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Communication

Reply to Comment by Szilagyi and Crago on "Physical Interpretation of the Complementary Relationship for Evapotranspiration"

Sha Zhou [1,2,*], Jinfeng Zhao [1,2] and Bofu Yu [3]

1 State Key Laboratory of Earth Surface Processes and Disaster Risk Reduction, Faculty of Geographical Science, Beijing Normal University, Beijing 1000875, China
2 Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing 1000875, China
3 School of Engineering and Built Environment, Griffith University, Nathan, QLD 4111, Australia
* Correspondence: shazhou21@bnu.edu.cn

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Abstract: This reply addresses comments on our physically derived complementary relationship (CR) framework, which challenge both the framework's practical performance and our physical interpretation of apparent potential evapotranspiration (PET_a). We clarify that PET_a represents an atmospheric aerodynamic upper limit instead of a surface energy-limited flux. Using the identical FLUXNET dataset of 124 sites to replicate the benchmark results reported in the comment, we quantify that errors in estimated evapotranspiration (ET) primarily originate from two sources: inaccurate parameterization of aerodynamic resistance (r_a) and surface energy imbalance in eddy-covariance measurements. Both factors directly introduce uncertainties in computed PET_a and propagate the errors in PET_a into final ET estimates. Generalized calibration schemes for r_a across diverse land cover types and further refinements to CR-based ET estimation frameworks are essential for mitigating ET estimation uncertainties in future CR applications.

Keywords: evapotranspiration; complementary relationship; surface energy balance; aerodynamic resistance parameterization

1. Introduction

We thank Szilagyi and Crago for their careful reading of our paper, their detailed and thoughtful comment, and for performing an extensive test of our theoretical complementary relationship (CR) formulation against eddy-covariance (EC) observations. The major concern raised in their comment is that our physically-based CR is theoretically sound but practically less reliable than thermodynamics-based CR versions. They further highlight that the main discrepancy among alternative CR formulations lies in the estimation of the apparent potential evapotranspiration (PET_a), whose magnitude is amplified in our formulation relative to that in thermodynamics-based approaches. The purpose of this reply includes: (1) to acknowledge and discuss the physical reasoning raised in their comment; (2) to clarify the intent and interpretation of our framework, particularly the physical meaning and role of PET_a; and (3) to highlight inherent uncertainties in data and parameterization that would inevitably affect attempts to validate CR formulations. With these clarifications, we aim to resolve interpretive ambiguities rather than prolong debate over model performance, and to promote a more consistent understanding of the underlying CR mechanisms.

2. Physical Rationality of Our CR Framework

We appreciate their thermodynamic perspective on the complementary relationship and agree that thermodynamic consistency and energy conservation are fundamental constraints for evapotranspiration (*ET*) modelling. We also acknowledge that thermodynamics-based CR formulations represent an important CR development, and linear CR and polynomial CR based on thermodynamics do appear to be better in terms of the amount of scatter for the data set selected in Figure 1 of Szilagyi and Crago [1]. It is worth noting that our CR framework does not contradict thermodynamic principles; instead, it focuses on clarifying the conceptual distinction between energy-constrained and atmosphere-controlled potential evapotranspiration, which we believe can complement thermodynamics-based formulations to enhance the understanding of complementary relationships. Our original study primarily aimed at clarifying the physical interpretation of the complementary relationship, specifically the origin and meaning of asymmetry through the wet Bowen ratio (β_w), and at distinguishing the conceptual roles of energy-constrained potential evapotranspiration (PET_e) and atmosphere-controlled PET_a [2].

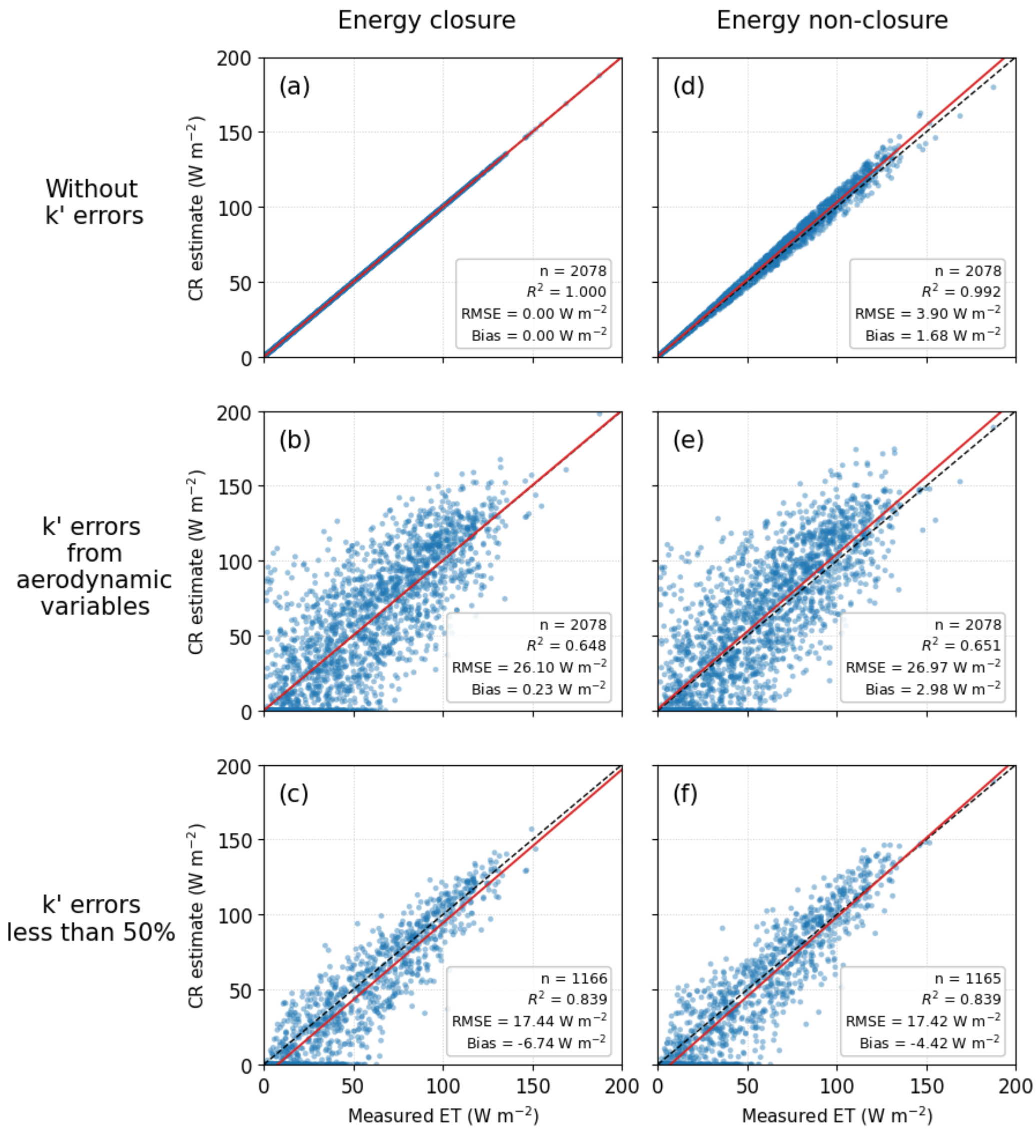

Figure 1. Comparison of *in situ* measured evapotranspiration (*ET*) to *ET* estimates derived from the complementary relationship (CR). Panels (**a**,**b**) show *ET* estimates using theoretical k' from Equation (6) and k' solved via Equations (2) and (4), with aerodynamic errors distorting the latter estimates. The full dataset contains 2078 site-month records from 124 eddy covariance towers, filtered to retain only months with energy balance residual errors below 10%. Panel (**c**) presents a subset of 1166 site-months where the relative error of solved k' remains less than 50% relative to theoretical reference values. In panels (**a**–**c**), available energy is constrained as the sum of latent and sensible heat fluxes to enforce full surface energy closure. Panels (**d**–**f**) repeat the identical calculation workflow of (**a**–**c**), but available energy is alternatively approximated as net radiation minus ground heat flux.

3. Clarification of the Physical Meaning of PET_a

A central concern raised by Szilagyi and Crago [1] relates to our treatment of PET_a and the assumption that the wet-patch surface temperature approximates that of the surrounding dry land. We emphasize that PET_a in our framework is intended as an upper-bound of the evaporative demand imposed by the atmosphere, not as a surface-energy-constrained evapotranspiration rate under all physical circumstances [3]. From a land–atmosphere coupling perspective [4], this atmospheric demand is shaped by prior and concurrent surface drying, air mass transformation, and mesoscale energy redistribution, and therefore does not need to depend solely on local radiative forcing. We agree that explicitly stating this distinction is essential and will improve the clarity and robustness of the framework.

Within the CR concept, PET_a has historically represented evaporation from a hypothetical small, saturated surface embedded in an unsaturated environment, whose primary purpose is to capture the atmospheric response to the reduced land evaporation [5]. Our definition makes this role explicit by identifying PET_a with the aerodynamic upper limit imposed by prevailing temperature, humidity, and turbulence of the overlying air, rather than with a wet-surface energy balance. Accordingly, while ET and PET_e are strictly constrained by surface energy availability, PET_a is allowed to vary depending on non-local energy inputs (e.g., advection and mesoscale atmospheric adjustments) that are not explicitly resolved at the surface scale.

We acknowledge that interpreting PET_a as a surface flux evaluated at an effectively enhanced energy supply can create conceptual tension when PET_a is compared directly with energy-constrained formulations in Figure 2 of Szilagyi and Crago [1]. We agree with Szilagyi and Crago that this distinction should be made clearer, and we accept that treating PET_a as a realizable surface flux may have led to degraded performance using the data chosen for this benchmarking test.

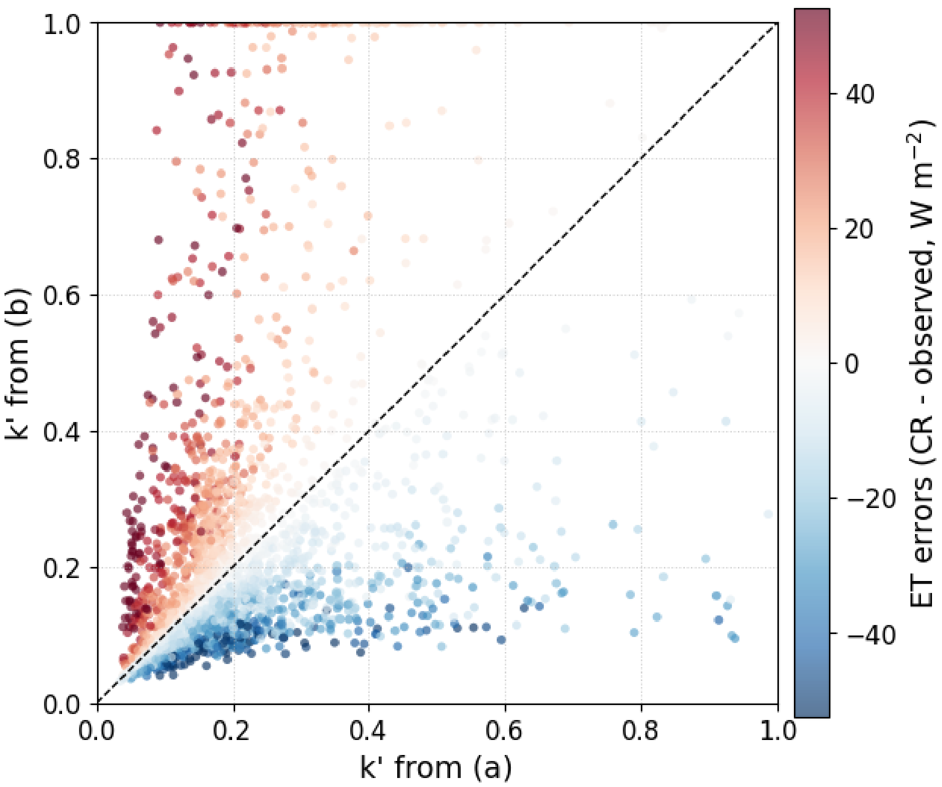

Figure 2. Impacts of k' deviations on ET estimation errors. The x-axis denotes theoretical reference k' values derived from Equation (6) in Figure 1a, whereas the y-axis represents numerically solved k' values calculated via Equations (2) and (4) from Figure 1b. The color scale quantifies the magnitude of ET estimation errors shown in Figure 1b for individual site-months.

4. Performance of the Proposed CR Framework

4.1. The CR-Based ET Estimation Framework

We first briefly recap our CR-based ET estimation framework, which requires only routine meteorological variables. All variables follow the definitions provided in Zhou and Yu [2] and are not reintroduced here. The CR formulation is derived from the surface energy balance:

$$ET = (1 + \beta_w)PET_e - \beta_w PET_a \tag{1}$$

PET_e is calculated via an energy-based equation using the available energy (R_n) and the wet Bowen ratio (β_w):

$$\lambda PET_e = \frac{R_n}{1 + \beta_w} \tag{2}$$

$$\beta_w = \alpha \cdot \frac{\gamma}{\Delta} \tag{3}$$

Alternatively, PET_e can be obtained from a modified Penman-Monteith equation with an adjustment parameter (k'):

$$\lambda PET_e = \frac{\Delta R_n + k' \dfrac{\rho c_p (e_a^* - e_a)}{r_a}}{\Delta + \gamma} \tag{4}$$

PET_a is calculated with PET_e and k' as

$$PET_a = \frac{PET_e}{k'} \tag{5}$$

As proposed in Zhou and Yu [2], k' can be solved for by equating the right-hand-sides of Equations (2) and (4). Importantly, k' theoretically depends on the actual and wet Bowen ratios:

$$k' = \frac{1 + \dfrac{1}{\beta}}{1 + \dfrac{1}{\beta_w}} \tag{6}$$

The value of k' calculated with Equation (6) serves as a theoretical reference benchmark to evaluate the numerically solved k' derived from Equations (2) and (4).

4.2. Two Major Uncertainty Sources Limiting ET Estimation

Despite the rigorous physical derivation from surface energy balance, the CR framework inevitably introduces errors when applied to raw EC flux observations. The first source of uncertainty originates from widespread non-closure of the surface energy balance in EC flux data, which directly introduces non-negligible errors. The second and more impactful uncertainty arises from errors in aerodynamic variables, including uncertainties in vapor pressure deficit and, most notably, inaccurate parameterization of aerodynamic resistance (r_a). Deviations in these aerodynamic quantities distort the k' solved via Equations (2) and (4), further propagating errors into PET_a calculated via Equation (5). These two types of uncertainty can lead to violations of the two boundary conditions underlying the CR framework, i.e., $ET = PET_e = PET_a$ under wet conditions and $ET < PET_e < PET_a$ under dry conditions, and consequently induce uncertainties into final *ET* estimates. For this reason, we emphasize that energy balance of the flux data and boundary conditions under wet and dry conditions should be checked first prior to any attempt at validation and cross-comparison of different CR formulations.

As documented in previous studies, the widely adopted Priestley–Taylor equation [6] for PET_e estimation and the Penman equation with empirical r_a parameterization methods [7,8] for PET_a estimation do not strictly satisfy these boundary constraints [3,9,10]. In addition, applying the Penman equation to estimate PET_a neglects additional energy inputs from the surrounding environment that are required to sustain *ET* from a small, saturated surface within a large dry area. Although the theoretical definitions of PET_e and PET_a, together with the derivation of our CR formulation, are fully aligned with these boundary conditions, their practical application remains vulnerable to unclosed surface energy balance and inaccurate r_a parameterization. Such limitations can generate substantial errors in *ET* estimation. In fact, achieving accurate parameterization of r_a across diverse land cover types remains a pervasive and unsolved challenge for the real-world application of nearly all CR formulations as well as a majority of alternative *ET* estimation models.

4.3. Quantitative Evaluation of Uncertainties Using FLUXNET Observations

To quantitatively separate and contrast the two uncertainty sources outlined above, we utilized monthly flux records from the same 124 FLUXNET sites examined by Szilagyi and Crago [1], yielding a total of 2078 site-month observations screened under their identical data filtering criteria. We further quantified the respective contributions of surface energy imbalance and aerodynamic errors to overall ET estimation errors, where the parameter α in Equation (3) was fixed at 0.15 to match the value adopted by Szilagyi and Crago [1]. All retained site-month records feature energy balance residual errors below 10%, meaning that systematic biases induced by incomplete energy closure remain modest for these sites (Figure 1d). In contrast, aerodynamic errors severely distort the numerically solved k' values, which induce errors in PET_a (Equation (5)) and propagate deviations into final ET estimates (Figure 1b). When k' matches its theoretical reference value derived from Equation (6), the CR framework produces bias-free ET estimates (Figure 1a). Figure 2 further illustrates that the sign and magnitude of ET errors are controlled by the discrepancy between aerodynamically derived k' and its theoretical benchmark. For the subset of 1166 site-months where the relative error of k' is smaller than 50%, our CR framework yields reliable ET predictions, with a coefficient of determination (R^2) of 0.84 and an RMSE of 17.44 W m^{-2} (Figure 1c). Given that uncertainties in solved k' originate predominantly from errors in aerodynamic terms, especially r_a, improved r_a parameterization schemes are essential for mitigating ET estimation uncertainties in future CR applications.

We concur with Szilagyi and Crago that future CR formulations should integrate thermodynamic rigor with explicit representation of surface energy balance and land–atmosphere feedbacks. Rather than viewing surface-energy-constrained and thermodynamic-oriented formulations as competing approaches, we suggest that they represent different but reconcilable projections of the same coupled system. And we look forward to improved predictive capability having duly considered uncertainties in measured ET and other input variables and parameters such as r_a that require calibration.

In conclusion, we view the comment by Szilagyi and Crago as a valuable opportunity to clarify conceptual distinctions within the CR framework, particularly regarding the interpretation of PET_a and the role of thermodynamic versus atmospheric constraints. While differing perspectives remain on how PET_a should be operationalized, we believe the points of agreement and clarification articulated here address the core concerns raised. We hope that this exchange helps sharpen the interpretation and application of CR formulations and serves as a constructive closure to this discussion.

Author Contributions

S.Z.: conceptualization, methodology, writing—original draft preparation; J.Z.: visualization, investigation; B.Y.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The Fluxnet2015 dataset is publicly available from https://fluxnet.org/data/fluxnet2015-dataset/ (accessed on 13 August 2026).

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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