

Short communication

Revisiting energetic limits on crop coefficients in heterogeneous canopies

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ABSTRACT

The crop coefficient (K_c) approach provides one of the simplest and most widely used means of estimating crop water demand. Previous studies have asserted that there is an upper limit to K_c of 1.2–1.3 compared to a standard grass reference surface based on presumed energy balance limitations. Some prominent sources argue that larger K_c values would be physically impossible and that measured or reported values greater than this should be rejected. However, these limits rely on simplifying assumptions that may not hold for the reality of conditions in the field. We argue that putative K_c maxima may not adequately consider the roles of aridity, canopy heterogeneity, aerodynamic coupling, and horizontal transfer of energy (i.e. advection) in enhancing transpiration. As a result, we recommend against the practice of discarding measurements of ET that exceed current putative energetic limits. Accounting for 3D canopy energy balance dynamics may be necessary to fully estimate energetic demand driving ET, particularly under advection and in heterogeneous canopies such as the California orchards used to characterize this study. Observed ET at or below putative K_c maxima under these conditions may result from water availability and physiological factors rather than energy balance limitations. Crop coefficients are a convenient and important tool for estimating canopy water demand; however, due to their inherent simplifying assumptions, they should not be treated as axiomatic indicators of energetic limitations on ET.

1. Introduction

Accurate estimates of evapotranspiration (ET) are necessary for irrigation management and water resource planning, particularly under increasing climate variability and water scarcity. Although direct measurement techniques such as eddy covariance and lysimetry have improved substantially in recent decades, these methods remain technically complex and costly to deploy at large spatial scales (Allen et al., 2011; Pereira et al., 2021b). This has led to continued reliance on model-based estimation of crop potential ET (ET_c).

Most methods of estimating ET_c (e.g., Allen et al., 1998, 2005) rely on the Penman-Monteith (PM) framework, which uses principles of mass and energy conservation, with latent and sensible heat fluxes represented as gradient-driven transport processes subject to aerodynamic and canopy resistances (r_a and r_s , respectively) (Pereira et al., 2021a). Values of r_a and r_s are standardized for different reference surfaces, the most widely used being the standard grass reference surface (ET_0) and a “tall” alfalfa reference surface (ET_r) (Allen et al., 2005).

ET_c is calculated as:

$$ET_c = K_c \times ET_0, \quad (1)$$

where ET_0 accounts for environmental influences on potential ET, and K_c empirically accounts for the (presumably consistent) species-specific divergence from that reference. Because ET_0 is widely reported by meteorological networks, this framework is commonly used for irrigation scheduling and for normalizing and calibrating ET rates in remote sensing and climate studies (Choudhury et al., 1994; Allen et al., 1998; Guerschman et al., 2009; Wang et al., 2021).

The ET_c approach assumes a homogeneous canopy that is well watered, such that soil moisture does not limit ET. ET_c is therefore considered the upper bound on ET for given weather conditions. In addition, K_c is often assumed to have a theoretical upper limit that sets the maximal ET possible for a given value of ET_0 (with maximum $K_c = 1.2$ – 1.3 relative to ET_0 , or an equivalent 1.0 relative to ET_r). These putative limits on K_c are based on limits to the transfer of water vapor away from evaporating surfaces implied by r_s and r_a , and by constraints on canopy temperature, and therefore vapor gradient, due to the finite supply of energy available to balance the latent heat consumed by evaporation (Allen et al., 2005, 2006, 2011; Rallo et al., 2021).

ET_c calculations implicitly assume that canopy properties and surface temperature are laterally homogeneous, and that advection is limited to the horizontal exchange allowed by alfalfa reference surface parameters under these conditions (Allen et al., 2011). However,

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this formulation does not directly account for large-scale or regional horizontal advection of sensible heat into the canopy airspace, and putative K_c limits rely on the assertion that ET from large areas of vegetation is governed by one-dimensional energy exchange principles (Pereira et al., 2025). Despite this assertion, substantial large-scale heterogeneity in ground cover and increased aerodynamic coupling between the canopy and the prevailing airspace may give rise to energy gradients that drive greater advection in orchard canopies. Recent research further shows that the magnitude of horizontal energy fluxes may be significantly greater than is typically assumed or directly measured by tower and remote sensing methods (Kool et al., 2018; Wang et al., 2024).

We argue below that the assumptions underlying putative energetic limits on K_c may not hold under several commonly occurring conditions: (1) tall canopies with a significantly reduced r_a compared to reference surfaces, (2) structurally heterogeneous canopies capable of generating horizontal gradients in temperature or vapor pressure, and (3) semi-arid or arid environments where advective energy inputs and subsequent thermodynamic divergence become significant components of canopy energy balance.

2. Assumptions governing theoretical K_c maxima

Food and Agriculture Organization (FAO) field measurements comparing crop water use (e.g., Wright, 1982) are often cited as a primary justification for putative K_c maxima. These measurements compared eight annual crops' ET rate against alfalfa, all of which were consistently below the alfalfa reference ET_r.

Allen et al. (2011) use these measurements to bolster the theoretical argument for putative K_c limitations, stating that “the tall (alfalfa) reference and its parameterizations in the PM equation tend to represent sufficiently low surface resistance and sufficiently high aerodynamic roughness to approximate near maximum rates of ET expected from large expanses of well-watered vegetation cover, even under conditions of strong regional advection”. They go on to argue that, although K_c will be most representative of true ET under semi-humid or humid conditions, even under arid conditions “the constraint of $K_c \sim 1.0$ – 1.1 for the alfalfa reference holds because of the tendency toward similarity in aerodynamic exchange and leaf area between even tall vegetation and the alfalfa reference”. With this justification, those authors state that “exceedance of measured or reported K_c above about 1.0 for alfalfa reference or 1.2 for grass reference in subhumid regions or above about 1.0 for alfalfa reference or about 1.2–1.4 for grass reference in arid regions should give cause for intense scrutiny”, and that “exceeding those values should also give cause for rejecting the data”. As a direct result, the community sometimes interprets the alfalfa reference as a hard physical limit that cannot be exceeded, which effectively places a ceiling on values of K_c reported in the literature.

2.1. Does the alfalfa reference accurately represent the upper limit to K_c in orchard crops?

Contrary to the assertions of Allen et al. (2011), the aerodynamic resistance of tall, heterogeneous canopies such as orchard crops may be dramatically lower than that of the alfalfa reference, allowing for greater potential water vapor transport than is implied by the asserted K_c limits. Those assertions were based on (1) empirical relationships described in Allen et al. (1989) and Pereira et al. (1999) showing that the alfalfa reference surface is a better approximation of tall canopies than the grass surface, and (2) comparisons made in Allen et al. (2011) against the previously cited data collected by Wright (1982) for annual herbaceous crops.

Although an alfalfa reference r_a may indeed be more representative of tall canopies than is the grass reference, it does not necessarily follow that it adequately represents woody perennial crops; the crops examined by Wright (1982) were annual herbaceous plants similar in

height and structure to the 0.5 m alfalfa reference canopy (namely, alfalfa, potato, snap bean, sugarbeet, pea, maize, and cereals). By contrast, woody crops common to semi-arid regions have canopies that are both much taller and more heterogeneous. Tall, rough and heterogeneous canopy architecture effectively extends the canopy-atmosphere interface, allowing for greater vertical air mixing (McNaughton and Jarvis, 1991), which may result in r_a values far lower than those of alfalfa and the other herbaceous crops measured by Wright.

The effects of canopy height on r_a can be estimated using the standard equations of Pereira et al. (1999) and Perrier (1975). For inputs equivalent to the alfalfa reference (LAI = 4.5, wind speed = 2 m s⁻¹, and measurement height 2 m above the top of the canopy), r_a continues to decrease as crop height increases above 0.5 m (the alfalfa reference height). For example, in a 6.0 m tall homogeneous canopy, r_a would be 3.9 s m⁻¹ according to these standard equations, which is nearly an order of magnitude less than the 30 s m⁻¹ alfalfa r_a value (Fig. 1). Even if these calculations are adjusted to assume wind speed is measured at 2 times the canopy height (i.e., above the roughness sublayer), r_a is still four-fold smaller than the alfalfa reference.

Classical parameterizations of aerodynamic resistance derive from Monin–Obukhov similarity theory and were developed primarily for horizontally homogeneous surfaces (Perrier, 1975; Pereira et al., 1999; Allen et al., 1998). In tall orchards, wake interference and spatial heterogeneity in canopy structure may complicate the application of bulk resistance formulations (Raupach, 1994; Finnigan, 2000). Eddy-covariance studies in orchards and forests have reported a wide range of effective aerodynamic coupling strengths depending on canopy structure, atmospheric stability, and measurement height, suggesting that r_a is neither spatially uniform nor trivially bounded by reference surfaces (Baldocchi, 1997, 2003). Our intent is not to assert a representative value of r_a for orchard crops, but rather to demonstrate that treating alfalfa reference parameterizations as universal lower bounds on aerodynamic resistance is not well justified for some canopies.

Note that the assumed r_s value for alfalfa is quite small, and is roughly half those typical of perennial tree crops. This aligns with typical observed stomatal conductance differences between these systems, so it is likely reasonable to treat alfalfa reference values of r_s as the minima possible under most conditions. However, even if perennial canopy r_s were 2–3 times greater than the alfalfa reference, 4–7-fold lower values of r_a could more than offset the resulting decrease in ET_c, according to the following calculations.

To evaluate the potential energy implications of reduced r_a , we conducted PM calculations for a semi-arid environment typical of many orchard crops (California's Central Valley). We used six years of hourly meteorological data (2019–2024) from the Davis, CA CIMIS (California Irrigation Management Information System) station (Snyder, 1984), and compared these values against ET_r calculated using the ASCE standardized PM calculation for alfalfa reference. ET_r is, on average, 1.4 × reported ET₀ values during this six year period. When r_a and r_s are modified to represent a 6-m-tall canopy (typical of woody crops grown in this region), ET_c consistently exceeds the putative limit imposed by ET_r (Fig. 2). When r_s is set at 2 × the alfalfa reference value, ET_c/ET_r averages 1.2 and only falls below 1.0 during the off-season. With $r_s = 3 \times$ the alfalfa reference, orchard ET_c/ET_r averages 0.9 for the entire period, but ET_c consistently exceeds the ET_r limit during the peak season when VPD is greatest.

2.2. Horizontal transfer of energy in orchard canopies

The ET_c approach can mathematically accommodate negative H under high wind speed and VPD, where the atmospheric transport portion of the PM equation becomes increasingly significant. This can lead to latent heat flux (λE) exceeding $R_n - G$ in ET_r and even occasionally in ET₀ (Fig. 3). However, though the equation accounts for potential energy balance divergence driven by local atmospheric transport via wind and VPD, it does not represent large-scale horizontal

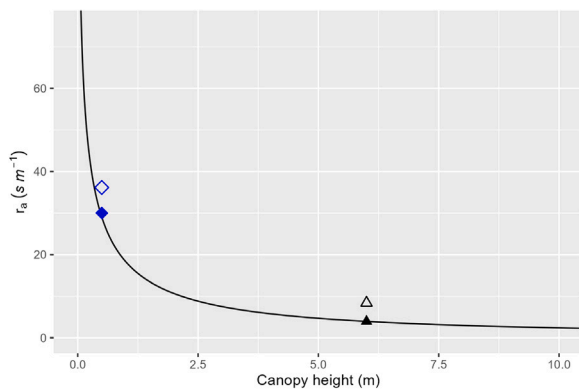


Fig. 1. Effect of canopy height on r_a . The line represents canopy aerodynamic resistance calculated while holding a constant LAI = 4.5, wind speed (u) = 2 m s^{-1} , with wind speed measured 2 m above canopy height to match the conditions assumed in the alfalfa reference. Closed points are marked to correspond with the r_a values used by Allen et al. (2011) to characterize the 0.5 m tall alfalfa reference (closed blue diamond), and the calculated value of a 6.0 m tall orchard canopy (closed black triangle) under the same LAI and wind speed. Open points represent the average value calculated for the alfalfa reference and the orchard canopy using hourly environmental inputs for the entire 2019–2024 period.

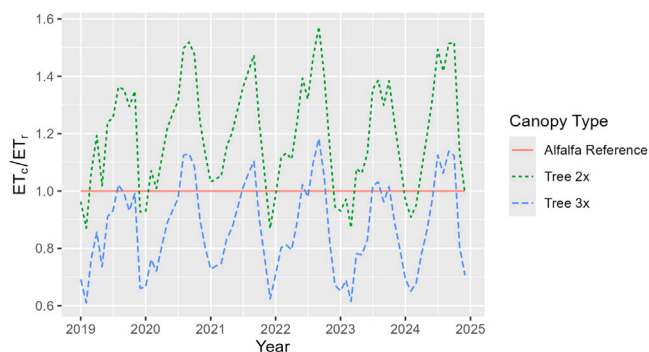


Fig. 2. Value of ET_c / ET_r . All calculations were performed using the Penman-Monteith approach at an hourly timescale using data from the Davis, CA CIMIS meteorological station from 2019–2024. Lines represent monthly averages of daily values for the ASCE standardized PM calculation of the “tall” alfalfa reference surface to get ET_r , and full-form PM calculations for 6 m tall tree canopies with r_s values equal to 2x or 3x those of the alfalfa reference standard to get ET_c .

advection of sensible heat into the canopy airspace. Furthermore, an explicit prerequisite of ET_c limitation assumptions is that net horizontal energy flux is limited to levels allowed by the aerodynamic transport and equilibrium forces represented by the alfalfa reference parameters as discussed above (Allen et al., 1998, 2005, 2011), and it is also explicitly assumed that ET will be “governed by one-dimensional energy exchange principles” over reference surfaces (Pereira et al., 2025).

Violation of these assumptions is perhaps unlikely in systems that are horizontally uniform over large spatial extents, such as broadacre herbaceous cropping systems. However, under some conditions large-scale advection may contribute substantially to canopy energy balance and allow for renewal of sensible heat content, particularly in canopies that differ significantly from their surroundings and are grown under a semi-arid or arid environment. Typical orchard systems, specifically, may not satisfy the assumption of extended lateral homogeneity of canopy architecture and temperature. They are also better aerodynamically coupled with the prevailing airspace than is the alfalfa reference due to their heterogeneity, surface roughness, and reduced r_a . As a result, the assumptions of aerodynamic transport and equilibrium

forces prevalent above the alfalfa reference as described by Allen et al. (2011) and Pereira et al. (2025) may not fully capture the potential for advection in orchard canopies. Canopies with significantly different aerodynamic and surface resistance profiles will not respond to differences in air temperature, air humidity and wind speed measurements in the same way, because they are not coupled with the atmosphere in the same way.

Spatiotemporal heterogeneity can significantly affect canopy energy balance by generating gradients in temperature and/or vapor pressure (Wang et al., 2024). Large eddies that develop due to gradients in temperature and vapor pressure between the canopy and its surroundings can lead to λE enhancement that is not captured through measurement of the vertical components of surface energy balance, as energy originates and/or water vapor is deposited outside of the measurement footprint (Eder et al., 2015; Kenny et al., 2017; Morrison et al., 2021; Zhou et al., 2023; Razmavaran et al., 2024; Wang et al., 2024).

Pereira et al. (2025) assume that regional advection will be captured under the FAO ET_0 guidelines, preventing K_c greater than putative limits, because “the changes in gradients over the irrigated fields are assumed to be similar to those experienced at a reference weather station that has a well-watered, transpiring surface and is located in a similar environment. In those situations, the FAO Penman-Monteith equation responds to the impacted temperature and humidity gradients established by the weather data and produces higher ET_0 . That higher ET_0 , in turn, corresponds to the higher ET that occurs from well-watered fields under regional advection. This phenomenon is common to irrigated fields in arid and semiarid regions and is accurately treated by the FAO Penman-Monteith ET_0 equation due to its use of solar radiation, air temperature, air humidity and wind speed measurements”. However, for the FAO PM equation to accurately represent limits to K_c , the canopy must respond to those environmental conditions in the same way as the reference surface. Orchard canopies’ significant differences in aerodynamic coupling and r_a from the reference surfaces violate this assumption.

Horizontal sensible heat transfer may be substantial in tall canopies like orchards, and more generally whenever the land surface and its aerodynamic and radiative properties are spatially heterogeneous, enhancing aerodynamic roughness and creating localized cooling and heating that can drive oasis effects and horizontal energy fluxes (Oke, 1987; Taha et al., 1991; Spronken-Smith et al., 2000; Potchter et al., 2008; Ruehr et al., 2020; Yu et al., 2024). The effects of horizontal energy transfer are especially apparent under semi-arid or arid conditions, due to the increased gradient potential in sensible heat and VPD (Lund and Soegaard, 2003; Kool et al., 2018; Wang et al., 2024).

Under these conditions, synoptic and mesoscale flow may continually renew the heat content of the air mass overlying the canopy, providing the capacity for a persistent negative sensible heat flux (Brakke et al., 1978; Oke, 1987; Figuerola and Berliner, 2005). As per Oke (1987), under conditions where a comparatively wet and cool canopy is embedded within arid surroundings, “we may expect evaporation to proceed at an increased rate compared with that from an extensive area of the same composition, and it is quite possible that the energy required to accomplish this will exceed the local radiative surplus”. In this case, sensible heat supplied by air-to-oasis inversion is able to maintain an overall annual latent heat flux larger than R_n , such that the annual integrated H is negative (Oke, 1987).

One rationale for ignoring this advective exchange is the supposition that any temperature gradient in the canopy occurs only very near its leading-edge, such that minimal gradients occur across the bulk of the canopy. Pereira et al. (2025), for example, state that local advection will typically only extend some tens of meters from the edge of a canopy, further asserting that, relative to ET_0 , “... K_c must adhere to upper limits for K_c of approximately 1.20–1.30, when the areal expanse of the vegetation is larger than about 2000 m^2 . This is required because ET from large areas of vegetation is governed by one-dimensional energy exchange principles and by the principle of

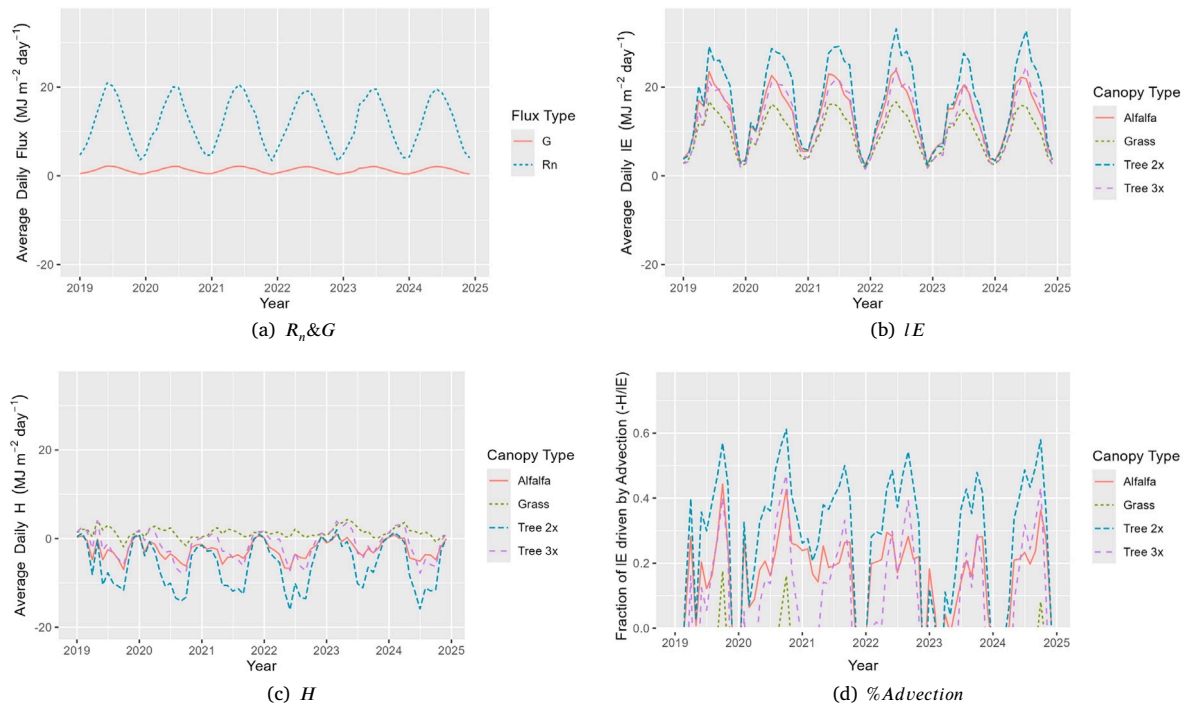


Fig. 3. (A) Daily average values of R_n and G energy fluxes ($MJ\ m^{-2}\ day^{-1}$), corrected as per ASCE standardization from hourly data collected at the Davis, CA, CIMIS meteorological station. (B) Daily average values of λE energy flux ($MJ\ m^{-2}\ day^{-1}$) converted from ET calculated at an hourly timescale using the ASCE standardized PM equation for grass and alfalfa reference surfaces and the full-form PM equation for 6 m tall tree canopies with r_s values equal to 2 & 3x standardized alfalfa reference values. (C) Daily average values of H energy flux calculated as the remainder needed to bring the surface energy balance to closure using inputs of the data in 3(a) & 3(b). (D) Fraction of total monthly λE flux calculated using the Penman-Monteith approach that would need to be offset by advection in order to reach energy balance closure ($-H/\lambda E$ for values of $H < 0$).

conservation of energy". To evaluate this assumption, we analyzed remotely sensed surface temperatures of 42,000 almond orchard blocks in California across a 6 year period (see Supplemental Information for details), and this assumption does not appear to hold, generally, under field conditions.

These data show that the surface temperature of almond orchard canopies is quite heterogeneous, particularly compared to their surroundings (Fig. 4). Orchards are, on average, significantly cooler than their surroundings during the growing season (overall mean of $-1.4\ ^\circ C$), with clear gradients of surface temperature commonly extending hundreds of meters into orchard blocks (Fig. 4(a)). The area affected by these gradients represents a large fraction of typical California almond orchards (Fig. 4(b)). Such gradients are consistent with the thermodynamic conditions required to support advective energy transfer over areas much larger than 2000 m^2 .

Although these surface temperature gradients do not directly prove the occurrence of lateral advection – the magnitude and persistence of advection also depend on wind speed, atmospheric stability, and the vertical structure of turbulence (Lang, 1973; Finnigan, 2000) – they nevertheless contradict the assumption of lateral homogeneity, which underpins the energy accounting on which putative energetic limits to K_c are based. The prevalence and spatial extent of these temperature gradients suggest that large portions of orchard canopies operate within environments where advection is physically likely and potentially influential (Kool et al., 2018; Wang et al., 2024). Persistent horizontal temperature gradients represent the fundamental thermodynamic driver of sensible heat advection, and their widespread occurrence indicates that the assumption of lateral homogeneity underlying the ET_c framework is frequently violated in orchard systems.

These measurements are also consistent with the description of Oke (1987) of leading-edge effects that occur at the transition from a hot, dry surface to cool vegetation. Along with a decrease in surface

temperature while moving into the canopy interior, there is a strong leading-edge divergence in the energy balance capable of driving an acute depression in H values near the transition as well as a strong leading-edge increase in ET . ET and H values are expected to return toward the normalized values of an extensive homogeneous canopy when moving toward the canopy interior, however ET is elevated and H is depressed from these normalized values for as long as there is a continued horizontal gradient in vapor pressure and surface temperature, respectively. The measurements are also consistent with studies that have found leading-edge effects that elevate transpiration and persist more than 100 m into the interior of tree canopies during the dry season of Central Brazil (Kunert et al., 2015).

The presence of a strong surface temperature gradient for hundreds of meters into the orchard canopies' interior in this study is indicative of potential depression in H and elevation in ET throughout the majority of the orchard blocks' footprint (Fig. 4). This portion of the canopy would require a separate energy balance calculation capable of encapsulating the leading-edge and oasis effects resulting from horizontal temperature and vapor pressure gradients to be fully represented.

Numerous studies have documented advective enhancement of latent heat flux, particularly in semi-arid environments, where ET may exceed net radiation by 8% to periods of 150% depending on crop type and environment (Lemon et al., 1957; McIlroy and Angus, 1964; Van Bavel, 1967; Rosenberg, 1969a,b; Hanks et al., 1971; Lang, 1973; Lang et al., 1974; Brakke et al., 1978; Verma et al., 1978; Oke, 1987; Prueger et al., 1996; Li and Yu, 2007; Kool et al., 2018). As such, it may be important to develop a more complete and standardized means of quantifying the energetic potential and effects of horizontal transfer of energy and water vapor on canopy water demand, particularly in semi-arid and arid environments.

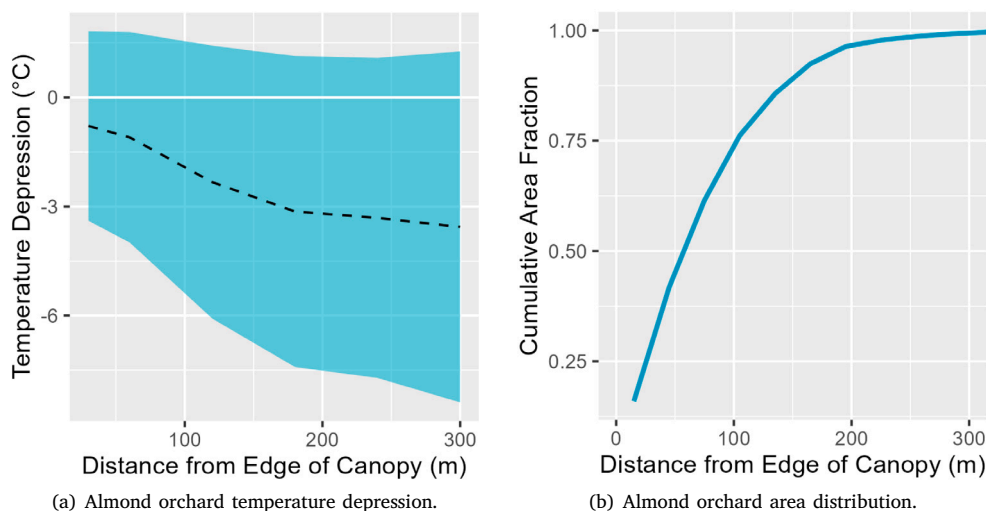


Fig. 4. (A) Canopy surface temperature relative to the surroundings of almond orchard blocks in California between May and August of 2018–2023. Dotted line representing the mean and the filled ribbon representing a 1-sd range. Interior surface temperature is significantly cooler than orchard surroundings, with a gradient in temperature, decreasing moving in from the canopy edge. (B) Cumulative area distribution of total orchard area within a given distance of the block's edge.

3. The potential for advection in canopies with low aerodynamic resistance

Given measurements of R_n and G , the PM estimates calculated above for λE for tall, low- r_a canopies indicate that a negative H (i.e., downward sensible heat flux) would be necessary to reach system energy balance closure for the majority of days in the six-year period (Fig. 3).

When using alfalfa reference values for aerodynamic resistance in our model calculations, annual λE exceeds $R_n - G$ such that an average of 19% of all λE would need to be provided by negative H . Even more (35%) of λE would require advection in 6 m-tall canopies with r_s double that of the alfalfa reference. During high-VPD months, even ET_0 would require up to 17% of total energy balance to come from advection (Fig. 3(d)). These ET_c values all fall within the range of reported λE possible given significant advection (McIlroy and Angus, 1964; Rosenberg, 1969a,b; Hanks et al., 1971; Lang, 1973; Lang et al., 1974; Brakke et al., 1978; Verma et al., 1978; Oke, 1987; Prueger et al., 1996; Li and Yu, 2007; Kool et al., 2018). This indicates that when conditions facilitate significant advection, which appear to be quite common, canopies may have the capacity to exceed putative maxima to K_c .

4. Implications for interpreting crop water demand

The arguments above do not necessarily imply that tall cropping systems use more water than previously thought, but rather that they may have the aerodynamic transfer and energetic potential to do so.

Real canopies are subject to additional constraints not represented in the standardized PM formulation. Other mechanisms can, and likely often do, limit K_c in the field, irrespective of low aerodynamic resistance and possible advection. Most notably, limited water availability can reduce stomatal opening and restrict water flow. Wang et al. (2024), for example, give a detailed account of possible stomatal feedback that can help prevent excessive water losses under advection, especially for canopies whose stomatal response is well coupled to VPD; the standardized PM model framework treats r_s as a constant for a given crop and season, and thus excludes the negative feedback created by stomatal closure at high VPD. In semi-arid environments, agricultural water use may often be limited by water availability rather than energy supply. Nevertheless, in periods following irrigation, λE

can often exceed R_n . For example, Kool et al. (2018) report that λE was elevated by 30%–40% above R_n following irrigation in a Negev vineyard, and by 8% for the study as a whole. Likewise, Van Bavel (1967) and Oke (1987) showed λE elevated by 50% above R_n in an alfalfa crop in Arizona following irrigation, with λE gradually falling back below R_n as the soil dried down and physiological stress led to an increase in r_s .

It is also worth noting that ET measurements performed by vertical micrometeorological and energy balance accounting (e.g. eddy covariance (EC) and surface renewal) have been reported to systematically underestimate λE compared to direct mass balance measurement by lysimeters, particularly under high VPD and advective conditions (Chávez et al., 2009; Alfieri et al., 2012; Widmoser and Wohlfahrt, 2018; Dhungel et al., 2021; Bambach et al., 2022). It is possible that, in some cases, such uncorrected underestimations of ET from EC could contribute to the perception that ET values typically do not exceed the putative limits to K_c , even for well-watered orchard canopies.

5. Conclusions

Aerodynamic resistance may be far smaller in tall perennial canopies than in those of the alfalfa reference surface used to infer energetic limits on K_c . Substituting representative r_a and r_s values for tree crops into the Penman-Monteith equation predicts K_c values that exceed those putative limits. The energy required to balance the greater latent heat implied by such large K_c values could be provided by advection in orchards and other heterogeneous canopies, particularly under semi-arid or arid conditions. Remote sensing of surface temperature heterogeneity in 42,000 almond orchard blocks in California shows strong and systematic within-canopy temperature gradients that extend throughout much of the orchard block, illustrating the potential for substantial advection and contradicting the assumption of lateral homogeneity that underlies putative energetic limits on K_c .

Putative K_c limits may effectively represent the homogeneous canopies and conditions assumed by Allen et al. (2005, 2011). However, tall, heterogeneous canopies that are well coupled with the boundary layer violate these assumptions. This may result in the K_c approach underestimating the maximum energetic potential for ET_c , particularly under arid and windy conditions. In this case, accurate ET estimation may require either the adoption of an approach that better

incorporates 3D dynamics of energy fluxes, or an empirical calibration of the Penman approach.

Low aerodynamic resistance and advective energy inputs may enable K_c values greater than current putative limits, but this does not necessarily entail that more water is being used in all canopies where these conditions are present. Under arid environments, there may be negative feedback between VPD and stomatal opening, and ET_c is often directly limited by water availability and application rate rather than the abundant supply of energy. Interpretation of K_c should therefore consider canopy physiology and management practices. If water is plentiful, 3D canopy energy balance dynamics may need to be considered for a complete estimate of energetic demand driving ET, particularly under arid conditions. We recommend against the practice of rejecting ET_c measurements that exceed putative K_c limitations, or of labeling these measurements as physically impossible solely on the basis of energy limitation.

Crop coefficients are a useful tool for estimating local ET. However, dogmatic acceptance of universalized hard limits on K_c may set a dangerous precedent, particularly in cases where those limits are based on data from significantly different canopy types and/or environmental conditions than those that exist in the canopy of interest.

CRedit authorship contribution statement

Ethan H. Frehner: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas N. Buckley:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Brian N. Bailey:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.agrformet.2026.111411>.

Data availability

No new data included in manuscript. All data used is publicly available.

References

- Alfieri, J.G., Kustas, W.P., Prueger, J.H., Hipps, L.E., Evett, S.R., Basara, J.B., Neale, C.M., French, A.N., Colaizzi, P., Agam, N., Cosh, M.H., Chavez, J.L., Howell, T.A., 2012. On the discrepancy between eddy covariance and lysimetry-based surface flux measurements under strongly advective conditions. *Adv. Water Resour.* 50, 62–78. <https://doi.org/10.1016/j.advwatres.2012.07.008>, the Bushland Evapotranspiration and Agricultural Remote Sensing Experiment 2008, URL: <https://www.sciencedirect.com/science/article/pii/S0309170812001960>.
- Allen, R.G., Jensen, M.E., Wright, J.L., Burman, R.D., 1989. Operational estimates of reference evapotranspiration. *Agron. J.* 81, 650–662. <https://doi.org/10.2134/agronj1989.00021962008100040019x>.
- Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting: I. factors governing measurement accuracy. *Agric. Water. Manag.* 98, 899–920. <https://doi.org/10.1016/j.agwat.2010.12.015>.
- Allen, R., Pereira, L., Raes, D., Smith, M., 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Food and Agriculture Organization of the United Nations.
- Allen, R.G., Pruitt, W.O., Wright, J.L., Howell, T.A., Ventura, F., Snyder, R., Itenfisu, D., Steduto, P., Berengena, J., Yrisarry, J.B., Smith, M., Pereira, L.S., Raes, D., Perrier, A., Alves, L., Walter, I., Elliott, R., 2006. A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. *Agric. Water. Manag.* 81, 1–22. <http://dx.doi.org/10.1016/j.agwat.2005.03.007>.
- Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T., Itenfisu, D., Jensen, M.E., 2005. The ASCE standardized reference evapotranspiration equation. In: Report of the Task Committee on Standardization of Reference Evapotranspiration. Environmental and Water Resources Institute of the American Society of Civil Engineers, Reston, Virginia, USA, <http://dx.doi.org/10.1061/9780784408056.fm>.
- Baldocchi, D., 1997. Measuring and modelling carbon dioxide and water vapour exchange over a temperate broad-leaved forest during the 1995 summer drought. *Plant, Cell & Environ.* 20, 1108–1122. <http://dx.doi.org/10.1046/j.1365-3040.1997.d01-147.x>.
- Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biol.* 9, 479–492. <http://dx.doi.org/10.1046/j.1365-2486.2003.00629.x>.
- Bambach, N., Kustas, W., Alfieri, J., Prueger, J., Hipps, L., McKee, L., Castro, S., Volk, J., Alsina, M., McElrone, A., 2022. Evapotranspiration uncertainty at micrometeorological scales: the impact of the eddy covariance energy imbalance and correction methods. *Irrig. Sci.* 40, 1–17. <http://dx.doi.org/10.1007/s00271-022-00783-1>.
- Brakke, T.W., Verma, S.B., Rosenberg, N.J., 1978. Local and regional components of sensible heat advection. *J. Appl. Meteorol.* (1962-1982) 17, 955–963, URL: <http://www.jstor.org/stable/26178560>.
- Chávez, J., Howell, T., Copeland, K., 2009. Evaluating eddy-covariance cotton et measurements in an advective environment with large weighing lysimeters. *Irrig. Sci.* 28, 35–50. <http://dx.doi.org/10.1007/s00271-009-0179-7>.
- Choudhury, B., Ahmed, N., Idso, S., Reginato, R., Daughtry, C., 1994. Relations between evaporation coefficients and vegetation indices studied by model simulations. *Remote Sens. Environ.* 50, 1–17. [http://dx.doi.org/10.1016/0034-4257\(94\)90090-6](http://dx.doi.org/10.1016/0034-4257(94)90090-6).
- Dhungel, R., Aiken, R., Evett, S.R., Colaizzi, P.D., Marek, G., Moorhead, J.E., Baumhardt, R.L., Brauer, D., Kutikoff, S., Lin, X., 2021. Energy imbalance and evapotranspiration hysteresis under an advective environment: Evidence from lysimeter, eddy covariance, and energy balance modeling. *Geophys. Res. Lett.* 48, <https://doi.org/10.1029/2020GL091203>, e2020GL091203, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL091203>, URL: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020GL091203>.
- Eder, F., De Roo, F., Rotenberg, E., Yakir, D., Schmid, H.P., Mauder, M., 2015. Secondary circulations at a solitary forest surrounded by semi-arid shrubland and their impact on eddy-covariance measurements. *Agric. Forest. Meteorol.* 211–212, 115–127. <http://dx.doi.org/10.1016/j.agrformet.2015.06.001>.
- Figuerola, P., Berliner, P., 2005. Evapotranspiration under advective conditions. *Int. J. Biometeorol.* 49, 403–416. <http://dx.doi.org/10.1007/s00484-004-0252-0>.
- Finnigan, J., 2000. Turbulence in plant canopies. *Annu. Rev. Fluid Mech.* 32, 519–571. <https://doi.org/10.1146/annurev.fluid.32.1.519>.
- Guerschman, J.P., Dijk, A.I.V., Mattersdorf, G., Beringer, J., Hutley, L.B., Leuning, R., Pipunic, R.C., Sherman, B.S., 2009. Scaling of potential evapotranspiration with modis data reproduces flux observations and catchment water balance observations across Australia. *J. Hydrol.* 369, 107–119. <http://dx.doi.org/10.1016/j.jhydrol.2009.02.013>.
- Hanks, R.J., Allen, L.H., Gardner, H.R., 1971. Advection and evapotranspiration of wide-row sorghum in the central great plains. *Agron. J.* 63, 520–527. <https://doi.org/10.2134/agronj1971.00021962006300040002x>.
- Kenny, W., Bohrer, G., Morin, T., Vogel, C., Matheny, A., Desai, A., 2017. A numerical case study of the implications of secondary circulations to the interpretation of eddy-covariance measurements over small lakes. *Bound.-Layer Meteorol.* 165, 311–332. <https://doi.org/10.1007/s10546-017-0268-8>.
- Kool, D., Ben-Gal, A., Agam, N., 2018. Within-field advection enhances evaporation and transpiration in a vineyard in an arid environment. *Agric. Forest. Meteorol.* 255, 104–113. <https://doi.org/10.1016/j.agrformet.2017.10.018>, honoring W.J. Massman's Discoveries: Bringing Physics to Agriculture.
- Kunert, N., Aparecido, L.M.T., Higuchi, N., dos Santos, J., Trumbore, S., 2015. Higher tree transpiration due to road-associated edge effects in a tropical moist lowland forest. *Agric. Forest. Meteorol.* 213, 183–192. <https://doi.org/10.1016/j.agrformet.2015.06.009>, URL: <https://www.sciencedirect.com/science/article/pii/S0168192315001884>.
- Lang, A., 1973. Measurement of evapotranspiration in the presence of advection, by means of a modified energy balance procedure. *Agric. Meteorol.* 12, 75–81. [https://doi.org/10.1016/0002-1571\(73\)90008-3](https://doi.org/10.1016/0002-1571(73)90008-3).
- Lang, A., Evans, G., Ho, P., 1974. The influence of local advection on evapotranspiration from irrigated rice in a semi-arid region. *Agric. Meteorol.* 13, 5–13. [https://doi.org/10.1016/0002-1571\(74\)90060-0](https://doi.org/10.1016/0002-1571(74)90060-0).
- Lemon, E.R., Glaser, A.H., Satterwhite, L.E., 1957. Some aspects of the relationship of soil, plant, and meteorological factors to evapotranspiration. *Soil Sci. Am. J.* 21, 464–468, URL: <https://api.semanticscholar.org/CorpusID:128607178>.

- Li, L., Yu, Q., 2007. Quantifying the effects of advection on canopy energy budgets and water use efficiency in an irrigated wheat field in the North China Plain. *Agricult. Water. Manag.* 89, 116–122. <http://dx.doi.org/10.1016/j.agwat.2006.12.003>.
- Lund, M., Soegaard, H., 2003. Modelling of evaporation in a sparse millet crop using a two-source model including sensible heat advection within the canopy. *J. Hydrol.* 280, 124–144. [http://dx.doi.org/10.1016/S0022-1694\(03\)00222-1](http://dx.doi.org/10.1016/S0022-1694(03)00222-1).
- McIlroy, I., Angus, D., 1964. Grass, water and soil evaporation at aspendale. *Agric. Meteorol.* 1, 201–224. [http://dx.doi.org/10.1016/0002-1571\(64\)90030-5](http://dx.doi.org/10.1016/0002-1571(64)90030-5).
- McNaughton, K.G., Jarvis, P.G., 1991. Effects of spatial scale on stomatal control of transpiration. *Agricult. Forest. Meteorol.* 54, 279–302.
- Morrison, T., Calaf, M., Higgins, C., Drake, S., Perelet, A., Pardyjak, E., 2021. The impact of surface temperature heterogeneity on near-surface heat transport. *Bound.-Layer Meteorol.* 180, 247–272. <http://dx.doi.org/10.1007/s10546-021-00624-2>.
- Oke, T.R., 1987. *Boundary Layer Climates*, second ed. Routledge, London.
- Pereira, L.S., Allen, R.G., Paredes, P., López-Urrea, R., Raes, D., Smith, M., Kilic, A., Salman, M., 2025. Crop evapotranspiration – guidelines for computing crop water requirements. In: Number 56 Rev.1 in FAO Irrigation and Drainage Paper. second edition, revised 2025 ed.. Food and Agriculture Organization of the United Nations, Rome, Italy, FAO Irrigation and Drainage Paper No. 56 Rev.1.
- Pereira, L.S., Paredes, P., Hunsaker, D.J., López-Urrea, R., Jovanovic, N., 2021a. Updates and advances to the FAO56 crop water requirements method. *Agricult. Water. Manag.* 248, <http://dx.doi.org/10.1016/j.agwat.2020.106697>.
- Pereira, L.S., Paredes, P., López-Urrea, R., Hunsaker, D.J., Mota, M., Shad, Z.M., 2021b. Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach. *Agricult. Water. Manag.* 243, 106196. <http://dx.doi.org/10.1016/J.AGWAT.2020.106196>.
- Pereira, L.S., Perrier, A., Allen, R.G., Alves, I., 1999. Evapotranspiration: Concepts and future trends. *J. Irrig. Drain. Eng.* 125, 45–51. [http://dx.doi.org/10.1061/\(ASCE\)0733-9437\(1999\)125:2\(45\)](http://dx.doi.org/10.1061/(ASCE)0733-9437(1999)125:2(45)).
- Perrier, A., 1975. Etude physique de l'évapotranspiration dans les conditions naturelles. III. évapotranspiration réelle et potentielle des couverts végétaux. *ANN. AGRON* 26, 229–243.
- Potchter, O., Goldman, D., Kadish, D., Iluz, D., 2008. The oasis effect in an extremely hot and arid climate: The case of Southern Israel. *J. Arid. Environ.* 72, 1721–1733. <http://dx.doi.org/10.1016/j.jaridenv.2008.03.004>.
- Prueger, J., Hipps, L., Cooper, D., 1996. Evaporation and the development of the local boundary layer over an irrigated surface in an arid region. *Agricult. Forest. Meteorol.* 78, 223–237. [http://dx.doi.org/10.1016/0168-1923\(95\)02234-1](http://dx.doi.org/10.1016/0168-1923(95)02234-1).
- Rallo, G., Paço, T.A., Paredes, P., Puig-Sirera, Massai, R., Provenzano, G., Pereira, L.S., 2021. Updated single and dual crop coefficients for tree and vine fruit crops. *Agricult. Water. Manag.* 250, 106645. <http://dx.doi.org/10.1016/J.AGWAT.2020.106645>.
- Raupach, M.R., 1994. Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. *Bound.-Layer Meteorol.* 71, 211–216. <http://dx.doi.org/10.1007/bf00709229>.
- Razmavaran, M.H., Sepaskhah, A.R., Ahmadi, S.H., 2024. Revisiting reference evapotranspiration calculation under regional advection and its effect on single and dual crop coefficients: An empirical approach for quinoa crop. *Meteorol. Appl.* 31, e2189. <http://dx.doi.org/10.1002/met.2189>.
- Rosenberg, N., 1969a. Advective contribution of energy utilized in evapotranspiration by Alfalfa in the East Central Great Plains (U.S.A.). *Agric. Meteorol.* 6, 179–184. [http://dx.doi.org/10.1016/0002-1571\(69\)90003-X](http://dx.doi.org/10.1016/0002-1571(69)90003-X).
- Rosenberg, N.J., 1969b. Seasonal patterns in evapotranspiration by irrigated Alfalfa in the central Great Plains 1. *Agron. J.* 61.
- Ruehr, S., Lee, X., Smith, R., Li, X., Xu, Z., Liu, S., Yang, X., Zhou, Y., 2020. A mechanistic investigation of the oasis effect in the Zhangye cropland in semiarid western China. *J. Arid. Environ.* 176, 104120. <http://dx.doi.org/10.1016/j.jaridenv.2020.104120>.
- Snyder, R.L., 1984. California irrigation management information system. *Am. Potato J.* 61, 229–234. <http://dx.doi.org/10.1007/BF02854009/METRICS>.
- Spronken-Smith, R.A., Oke, T.R., Lowry, W.P., 2000. Advection and the surface energy balance across an irrigated urban park. *Int. J. Climatol.* 20, 1033–1047. URL: <https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/1097-0088%28200007%2920%3A9%3C1033%3A%3AAID-JOC508%3E3.0.CO%3B2-U>.
- Taha, H., Akbari, H., Rosenfeld, A., 1991. Heat island and oasis effects of vegetative canopies: Micro-meteorological field-measurements. *Theor. Appl. Climatol.* 44, 123–138. <http://dx.doi.org/10.1007/BF00867999>.
- Van Bavel, C., 1967. Changes in canopy resistance to water loss from alfalfa induced by soil water depletion. *Agric. Meteorol.* 4, 165–176. [http://dx.doi.org/10.1016/0002-1571\(67\)90001-5](http://dx.doi.org/10.1016/0002-1571(67)90001-5), URL: <https://www.sciencedirect.com/science/article/pii/0002157167900015>.
- Verma, S.B., Rosenberg, N.J., Blad, B.L., 1978. Turbulent exchange coefficients for sensible heat and water vapor under advective conditions. *J. Appl. Meteorol.* (1962-1982) 17, 330–338, URL: <http://www.jstor.org/stable/26178007>.
- Wang, T., Alfieri, J., Mallick, K., Arias-Ortiz, A., Anderson, M., Fisher, J.B., Giotto, M., Szutu, D., Verfaillie, J., Baldocchi, D., 2024. How advection affects the surface energy balance and its closure at an irrigated alfalfa field. *Agricult. Forest. Meteorol.* 357, 110196. <http://dx.doi.org/10.1016/J.AGRFORMET.2024.110196>.
- Wang, T., Melton, F.S., Pôças, I., Johnson, L.F., Thao, T., Post, K., Cassel-Sharma, F., 2021. Evaluation of crop coefficient and evapotranspiration data for sugar beets from landsat surface reflectances using micrometeorological measurements and weighing lysimetry. *Agricult. Water. Manag.* 244, 106533. <http://dx.doi.org/10.1016/j.agwat.2020.106533>.
- Widmoser, P., Wohlfahrt, G., 2018. Attributing the energy imbalance by concurrent lysimeter and eddy covariance evapotranspiration measurements. *Agricult. Forest. Meteorol.* 263, 287–291. <http://dx.doi.org/10.1016/j.agrformet.2018.09.003>, URL: <https://www.sciencedirect.com/science/article/pii/S0168192318302983>.
- Wright, J.L., 1982. New evapotranspiration crop coefficients. *J. Irrig. Drain. Div.* 108, 57–74.
- Yu, H., Yang, T., Li, S., Kang, S., Du, T., Wang, Y., Chen, H., Guo, H., 2024. Surface energy fluxes in a drip-irrigated agroecosystem: Unique advection effect of oasis. *Agricult. Forest. Meteorol.* 357, 110204. <http://dx.doi.org/10.1016/j.agrformet.2024.110204>, URL: <https://www.sciencedirect.com/science/article/pii/S0168192324003174>.
- Zhou, Y., Sühling, M., Li, X., 2023. Evaluation of energy balance closure adjustment and imbalance prediction methods in the convective boundary layer – a large eddy simulation study. *Agricult. Forest. Meteorol.* 333, 109382. <http://dx.doi.org/10.1016/j.agrformet.2023.109382>.