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Key Points:

- A widely used method for attributing surface temperature changes assumes that the Bowen ratio is independent of aerodynamic resistance
- The independence assumption leads to an overestimation of the impact of aerodynamic resistance
- A new method that does not invoke the assumption of independence between the Bowen ratio and aerodynamic resistance is proposed

Supporting Information:

- Supporting Information S1

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Attribution of surface temperature anomalies induced by land use and land cover changes

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Abstract Land use/land cover changes (LULCC) directly impact the surface temperature by modifying the radiative, physiological, and aerodynamic properties controlling the surface energy and water balances. In this study, we propose a new method to attribute changes in the surface temperature induced by LULCC to changes in radiative and turbulent heat fluxes, with the partition of turbulent fluxes controlled by aerodynamic and surface resistances. We demonstrate that previous attribution studies have overestimated the contribution of aerodynamic resistance by assuming independence between the aerodynamic resistance and the Bowen ratio. Our results further demonstrate that acceptable agreement between modeled and observed temperature anomalies does not guarantee correct attribution by the model. When performing an attribution analysis, the covariance among attributing variables needs to be taken into consideration in order to accurately interpret the results.

1. Introduction

Land use/land cover changes (LULCC) directly induce temperature anomalies at and near the surface [*Bonan*, 2008; *Pielke et al*., 2011; *Wickham et al*., 2012; *Mahmood et al*., 2013; *Li et al*., 2015; *Alkama and Cescatti*, 2016], which are stronger than temperature changes due to the greenhouse gas forcing in many regions [*Feddema et al*., 2005]. Attributing these temperature anomalies induced by LULCC to changes in different biophysical factors such as albedo and surface roughness (represented by the aerodynamic resistance) has important implications for understanding the physical mechanisms [*Boisier et al*., 2012], predicting future climate [*Feddema et al*., 2005], and developing strategies to mitigate climate warming [*Naudts et al*., 2016].

Recently, various methods have been proposed to attribute surface temperature anomalies based on the surface energy balance equation [*Juang et al*., 2007; *Lee et al*., 2011; *Luyssaert et al*., 2014]. By parameterizing the sensible heat flux with an aerodynamic resistance concept and computing the latent heat flux with a Priestley-Taylor approach [*Priestley and Taylor*, 1972], *Juang et al*. [2007] attributed the surface temperature anomaly included by LULCC to changes in albedo, emissivity, ground heat flux, and a parameter that lumps the effects of aerodynamic resistance and the Priestley-Taylor coefficient. Their method did not separate the effects of aerodynamic resistance and other ecophysiological factors (represented by the Priestley-Taylor coefficient) that also impact surface temperature. Following *Juang et al*. [2007] but without invoking parameterizations for turbulent sensible and latent heat fluxes, *Luyssaert et al*. [2014] used the observed fluxes for the attribution of surface temperature anomalies induced by land use change and land use management. As a result, *Luyssaert et al*. [2014] did not link changes in turbulent fluxes with changes in biophysical factors such as surface roughness.

Another widely used method is the intrinsic biophysical mechanism (IBM) method proposed by *Lee et al*. [2011], which attributes changes in surface temperature (ΔT_s) to changes in the radiative forcing (mainly caused by changes in the albedo) and changes in the energy redistribution (f), the latter of which were further attributed to changes in the aerodynamic resistance (r_a) and the Bowen ratio (β) defined as the ratio of sensible to latent heat fluxes. The IBM method attempts to separate the effects of aerodynamic resistance from other biophysical mechanisms (represented by the Bowen ratio) on surface temperature. This is important because it provides a linkage between biophysical parameters, which can be more directly tied to planning and mitigation strategies, and surface temperature. Analyses at six paired FLUXNET sites showed that warming induced by deforestation was largely due to changes in the aerodynamic resistance rather than changes in the Bowen ratio except at one tropical location [*Lee et al*., 2011]. This method was adopted by several more recent studies [*Lee et al*., 2011; *Zhao et al*., 2014; *Cao et al*., 2016; *Chen and Dirmeyer*, 2016; *Bright et al*., 2017], most of which showed that the aerodynamic resistance makes the largest contribution to temperature anomalies induced by

LULCC and the contribution of the Bowen ratio is generally smaller than the contribution of aerodynamic resistance. For example, using paired FLUXNET sites together with land surface model sensitivity experiments [*Chen and Dirmeyer*, 2016], the effects of changes in the aerodynamic resistance were found to dominate the direct biogeophysical influence of LULCC even when land-atmosphere feedbacks were included. Also, using the IBM method, the spatial variations in the daytime surface urban heat islands, or temperature increases in urban areas over the surrounding rural areas, were found to be controlled by the spatial variations in the urban-rural contrast of aerodynamic resistance [*Zhao et al*., 2014]. This is contradictory to the traditional view that the reduced evapotranspiration (or the increased Bowen ratio) in urban areas is the primary cause of daytime urban heat islands [*Carlson and Boland*, 1978; *Oke*, 1982; *Taha*, 1997; *Grimmond*, 2007].

Motivated by these intriguing conclusions, we revisit the assumptions made in the IBM method. We find that the IBM method assumes that changes in the albedo, the aerodynamic resistance, and the Bowen ratio are independent of each other. The assumption of independence between the aerodynamic resistance and the Bowen ratio is certainly counterintuitive and potentially has important consequences. On the other hand, the methods used in *Juang et al*. [2007] and *Luyssaert et al*. [2014] did not suffer this independence assumption since they did not try to separate the effects of aerodynamic resistance from other biophysical mechanisms. As a result, this study focuses on quantifying the impact of this independence assumption in the IBM method and proposing a new method without invoking such an assumption.

The paper is organized as follows: section 2 describes the original IBM method and our methodology to quantify the impact of the independence assumption; section 3 presents the results related to the IBM method; section 4 proposes a new method called the two-resistance mechanism (TRM) method, which does not invoke the independence assumption; section 5 compares the two methods, and section 6 concludes the study.

2. The IBM Method and Its Assumption of Independence Between the Aerodynamic Resistance and the Bowen Ratio

2.1. The Original IBM Method

The IBM method assumes that all atmospheric variables are measured above the blending height and thus are not affected by LULCC at the surface [*Lee et al*., 2011]. In essence, the method assumes that the atmosphere does not respond to LULCC. Based on a linearized surface energy budget equation, the surface temperature change (ΔT_s, where Δ refers to a perturbation induced by LULCC) can be attributed to changes in the apparent net radiation (R_n^*) and the energy redistribution factor (f), following:

$$\Delta T_s = \frac{\partial T}{\partial R_n^*}\Delta R_n^* + \frac{\partial T}{\partial f}\Delta f, \tag{1}$$

where $\frac{\partial T}{\partial R_n^*} = \frac{\lambda_o}{1+f}$ and $\frac{\partial T}{\partial f} = -\frac{\lambda_o R_n^*}{(1+f)^2}$. The apparent net radiation is defined as $R_n^* = S_{\text{in}}(1-\alpha) + \varepsilon L_{\text{in}} - \varepsilon\sigma T_a^4$, where S_{in} and L_{in} are the incoming shortwave and longwave radiation, respectively, α is the albedo, ε is the emissivity, σ is the Stephan-Boltzmann constant, and T_a is the atmospheric temperature. λ_o is defined as $1/\left(4\varepsilon\sigma T_a^3\right)$. Due to the minor role of changes in the emissivity [*Lee et al*., 2011], ΔR_n^* is mainly caused by changes in the albedo ($\Delta\alpha$). The energy redistribution factor (f) is related to the aerodynamic resistance (r_a) and the Bowen ratio (β), as follows:

$$f = \frac{r_o}{r_a}\left(1 + \frac{1}{\beta}\right), \tag{2}$$

where $r_o = \rho c_p \lambda_o$, ρ is the air density, and c_p is the air-specific heat at constant pressure. As such, changes in the energy redistribution factor can be further attributed to changes in the aerodynamic resistance (Δr_a) and the Bowen ratio ($\Delta\beta$), following $\Delta f = \Delta f_1 + \Delta f_2$, where

$$\Delta f_1 = \frac{\partial f}{\partial r_a}\Delta r_a = -\frac{r_o}{r_a}\left(1 + \frac{1}{\beta}\right)\frac{\Delta r_a}{r_a}, \tag{3}$$

$$\Delta f_2 = \frac{\partial f}{\partial \beta}\Delta\beta = -\frac{r_o}{r_a}\frac{\Delta\beta}{\beta^2}. \tag{4}$$

Later on, the ground heat flux (G) and anthropogenic heat flux (Q_{AH}, heat generated from human energy use) were also accounted for in the IBM method by replacing R_n^* with $R_n^* + Q_{\text{AH}} - G$ [*Zhao et al*., 2014], and the influence of land-atmosphere feedbacks was also included [*Chen and Dirmeyer*, 2016].

To use the IBM method, one needs to obtain the atmospheric forcing variables (S_{in}, L_{in}, T_a), which are again assumed to be uniform for all land cover types. In addition, one needs to also obtain the albedo (α), emissivity (ε), aerodynamic resistance (r_a), and Bowen ratio (β) of all land use/land cover types that are to be compared. In particular, the aerodynamic resistance (r_a) is estimated from the sensible heat flux (H) and surface temperature (T_s) through $r_a = \rho c_p(T_s - T_a)/H$ and the Bowen ratio (β) is estimated as the ratio of sensible heat flux (H) to latent heat flux (LE). As such, the requirement of aerodynamic resistance (r_a) and the Bowen ratio (β) in the IBM method is equivalent to requiring the sensible heat flux (H), surface temperature (T_s), and latent heat flux (LE) for all land cover types.

2.2. Quantifying the Influence of Assuming Independence Between the Aerodynamic Resistance and the Bowen Ratio in the IBM Method

Mathematically, the IBM method only retains the first-order terms in the Taylor series expansion and neglects higher-order partial and cross-partial derivatives, which is equivalent to assuming that changes in the apparent net radiation, the aerodynamic resistance, and the Bowen ratio are independent of each other. This is justified if and only if all perturbations induced by LULCC are sufficiently small. However, in the process of LULCC the perturbations of biophysical factors are not necessarily small. Thus, the perturbations cannot be treated as independent a priori and it is important to examine the consequence of this "independence" assumption. Here we focus on changes in aerodynamic resistance (Δr_a) and Bowen ratio ($\Delta\beta$), as their contributions are critical for the intriguing conclusions of many previous studies mentioned in section 1. However, we point out that changes in the radiative forcing (ΔR_n^*) and Bowen ratio ($\Delta\beta$) are not necessarily independent of each other either.

To quantify the impact of assuming independence between the aerodynamic resistance and the Bowen ratio, we employ the same linearized surface energy balance equation as the IBM method and also assume that the atmospheric properties are not affected by LULCC. However, different from the original IBM method, we treat the Bowen ratio as a function of the aerodynamic resistance and other factors Ω_i (e.g., soil moisture), that is, $\beta = \beta(r_a, \Omega_i)$; thus, $\Delta\beta = (\partial\beta/\partial r_a)\Delta r_a + \Delta\beta_{\Omega_i}$ where $\Delta\beta_{\Omega_i}$ is the change in the Bowen ratio caused by factors other than the aerodynamic resistance. Substituting this expression into the original IBM method and not considering changes in the apparent net radiation yield $\Delta T_s = -\frac{r_o}{r_a}\left[\left(1+\frac{1}{\beta}\right)\frac{\Delta r_a}{r_a} + \frac{1}{\beta^2}\frac{\partial\beta}{\partial r_a}\Delta r_a + \frac{1}{\beta^2}\Delta\beta_{\Omega_i}\right]$. It is thus clear that the contribution of aerodynamic resistance becomes $-\frac{r_o}{r_a}\left[\left(1+\frac{1}{\beta}\right)\frac{\Delta r_a}{r_a} + \frac{1}{\beta^2}\frac{\partial\beta}{\partial r_a}\Delta r_a\right]$ instead of $-\frac{r_o}{r_a}\left(1+\frac{1}{\beta}\right)\frac{\Delta r_a}{r_a}$ presented in the original IBM method (equation (3)). The ratio of the two is $R_1 = 1 + \frac{1}{\beta+1}\frac{r_a}{\beta}\frac{\partial\beta}{\partial r_a}$, which is actually independent of Δr_a (i.e., regardless of the magnitude of the original estimate). The original IBM method essentially assumes that $\frac{\partial\beta}{\partial r_a} = 0$ and thus $R_1 = 1$. A value of R_1 less than unity indicates that considering the dependence between the aerodynamic resistance and the Bowen ratio, as compared to the original IBM method, reduces the contribution of aerodynamic resistance to ΔT_s. Thus, R_1 can be used as a metric to assess the impact of assuming independence between the Bowen ratio and the aerodynamic resistance. To estimate $(r_a/\beta)(\partial\beta/\partial r_a)$ in R_1, we need to provide a model to connect β with r_a and other variables. To do so, Monin-Obukhov similarity theory is used to parameterize r_a as a function of both momentum roughness length (z_o) and thermal roughness length (z_{oh}), as follows:

$$r_a = \frac{1}{\kappa_v^2 U}\left[\log\left(\frac{z_m - d}{z_o}\right) - \Psi_m\left(\frac{z-d}{L}\right) + \Psi_m\left(\frac{z_o}{L}\right)\right]\left[\log\left(\frac{z_m - d}{z_{oh}}\right) - \Psi_h\left(\frac{z-d}{L}\right) + \Psi_h\left(\frac{z_{oh}}{L}\right)\right], \quad (5)$$

where U is the atmospheric wind speed, κ_v is the von-Karman constant, z_m is the measurement height, d is the displacement height (assumed to be 70% of the vegetation height), L is the Obukhov length, and Ψ_m and Ψ_h are stability correction functions for which the Businger-Dyer relations are used [*Garratt*, 1994; *Brutsaert*, 2005]. With this r_a, the sensible heat flux can be directly calculated. In addition, the latent heat flux (LE) is parameterized as $LE = \frac{\rho L_v\left(q_s^*(T_s) - q_a\right)}{r_a + r_s}$, where L is latent heat for vaporization, q_{s^*} is the saturated surface-specific humidity that is only a function of T_s and atmospheric pressure, q_a is the atmospheric specific humidity, and r_s is the surface resistance to water vapor transport.

In this study, we utilized multiple years of data from 75 AmeriFlux sites (see supporting information for site information, data processing, and quality control) of which about 75% has more than 200 days of data in summer (June, July, and August or JJA) and winter (December, January, and February or DJF) seasons. For each site we estimated the optimal z_o, z_{oh}, and r_s at daily time scales. To do so, we first determined the daily momentum roughness length (z_o) that best reproduced the measured friction velocity (u_*) (i.e., minimized the sum of the square errors over the day) assuming neutral stability (Figure S1a). Friction velocities less than 0.01 m/s were excluded from the analysis. Using estimates of surface temperature obtained by inverting measurements of outgoing longwave radiation (assuming a constant emissivity of 0.98), we determined the daily thermal roughness length (z_{oh}) that best reproduced the measured H (Figure S1b). Assuming that the aerodynamic resistance is equivalent for heat and water vapor, we then determined the optimal r_s by finding the r_s that best predicted the observed LE (Figure S1c). Once the z_o, z_{oh}, and r_s were optimized, we used them in a simple land surface model to estimate surface fluxes assuming that ground heat flux was zero, which is similar to *Lee et al*. [2011]. An example of our calculations at Fort Peck is demonstrated in Figure S1. It is clear from Figure S1d that the modeled Bowen ratios agree well with the measured ones at Fort Peck (as expected since we used daily optimal z_o, z_{oh}, and r_s to model the Bowen ratio). Across all AmeriFlux sites considered here, the median Pearson correlation coefficient for sensible heat flux is 0.91 and the median Pearson correlation coefficient for latent heat flux is 0.96 (see Table S1).

To estimate $(r_a/\beta)(\partial\beta/\partial r_a)$ in R_1, we assumed that changes in z_o induced changes in r_a and thus β. To determine the sensitivity of β to perturbations in r_a, we varied daily z_o by ±10%, ±20%, and ±30% of the optimal value. We used a least squares linear regression to estimate $\partial\beta/\partial r_a$, as shown in Figure S2. Because previous studies demonstrate that the aerodynamic resistance contribution was more significant in daytime [*Lee et al*., 2011; *Zhao et al*., 2014], we performed the linear regression on daytime results when the incoming shortwave radiation was larger than 25 W m^{-2}.

Lastly, we conducted two separate analyses to ensure robust methodology. First, since r_a is also dependent on the thermal roughness length (z_{oh}) in addition to the momentum roughness length (z_0), we reconducted the analysis assuming that changes in momentum and thermal roughness lengths due to LULCC are independent. Hence, the sensitivity of β to r_a is further estimated as $\frac{\partial\beta}{\partial r_a} = \frac{\partial\beta}{\partial z_o}\frac{\partial z_o}{\partial r_a} + \frac{\partial\beta}{\partial z_{oh}}\frac{\partial z_{oh}}{\partial r_a}$. The R_1 calculated in this way is denoted with a subscript "*b*" (R_{1b}). Second, since r_a is weakly dependent on the buoyancy fluxes (i.e., sensible and latent heat fluxes) calculated by the model, we reconducted the analysis without considering the stability correction terms (Ψ_m and Ψ_h) in the parameterization of r_a. This ensures that r_a only depends on model inputs (z_o and z_{oh}) and is completely independent of r_s (also a model input). This is justified since we are interested in the long-term (multiyear mean) sensitivity of β to r_a. The R_1 calculated in this way is denoted with a subscript "*c*" (R_{1c}).

3. Results

First, we illustrate the dependence of the Bowen ratio on the aerodynamic resistance. Figure 1 shows the relationship between the summertime (JJA) daily-averaged daytime Bowen ratio and aerodynamic resistance at four AmeriFlux sites across different landscapes and climates. The colored lines represent the relations between β and r_a for a range of fixed r_s values. As seen in Figure 1, it is clear that β is not independent of r_a, as expected [*Baldocchi and Ma*, 2013], and it generally decreases with increasing r_a. The surface resistance to water vapor transfer (r_s) modulates the relation between β and r_a. This dependence of the Bowen ratio on aerodynamic resistance is not a simple statistical result and is not tied to a particular temporal scale (e.g., daily) but is recognized in all textbooks of hydrology and boundary layer meteorology at all temporal scales [*Garratt*, 1994; *Brutsaert*, 2005].

Second, we assess the implications of assuming independence between the Bowen ratio and aerodynamic resistance in the IBM method. Figure 2 shows the estimated R_1 using daytime data at 75 AmeriFlux sites. We aggregate the results based on climate zones (continental, arid, and temperate) following a pervious study [*Zhao et al*., 2014] that used the IBM method over a similar domain. Across climate zones, R_1 is on average less than unity, especially in summer. The values of R_1 indicate that the aerodynamic resistance contribution to ΔT_s was overestimated by 10–25%. The temperate climate

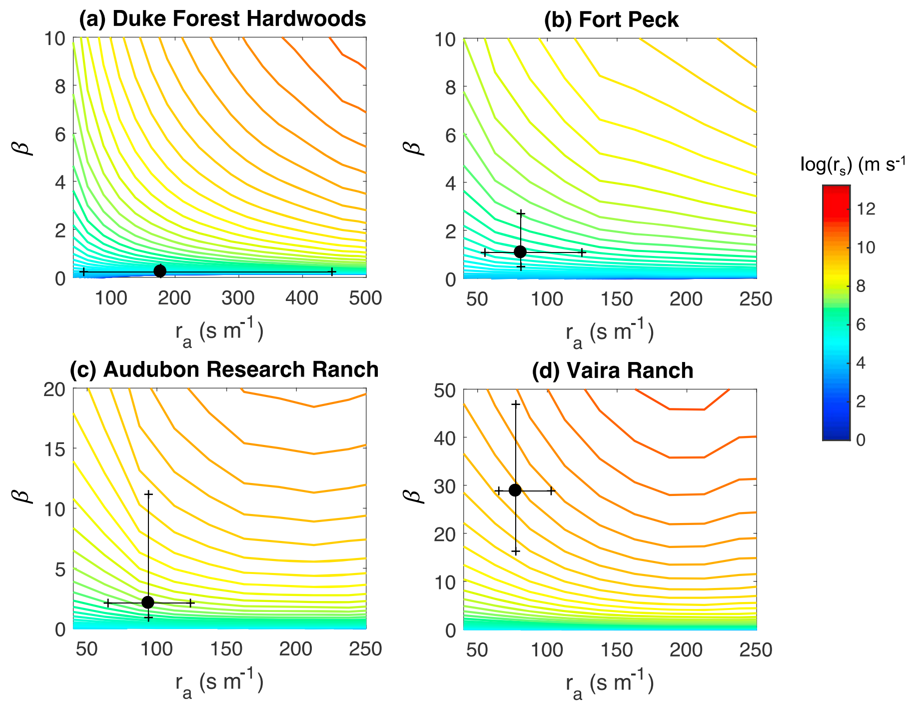

Figure 1. The daytime-averaged Bowen ratio (β) as a function of increasing aerodynamic resistance (r_a) at (a) Duke Forest Hardwood (deciduous broadleaf forest, fully humid warm temperate with hot summer), (b) Fort Peck (grassland, arid steppe cold), (c) Audubon Research Ranch (grassland, arid steppe cold), and (d) Vaira Ranch (grassland, Mediterranean). These results are generated from multiple years of summertime data. The contours refer to fixed values of surface resistance (r_s). The black dots represent β and r_a optimally fitted to observations, with black lines indicating the 25th and 75th percentiles.

region exhibits the largest variability in R_1, as indicated by the error bars in Figures 2b–2d. The values of R_1 in Figure 2 are actually conservative estimates since changes in aerodynamic resistance here were only induced by changes in the momentum roughness length (see Figure S2). Following the definition of aerodynamic resistance used in the IBM method, changes in aerodynamic resistance can also be caused by changes in the thermal roughness length [*Garratt*, 1994]. Figure 2 also shows the estimated R_{1b}, which takes into account changes in the thermal roughness length. Those R_{1b} values are smaller than the R_1 values in arid and temperate regions.

Our analysis indicates that acceptable agreement between modeled and observed ΔT_s does not necessarily guarantee the correct attribution of ΔT_s. The original IBM method and the correction made here yield the same total contribution of aerodynamic resistance and Bowen ratio to ΔT_s. However, the original IBM method included the contribution of aerodynamic resistance through altering the Bowen ratio in the contribution of Bowen ratio, while the correction here treats it as the contribution of aerodynamic resistance. Because such contributions are often negative (which can be inferred from Figure 1), this led to an overestimation of the contribution of aerodynamic resistance and concomitantly an underestimation of the Bowen ratio contribution in the original IBM method.

Due to the fact that r_a is weakly dependent on the buoyancy fluxes (i.e., sensible and latent heat fluxes) in the Monin-Obukhov similarity theory (equation (5)), one could argue that r_a and r_s are not completely independent of each other. Our third analysis is designed to address this concern. To do so, we reconduct the analysis in which the stability correction terms (Ψ_m and Ψ_h) in the parameterization of r_a are excluded and the resulting R_1 is denoted as R_{1c} (see Figure 2). In this case, r_a is not affected by the buoyancy fluxes and is completely independent of r_s. As shown in Figure 2, excluding the stability effect on r_a does not alter our finding that the IBM method overestimates the contribution of aerodynamic resistance by 10–25%. This independence between r_a and r_s is also the foundation for proposing an alternative to the IBM method, as shown in the next section.

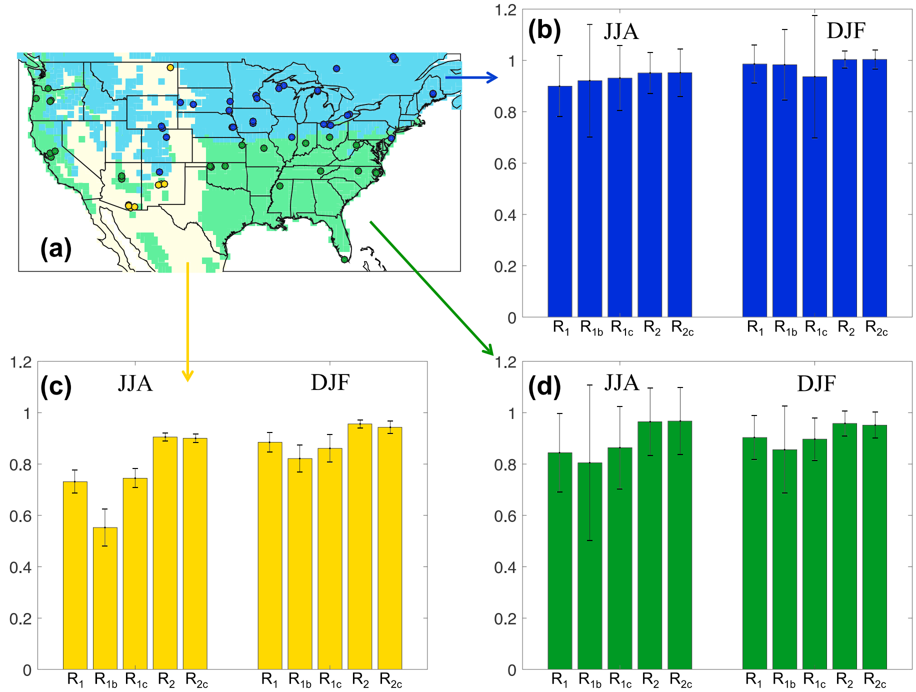

Figure 2. (a) Map of AmeriFlux sites, with colors indicating the climate zone based on the Köppen-Geiger climate classification (blue: continental; yellow: arid; and green: temperate) and the estimated R_1, R_{1b}, R_{1c}, R_2, and R_{2c} for June, July, and August (JJA, left grouping of bars) and December, January, and February (DJF, right grouping of bars) aggregated across (b) continental sites, (c) arid sites, and (d) temperate sites. R_1 is the ratio of corrected to original estimates of daytime aerodynamic resistance contribution to surface temperature change using the IBM method. In the original estimates, the Bowen ratio is assumed to be independent of aerodynamic resistance, while in the corrected estimates, the Bowen ratio is treated as a function of aerodynamic resistance and other factors. R_2 is the ratio of TRM to IBM estimates of daytime aerodynamic resistance contribution to surface temperature change. The subscript *b* indicates that changes in thermal roughness length are also considered, and the subscript *c* indicates that stability corrections in the parameterization of r_a are not included. To generate the *R* values for each climate zone, the daily *R* values are averaged at each site first and then the site-specific values are used to generate the bars (the mean) and error bars (the standard deviation).

4. The TRM Method

In this section, we propose an alternative approach for attributing ΔT_s by replacing the Bowen ratio by the surface resistance, which we refer to as the two-resistance mechanism (TRM) method. We argue that from a land surface modeling perspective and when land-atmosphere feedbacks are not considered (an assumption also made in the IBM method), the surface resistance can be viewed as an input and is independent of the aerodynamic resistance. We do not use the Bowen ratio in the attribution because the surface temperature and the Bowen ratio are state variables and outputs from land surface models; thus, they are not independent of either aerodynamic resistance or surface resistance. Detailed derivations are presented in the supporting information, and here only the final results are reproduced. In the TRM method, the change in surface temperature is attributed to changes in the radiative forcing, aerodynamic resistance, and surface resistance, following

$$\Delta T_s = \left(\frac{\partial T_s}{\partial R_n^*}\right)^{\mathrm{TRM}} \Delta R_n^* + \left(\frac{\partial T_s}{\partial r_a}\right)^{\mathrm{TRM}} \Delta r_a + \left(\frac{\partial T_s}{\partial r_s}\right)^{\mathrm{TRM}} \Delta r_s. \quad (6)$$

The terms on the right-hand side of the equation represent the impact of changes in the radiative forcing (again mainly caused by changes in the albedo), aerodynamic resistance, and surface resistance on surface temperature. Note that here the heat storage and anthropogenic heat flux are not included but they can be easily incorporated. Additionally, one can include a flux imbalance term [*Stoy et al.*, 2006] or minimize its impact by carefully choosing sites that have a small flux imbalance [*Luyssaert et al.*, 2014]. Full expressions of the partial derivatives or the sensitivities can be found in the supporting information.

Table 1. Comparison Between the IBM and TRM Methods

Methods	Attributing Variables	Required Inputs: Land Cover Type Based	Required Inputs: Atmospheric Properties
IBM	β, r_a, R_n^*	$H,\ LE,\ T_s,\ R_n^*,\ \alpha,\ \varepsilon$	T_a
TRM	r_s, r_a, R_n^*	$H,\ LE,\ T_s,\ R_n^*,\ \alpha,\ \varepsilon$	T_a, q_a, P

Two key remaining questions are whether the TRM method introduces new dependences among attributing variables and whether it also addresses the dependence between ΔR_n^* and β in the IBM method, which was not previously discussed. To answer these questions, it is important to keep in mind that both the TRM method and the IBM method are designed for the attribution of surface temperature change due to LULCC. Hence, they are supposed to capture changes in the biophysical factors due to changes in the land cover type, not due to changes in some other intermediate variables (e.g., roughness characteristics and soil moisture) within a land cover type [*Idso et al*., 1975; *Chappell and Heritage*, 2007; *Chappell et al*., 2010]. Across land cover types, changes in the attributing variables in the TRM method, including albedo, aerodynamic resistance, and surface resistance, can be viewed as independent of each other. On the other hand, changes in the Bowen ratio are directly influenced by changes in the albedo and aerodynamic resistance and thus they are not independent of each other.

5. Comparison Between the IBM and TRM Methods

In this section, the IBM and TRM methods are compared. Here we do not include the methods proposed by *Juang et al*. [2007] and *Luyssaert et al*. [2014] because they did not separate the effects of aerodynamic resistance from other biophysical mechanisms. Nonetheless, it is pointed out again that the methods used by *Juang et al*. [2007] and *Luyssaert et al*. [2014] do not invoke the independence assumption as the IBM method.

The attributing variables and required inputs in the IBM and TRM methods are compared in Table 1. It is clear that the most important difference between the IBM and TRM methods lies in the attributing variables: The IBM uses the Bowen ratio (β), but the TRM method uses the surface resistance (r_s). Similar to the IBM method that determines the Bowen ratio (and aerodynamic resistance) from sensible and latent heat fluxes, the surface resistance (and aerodynamic resistance) in the TRM method can be also derived from sensible and latent heat fluxes.

The TRM method seems to require two more input variables than the IBM method, which are the atmospheric specific humidity and air pressure. However, compared to required inputs for each land cover type (including H, LE, T_s, R_n^*, α, ε), the atmospheric specific humidity and air pressure are much easier to obtain. In addition, the atmospheric specific humidity and air pressure are often measured together with air temperature, which is required by both methods.

The differences in the attributing variables and required inputs are manifested in the formulations of the two methods. The original IBM method gives $T_s - T_a = \frac{\lambda_o R_n^*}{1+f_{\mathrm{IBM}}}$, where $f_{\mathrm{IBM}} = \frac{r_o}{r_a}\left(1+\frac{1}{\beta}\right)$. The TRM method, however, gives $T_s - T_a = \frac{\lambda_o\left[R_n^* - \frac{\rho L_v}{(r_a+r_s)}\left(q_a^*(T_a)-q_a\right)\right]}{1+f_{\mathrm{TRM}}}$, where $f_{\mathrm{TRM}} = \frac{r_o}{r_a}\left[1+\frac{\Delta}{\gamma}\left(\frac{r_a}{r_a+r_s}\right)\right]$. The difference between f_{TRM} and f_{IBM}, which are termed energy redistribution factors, is caused by the difference in the parameterization of latent heat flux: the IBM method uses the sensible heat flux and the Bowen ratio to parameterize latent heat flux, and the TRM method parameterizes latent heat flux using aerodynamic and surface resistances. The extra term $\frac{\rho L_v}{(r_a+r_s)}\left(q_a^*(T_a)-q_a\right)$ in the TRM method arises from linearizing the saturated specific humidity. The differences in the attributing variables and model formulations result in different sensitivities of surface temperature to biophysical factors. In particular, the sensitivity to changes in the aerodynamic resistance can be intercompared. It is straightforward to show that the ratio between the two methods is

$$R_2 = \frac{\left(\frac{\partial T_s}{\partial r_a}\right)^{\mathrm{TRM}}}{\left(\frac{\partial T_s}{\partial r_a}\right)^{\mathrm{IBM}}} = \frac{\frac{\lambda_o \rho L_v\left(q_a^*(T_a)-q_a\right)}{(r_a+r_s)^2}\frac{1}{(1+f_{\mathrm{TRM}})} + \frac{\partial f_{\mathrm{TRM}}}{\partial r_a}\lambda_o\left[R_n^* - \frac{\rho L_v\left(q_a^*(T_a)-q_a\right)}{(r_a+r_s)}\right]\frac{1}{(1+f_{\mathrm{TRM}})^2}}{-\frac{\lambda_o R_n^*}{(1+f_{\mathrm{IBM}})^2}\frac{\partial f_{\mathrm{IBM}}}{\partial r_a}}. \tag{7}$$

Figure 2 shows the R_2 estimated at each AmeriFlux site, which directly measures the difference between the TRM and IBM methods in terms of the sensitivity of surface temperature to aerodynamic resistance changes. It also indirectly estimates the consequence of assuming independence between the aerodynamic resistance and the turbulent flux partitioning in the IBM method. It is clear that R_2 is also on average less than unity (~ 0.9 in summer and 0.95 in winter), suggesting a smaller contribution of aerodynamic resistance in the TRM method. These results are broadly consistent with the results of R_1, but the values of R_2 are generally larger than R_1 and are closer to unity. The values of R_{2c} (where the subscript c again indicates that the stability effects on r_a are ignored) are similar to the R_2 values. The difference between R_1 and R_2 arises from the fact that R_1 is still based on the IBM method, while the TRM estimates are independent of those from the IBM method. In other words, R_1 is the correction to the original IBM method comparing the aerodynamic resistance contribution to the Bowen ratio contribution, while R_2 is the ratio of aerodynamic resistance contribution from the TRM method, which compares it to the surface resistance contribution, to that from the original IBM method.

6. Conclusion

This study identifies and assesses a key assumption in a widely used method (the IBM method) for attributing surface temperature anomalies induced by LULCC, that is, the independence between the Bowen ratio and the aerodynamic resistance. Using AmeriFlux eddy covariance data, we demonstrated that the Bowen ratio and the aerodynamic resistance are clearly not independent, as expected. We found that previous studies using the IBM method may overestimate the contribution of aerodynamic resistance to surface temperature change by 10–25% because of the independence assumption. We also proposed a new method that does not invoke such independence assumptions.

Our analyses show that when performing an attribution analysis, the covariance among attributing variables should be taken into consideration. Perhaps more subtly, our analyses indicate that acceptable agreement between modeled and observed ΔT_s does not necessarily guarantee the correct attribution of ΔT_s. This is simply because when the attributing variables are not independent of each other, their total contribution is not bounded by unity. The original IBM method and the correction proposed here in section 2 (involving R_1) yield the same total contribution of aerodynamic resistance and Bowen ratio to ΔT_s. However, the original IBM method included the contribution of aerodynamic resistance through altering the Bowen ratio in the contribution of Bowen ratio, which led to an overestimation of the contribution of aerodynamic resistance and concomitantly an underestimation of the Bowen ratio contribution.

Our study here only focuses on the magnitude of R_1 and R_2. Equally importantly, the spatial variability of R_1 and R_2, indicated by the error bar in Figure 2, is significant, especially in the temperate region where the contribution from aerodynamic resistance was found to be the largest in a previous study over the same domain [*Zhao et al*., 2014]. This could have important implications as their conclusion was based on the strong correlation between spatial variations of ΔT_s and the aerodynamic resistance contribution. However, our study here did not use paired data, as our results were always normalized by the original IBM estimates; hence, we could not directly compare the spatial correlations between ΔT_s and the contribution of aerodynamic resistance calculated from the TRM method to those reported in *Zhao et al*. [2014]. Further investigations using data from paired sites or numerical simulations are strongly recommended.

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