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Do windbreaks reduce the water consumption of a crop field?

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A R T I C L E I N F O

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A B S T R A C T

Two ratios, $A_c = \left[\frac{(q^*_c - q_a)|_{u=\alpha u_0}}{(q^*_c - q_a)|_{u=u_0}}\right] \Big/ \left[\frac{(r_c + r_{avc})|_{u=\alpha u_0}}{(r_c + r_{avc})|_{u=u_0}}\right]$ for the canopy layer and equivalent ratio A_g for the soil layer, were proposed for use to assess if soil evaporation (E_g) and canopy transpiration (E_c) decrease when wind speeds are reduced by windbreaks by a fraction of α, with q_a being the specific humidity of the air, q^*_c the saturated specific humidity of the canopy layer, r_c the canopy resistance, and r_{avc} the aerodynamic resistance for moisture transfer. These ratios can be organized to form criteria, $\Delta E_c < 0$ ($A_c < 1$) and $\Delta E_g < 0$ ($A_g < 1$). Thus $\Delta E < 0$ if $A_c < 1$ and $A_g < 1$. If only one of the ratios is smaller than unity, the sign of ΔE depends on that of $\Delta E_g + \Delta E_c$. The criteria were examined by a dual-source crop community model to simulate energy and water balances of a crop field with data obtained in the Nile Delta. It was found that both $\Delta E \geq 0$ and $\Delta E < 0$ were possible and ΔE was mainly determined by ΔE_g during the fallow and early stages of the cropping seasons and by ΔE_c in the late cropping period. Overall, the scale of the roughness elements h_c and soil moisture θ were found to be the major factors to determine ΔE_c, ΔE_g, and ΔE. A larger h_c tends to produce $\Delta E \geq 0$; and ΔE_c and ΔE_g decrease as θ increases.

1. Introduction

Effects of introducing windbreaks (WBs) on crop fields are one of the subjects that have drawn much interest in agricultural meteorology as well as in other disciplines (see, e.g., Van Eimern et al. (1964) and Rosenberg (1979) for a review of earlier studies, and Cleugh (1998), Steven (1998), Cleugh (2002), Brandle et al. (2004) and Helfer et al. (2009) for a review on more recent works). This was because WBs have been expected to produce positive effects in a wide range of practical applications in agronomy. Evapotranspiration reduction has been one of them.

In spite of the long history of the WBs studies, however, we do not appear to have a full understanding of evapotranspiration differences caused by an introduction of WBs. For example, a review of Brandle et al. (2004) states that "Evaporation from bare soil is reduced in shelter… Evaporation from leaf surface is also reduced…" as if there is no exception. Campi et al. (2009, 2012) appear to be in this position. McNaughton (1988) and Cleugh (1998, 2002), on the other hand, mentioned that both decrease and increase of evapotranspiration were possible (see below in Section 2.3 for more details). In reality, there have been studies that reported increase (e.g., Baker et al., 1989), decrease (e.g., Miller et al., 1973; Campi et al., 2009, 2012), and both decrease and increase (e.g., Brown and Rosenberg, 1972; Cleugh, 2002) of evapotranspiration. This contradiction is perhaps not surprising because the influence of WBs on crop fields is quite complex.

McNaughton (1983) argued one such complexity of WBs that there are both direct and indirect effects on evapotranspiration of WBs. The direct effects arise from an altered turbulent exchange between the surface and the atmosphere. The indirect effects represent changes in evapotranspiration due to modified crop characteristics developed in different microclimates caused by WBs. Field studies based on measurements in a crop field with WBs often observe the combined effects of the direct and indirect effects. Theoretical approaches often focus on part(s) of such effects.

Thus the purposes of our study were (i) to revisit this problem of whether or not, evapotranspiration should decrease by the introduction of WBs; and (ii) to clarify major factors that cause the evapotranspiration differences due to WBs. In order to achieve these goals, first, we summarize available theories to study WBs influences, followed by the Methods section which introduces dual-source and single-source crop community models and dataset to be used in numerical experiments to simulate and compare energy and water balance with and without WBs. Finally, the Results and Discussion section list and discuss our findings. We focus our study on the direct influence of WBs on evapotranspiration, mainly based on the dual-source treatment of crop community. However, to facilitate comparison with previous studies, results from the single-source model are also presented. Also, in our experiments, the microclimate including temperature, humidity, and wind speeds in the internal boundary layer above the vegetated surface in the leeward of WBs is assumed given.

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2. Theory

2.1. Influence of wind speeds reduction on a crop community

To study the influence of WBs, it was first assumed that a crop community consists of two layers, the canopy layer and the soil layer. Surface latent heat fluxes are expressed by the following bulk transfer equations (see, e.g., Brutsaert, 1982; Garratt, 1992)

$$L_eE_c = \frac{\rho L_e(q^*_c - q_a)}{(r_c + r_{avc})} = \frac{\rho c_p(e^*_c - e_a)}{\gamma(r_c + r_{avc})} \tag{1}$$

for the canopy layer, and

$$L_eE_g = \frac{\rho L_e(q^*_g - q_a)}{(r_g + r_{avg})} = \frac{\rho c_p(e^*_g - e_a)}{\gamma(r_g + r_{avg})} \tag{2}$$

for the soil layer. L_e is the latent heat of vaporization; ρ is the atmospheric density; c_p is the specific heat of air at constant pressure; γ is the psychrometric constant; e_a and q_a are respectively the vapor pressure and specific humidity both in the air; and e^* and q^* are the saturated value of vapor pressure and specific humidity at single-source surface temperature. In Eqs. (1)–(2), and in the rest of this study, the subscript g and c represent the soil layer and canopy layer, respectively, and those without a subscript indicates the whole community. Thus E_g is the soil evaporation; E_c is the canopy transpiration; and E is the crop community evapotranspiration. r_c is the canopy resistance; r_g is the soil resistance; and r_{avc} and r_{avg} are the aerodynamic resistance for scalar transfer. Similarly, the sensible heat fluxes H_c and H_g are formulated by the following bulk equations (e.g., Brutsaert, 1982; Garratt, 1992)

$$H_c = \rho c_p C_{hc} u(T_c - T_a) \tag{3}$$

$$H_g = \rho c_p C_{hg} u(T_g - T_a). \tag{4}$$

where C_h is the bulk transfer coefficient for sensible heat which is assumed to be the same as C_e, an equivalent coefficient for water vapor. T_a is the air temperature, T is the single-source surface temperature, and u is the wind speed.

When wind speed is reduced above each layer, the following reaction should take place according to Eqs. (1) and (2):

$$[u\downarrow] \rightarrow [r_{avc}\uparrow] \rightarrow \left[\frac{1}{(r_c + r_{avc})}\Big\downarrow\right] \rightarrow \begin{bmatrix} E_c\downarrow \\ H_c\downarrow \end{bmatrix} \tag{5}$$

and

$$[u\downarrow] \rightarrow [r_{avg}\uparrow] \rightarrow \left[\frac{1}{(r_s + r_{avg})}\Big\downarrow\right] \rightarrow \begin{bmatrix} E_g\downarrow \\ H_g\downarrow \end{bmatrix}. \tag{6}$$

An up or downward arrow beside each variable(s) indicates an increase or a decrease of the variable(s), respectively. From the 1st to the 2nd term of Eqs. (5) and (6), turbulence is weakened as shown by the increase of r_{avc} and r_{avg}, which should then reduce the turbulent exchanges of E_c, H_c, E_g, and H_g (3rd and 4th terms). However, the decrease of the outgoing fluxes (4th term) would induce an increase of source concentration, i.e., the single-source surface temperature T_c and T_g, as well as saturated specific humidity. These reactions can be summarized as follows:

$$\begin{bmatrix} E_c\downarrow \\ H_c\downarrow \end{bmatrix} \rightarrow \begin{bmatrix} T_c\uparrow \\ q^*_c\uparrow \end{bmatrix} \rightarrow \begin{cases} \begin{bmatrix} (T_c - T_a)\uparrow \\ (q^*_c - q_a)\uparrow \end{bmatrix} \rightarrow \begin{bmatrix} E_c\uparrow \\ H_c\uparrow \end{bmatrix} \\ [\sigma T_c^4\uparrow] \rightarrow [R_{nc}\downarrow] \rightarrow \begin{bmatrix} E_c\downarrow \\ H_c\downarrow \end{bmatrix} \end{cases} \tag{7}$$

and

$$\begin{bmatrix} E_g\downarrow \\ H_g\downarrow \end{bmatrix} \rightarrow \begin{bmatrix} T_g\uparrow \\ q^*_g\uparrow \end{bmatrix} \rightarrow \begin{cases} \begin{bmatrix} (T_g - T_a)\uparrow \\ (q^*_g - q_a)\uparrow \end{bmatrix} \rightarrow \begin{bmatrix} E_g\uparrow \\ H_g\uparrow \end{bmatrix} \\ [\sigma T_g^4\uparrow] \rightarrow [R_{ng}\downarrow] \rightarrow \begin{bmatrix} E_g\downarrow \\ H_g\downarrow \end{bmatrix} \end{cases} \tag{8}$$

where R_n is the net radiation; σ is the Stefan-Boltzmann constant; T is in K. From the 3rd term of Eqs. (7) and (8), there are two separate paths, one indicating increases of the gradients leading to the fluxes increases (negative feedback), and another showing a decrease of the net radiation, and the resulting decrease of H and E fluxes (positive feedback). Because there are feedback loops, an equilibrium should be reached (at least temporarily) for a given condition, somewhere in Eqs. (5) and (7), and Eqs. (6) and (8). The key variables that determine the equilibrium position are T_c and T_g because they link the bulk equations Eqs. (1)–(4) with energy balance equations of the crop community (see A.1.1. in the Appendix). Thus the equilibrium must be reached at the position where particular values of T_c and T_g satisfy all these equations simultaneously.

2.2. Criteria to determine the fate of evapotranspiration

In view of Eqs. (1) and (2), it is convenient to define the ratio A_c

$$A_c = \frac{E_c|_{u=\alpha u_0}}{E_c|_{u=u_0}} = \frac{(q^*_c - q_a)}{(r_c + r_{avc})}\bigg|_{u=\alpha u_0} \bigg/ \frac{(q^*_c - q_a)}{(r_c + r_{avc})}\bigg|_{u=u_0} = \left[\frac{(q^*_c - q_a)|_{u=\alpha u_0}}{(q^*_c - q_a)|_{u=u_0}}\right] \bigg/ \left[\frac{(r_c + r_{avc})|_{u=\alpha u_0}}{(r_c + r_{avc})|_{u=u_0}}\right] \tag{9}$$

and the ratio A_g

$$A_g = \frac{E_g|_{u=\alpha u_0}}{E_g|_{u=u_0}} = \frac{(q^*_g - q_a)}{(r_s + r_{avg})}\bigg|_{u=\alpha u_0} \bigg/ \frac{(q^*_g - q_a)}{(r_s + r_{avg})}\bigg|_{u=u_0} = \left[\frac{(q^*_g - q_a)|_{u=\alpha u_0}}{(q^*_g - q_a)|_{u=u_0}}\right] \bigg/ \left[\frac{(r_g + r_{avg})|_{u=\alpha u_0}}{(r_g + r_{avg})|_{u=u_0}}\right] \tag{10}$$

to argue the fate of E_g, E_c, and E when u becomes weaker from $u = u_0$ to $u = \alpha u_0$ ($0 \le \alpha < 1$). As is clear, whether WBs should reduce evapotranspiration can be judged by comparing the magnitude of the change in the gradient of the q concentration and that in resistances for the humidity transport. When the gradient change is larger ($A_c > 1$ or $A_g > 1$), the equilibrium is reached in the 2nd–4th term in the upper path of Eqs. (7) and (8), and E_c and E_g should increase. Conversely, when the resistance change is larger ($A_c < 1$ or $A_g < 1$), the equilibrium is likely reached in Eqs. (5) and (6) and E_c and E_g should decrease. Thus A_c and A_g can be organized to formulate the following criteria,

$$\Delta E_c \begin{Bmatrix} >0 & (A_c > 1) \\ =0 & (A_c = 1) \\ <0 & (A_c < 1) \end{Bmatrix}, \tag{11}$$

$$\Delta E_g \begin{Bmatrix} >0 & (A_g > 1) \\ =0 & (A_g = 1) \\ <0 & (A_g < 1) \end{Bmatrix} \tag{12}$$

and

$$\Delta E \begin{Bmatrix} >0 & \begin{pmatrix} \{(A_c > 1) \wedge (A_g > 1)\}\vee \\ \{(A_c < 1) \wedge (A_g > 1) \wedge (|\Delta E_c| < |\Delta E_g|)\}\vee \\ \{(A_c > 1) \wedge (A_g < 1) \wedge (|\Delta E_c| > |\Delta E_g|)\} \end{pmatrix} \\ =0 & \begin{pmatrix} \{(A_c = 1) \wedge (A_g = 1)\}\vee \\ \{(A_c < 1) \wedge (A_g > 1) \wedge (|\Delta E_c| = |\Delta E_g|)\}\vee \\ \{(A_c > 1) \wedge (A_g < 1) \wedge (|\Delta E_c| = |\Delta E_g|)\} \end{pmatrix} \\ <0 & \begin{pmatrix} \{(A_c < 1) \wedge (A_g < 1)\}\vee \\ \{(A_c < 1) \wedge (A_g > 1) \wedge (|\Delta E_c| > |\Delta E_g|)\}\vee \\ \{(A_c > 1) \wedge (A_g < 1) \wedge (|\Delta E_c| < |\Delta E_g|)\} \end{pmatrix} \end{Bmatrix} \tag{13}$$

in which symbols ⋀ and ⋁ represent the logical operation of “and”