defined narrow low wind speed range, for the Canterbury site. A similar process was applied to the Waikato data to give some further low-speed data. The overlap of both data sets in a scatter plot is suggestive of a common linear relation (Fig. 3), with a linear regression applied to the combined data giving:

$$E = 0.00041\,Rn - 0.017 \qquad (1)$$

where E is evaporation (mm) per half hour and Rn is in Wm^{-2}.

This linear function of *Rn* represents the combined data quite well ($r^2 = 0.85$). For the two sites, this can be interpreted as showing that summer evaporation with water availability can be approximated as a linear function of *Rn* for wind speeds up to 1 ms^{-1}, largely independent of other variables. If this is confirmed for other localities, then a linear regression expression might be used generally to anticipate the extent of evaporation reduction from a hypothetical lowering of site wind speeds to 1 ms^{-1} or less. It needs to be noted, however, that ground heat flux, *G*, is not always insignificant for this data, as can been seen from comparison of the *x* axes of Figures 2 and 3.

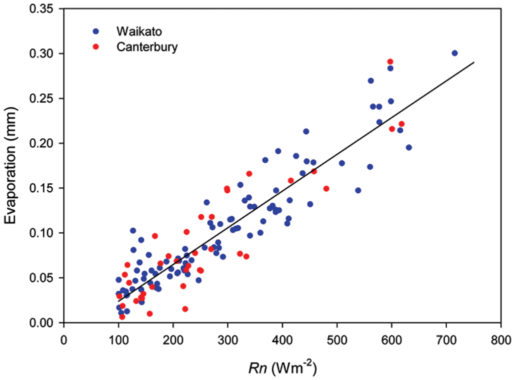

Figure 3 – Summer 30-minute evaporation values plotted against net radiation for wind speed in the range $0.8 < u < 1\ ms^{-1}$, for the Canterbury and Waikato eddy correlation sites. The solid line is a plot of Eq. (1).

Estimating evaporation reduction potential

A wind speed influence on evaporation at the Canterbury site is shown from the evaporation subset with wind speeds > 4 ms^{-1} plotting more frequently above the regression line for low wind speeds (Fig. 4). There is a greater degree of variability for evaporation with higher wind speeds because other factors such as air temperature will then be of importance in addition to *Rn*. However, the suggestion remains from Figure 4 that if the wind speeds exceeding 4 ms^{-1} could be reduced to 1 ms^{-1} there would be a net reduction in evaporation. This would be expected to hold irrespective of any consequential changes in saturation vapour pressure deficit and air temperature, provided the 1 ms^{-1} wind speed is sufficiently low for *Rn* to dominate evaporation rates.

A considerable portion of wind speeds at the Canterbury site fall within the interval $1 < u < 4$ ms^{-1} (Fig. 1). This wind speed fraction extends down to the 1 ms^{-1} upper bound of the lower wind speed range so the evaporation contrast with the low wind speeds is now not so clear (Fig. 5).

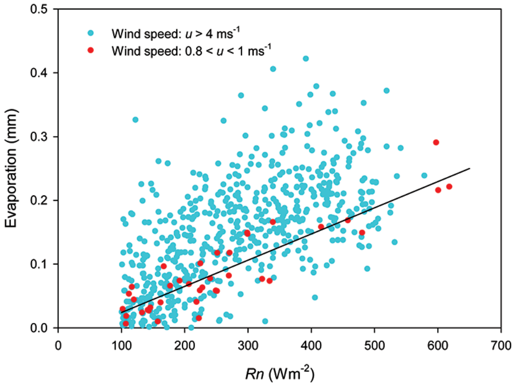

Figure 4 – Half-hour evaporation totals for $u > 4$ ms^{-1} plotted against *Rn*, together with site evaporation values for the low wind speed range. The solid line is a plot of Eq. (1).

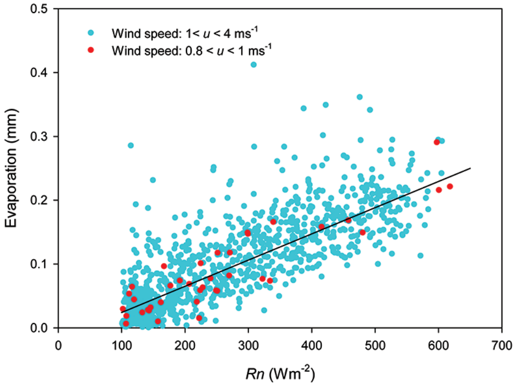

Figure 5 – 30-minute evaporation values for $1 < u < 4$ ms^{-1} plotted against *Rn*, together with the evaporation values for the low wind speed range. The solid line is a plot of Eq. (1).

For all the evaporation values associated with $u > 1$ ms^{-1}, the mean distance between the evaporation values and the regression line of Eq. (1) is significantly greater than zero, with the upper and lower 95% confidence bounds being 0.026 and 0.021 mm, respectively.

A quantitative indication of evaporation reduction potential is achieved by assuming that all the selected wind speeds for $u > 1$ ms^{-1} can be reduced to 1 ms^{-1}. The resulting reduced evaporation values are then estimated by inserting their respective *Rn* values into Eq. (1). In this way, the net overall evaporation reduction potential is estimated at 21%, reflecting the dominance of positive differences from the regression line.

The evaporation reduction potential for $u > 1$ ms^{-1} is with respect to only 55% of all the possible 30-minute means that are subject to $Rn > 100$ and energy closure within 100 Wm^{-2}. The remaining 45% were excluded because those data points plotted outside the low wind speed region of energy closure in Figure 2. This exclusion was to reduce the possibility of bias, as noted earlier. However, selecting the higher wind speed set in this way might also introduce bias because the mean *Rn* value for the 55% data set (281 Wm^{-2}) was somewhat lower than that of the 45% set (464 Wm^{-2}). That is, for high *Rn* there remains some uncertainty over the extent of evaporation reduction achievable from reducing wind speeds.

As a check, the evaporation data set for higher wind speeds was expanded to include the 45% set. Figure 6 plots the expanded data, with the additional data values for $Rn > 600$ Wm^{-2} being particularly evident when compared to Figure 5. A 23% estimated evaporation reduction potential value was then obtained, little different from the 21% value from the original data.

This consistency gives some support for summer evaporation reduction up to as much as 20% for the Canterbury site and is within the range of previous work at other Canterbury locations. For example, de Vries *et al.* (2010) found that windbreaks can potentially reduce annual on-farm water consumption by 10 to 20%. A larger evaporation reduction of 25% is referenced by Littlejohn *et al.* (2015), from measurements in the lee of an experimental tall grass windbreak. From the perspective of eliminating windbreaks, the removal of existing Canterbury windbreaks is estimated to increase growing season evaporation by as much as 16% on an irrigated field (Kilaka, 2015).

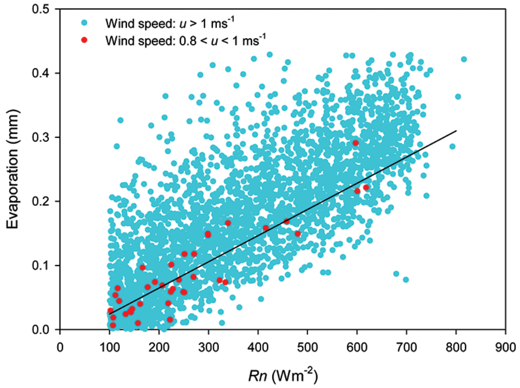

Figure 6 – Expanded data set. Evaporation values for $u > 1$ ms^{-1} plotted against Rn, together with the evaporation values for the low wind speed range. The solid line is a plot of Eq. (1). The evaporation values for $u > 1$ ms^{-1} are for all data with $Rn > 100$ Wm^{-2} and energy closure within 100 Wm^{-2}.

Discussion and conclusion

The emphasis in this short communication is on the possibility of estimating the maximum achievable amount of evaporation reduction from lowered surface wind speeds. Whether wind speed reductions down to 1 ms^{-1} can be achieved in practice is left an open question. It may happen that a possible 20% reduction in evaporation could provide incentive to develop some forms of agriculture in Canterbury that are compatible with more closely-spaced windbreaks.

To our knowledge, ours is the first suggestion to apply a narrow window of low wind speeds from eddy correlation data in order to estimate site evaporation reduction potential. The results presented here are promising but remain tentative pending more detailed analysis. This applies particularly for confirming whether Rn dominates evaporation for achievable windbreak-lowered wind speeds.

The nature of eddy correlation data requires consideration of evaporation at a relatively high time resolution to help reduce the possibility of bias effects. In support of conclusions deduced from eddy correlation analysis, it would be helpful to have a more direct measurement of the maximum extent of evaporation reduction from reduced wind speeds. This could be achieved by modifying some existing drainage lysimeter sites monitoring groundwater recharge, with the setting up of small windbreaks without changing lysimeter Rn. Analogous to catchment experiments, before/after lysimeter studies might be carried out with evaporation reduction recorded as increased drainage. Alternatively, the windbreak modification could be applied to one of a lysimeter pair, with any change in the ratio of water drainage noted. As with paired catchments, the ratio approach would have the advantage of being robust against climatic shift effects.

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