Factoring in canopy cover heterogeneity on evapotranspiration partitioning: Beyond big-leaf surface homogeneity assumptions

Juan Camilo Villegas, Javier E. Espeleta, Clayton T. Morrison, David D. Breshears, and Travis E. Huxman

The vast majority of water on Earth’s terrestrial surface is lost through evapotranspiration (ET; vaporization processes that include evaporation [E] of intercepted water, E from free-water surfaces, and transpiration [T] from vegetation [Savenije 2004]) (Jasechko et al. 2013). Management and conservation of water resources require explicit understanding of ET, particularly due to the potential for global change to alter water fluxes. Although mostly considered by its hydrological nature, ET is the result of a suite of both physical and biological processes interacting at multiple spatial and temporal scales (Jarvis 1995) and constitutes a key driver of ecosystem function via the effects of T on ecosystem water and energy balance, impacting productivity (Jackson et al. 2001).

During the twentieth century, important empirical and theoretical models that described ET based on its physical drivers—particularly relevant to agriculture and water resource management—as well as sophisticated measurement techniques relevant to local scales were developed (Shuttleworth 2007). Although vegetation is acknowledged to strongly influence ET, theories that explicitly considered vegetation applied generally to two extreme cases: bare or fully vegetated soil (Shuttleworth 2007; Caylor et al. 2005). Widely used empirical models for ET, mostly derived from the Penman-Montith equation (Montith 1965), use a simplifying assumption where vegetation is aggregated vertically and horizontally to behave as a homogeneous “big leaf” described by metrics like Leaf Area Index (LAI; figure 1a) (Shuttleworth 2007). Such big-leaf models are effective in predicting ET for areas with homogeneous grass, crops, or forest cover, or for understanding processes at large spatial scales, where homogenization of vegetation cover may be appropriate.

Heterogeneous cover is common in the terrestrial biosphere, particularly in drylands, where mosaics of plants and the spaces that...
Evapotranspiration has been experimentally partitioned in both natural and agricultural lands where vegetation cover is relatively homogenous (Wilson et al. 2001; Kurpius et al. 2003). Some studies have partitioned ET for heterogeneous vegetation by measuring ET components separately, through mass and energy balance approaches and through the use of stable isotopes (Williams et al. 2004; Yepez et al. 2005). Evapotranspiration for heterogeneous cover is most commonly partitioned by integrating measurements from different sites with different environmental conditions or by scaling up T from leaf or individual plant to ecosystems using vegetation metrics such as LAI, assuming that all leaf area transpires at the same rate as the measured individual leaves (Ritchie et al. 1972; Harley and Baldocchi 1995; Lawrence et al. 2007). Yet, LAI-scaled T may incorrectly partition ET in heterogeneous systems since systems with different amounts of vegetation cover can have the same LAI due to differences in canopy architecture and foliar density, which may lead to differences in both E and T components of ET (figure 2b). Consequently, LAI can be an incomplete descriptor for ET partitioning because it relates only to T, but provides no information on intercanopy areas where soil E can dominate, or on the interactive effects of canopies’ energy balance and transport properties. Other measures, such as canopy cover, can provide additional information complementing LAI via encompassing differential spatial effects of vegetation on both canopy and intercanopy areas, which are, respectively, sources of T and E (figure 2c).

Canopy cover, particularly woody plant canopies, strongly controls two main drivers of ET at both leaf and plant scales: soil microclimate and surface roughness. Near-surface microclimate (figure 3a) and soil temperature (figure 3b) both decrease relative to beneath-canopy sites as canopy cover increases (Royer et al. 2012), and the extent of this effect depends on canopy architectural attributes (Villegas et al. 2010a). This can affect near-ground potential E (figure 3c) (Royer et al. 2012). Plants act as roughness elements and modify airflow, changing turbulence regimes as canopy cover changes with maximum turbulence at intermediate densities, potentially affecting mass and energy exchange with the atmosphere (figure 3d) (Breshears et al. 2009). Canopy attributes such as canopy height, height to lower foliage, canopy density, and foliar density can modify these patterns (figure 3e) (Villegas et al. 2010a).

In this paper, we outline a conceptual framework to relate patterns of canopy cover to their influence on ET partitioning that, when fully developed, can help account for heterogeneity in vegetation and improve estimation of ET partitioning in a greater fraction of the terrestrial surface. We explore this framework with the limited available data, which highlight both its potential utility and the need for further refinement.

A CONCEPTUAL FRAMEWORK INCORPORATING CANOPY HETERGENEITY INTO EVAPOTRANSPIRATION PARTITIONING

The simplest way to assume ET partitioning response to increases in canopy cover is through a unit increase in T per unit addition of canopy cover (with a corresponding proportional decrease in soil E), resulting in a linear relationship with a slope of 1 between canopy cover and the ratio of T to ET (T/ET). In this response, no changes in energy balance driving water flux from the system occur with canopy additions because leaf area has no interactive effects on neighboring intercanopy or canopy patches. This basic assumption has been adopted in regional land-surface-atmosphere models, where leaf area on the landscape is represented by a single transpiring layer that does not interact with neighboring areas (Lawrence et al. 2007).

Plants of sufficient foliar density not only affect areas beneath them but also affect neighboring areas via modifications on nearby surface energy balance and, consequently, can modify overall ET and its components (figure 2c). The effects of canopy cover on surface energy balance depend on a combination of canopy cover and canopy structural attributes, in addition to characteristics like root depth distributions, thereby varying complexly with canopy cover (Martens et al. 2000; Villegas et al. 2010a). Consequently, the effects of canopy cover on neighboring bare areas should lead to a disproportionate reduction of E in that location compared to the increase in T from the densely vegetated site (assuming per-unit increase in T with local LAI remains). In this
Figure 2
(a) Earth’s ecosystems, and particularly drylands, exhibit high horizontal heterogeneity due to variation in aerial canopy cover and can be represented as gradients of canopy cover. Along with this variation in cover, other attributes, such as Leaf Area Index (LAI), vary and may induce changes in other ecosystem properties. (b) However, using solely LAI as a descriptor of vegetation heterogeneity in the landscape may be misleading because, due to architectural attributes of vegetation, systems with same LAI can exhibit different amounts of canopy cover. (c) Consequently, other attributes of vegetation, such as canopy cover, can be useful in describing processes such as the partitioning of evaporation, as canopy cover affects evapotranspiration drivers such as surface energy availability and surface roughness; more specifically, vegetated patches not only become sources of transpiration (Tc), but also influence bare patches (intercanopy areas, which are sources of surface evaporation [Eic]), and other vegetated patches (neighbor canopy, sources of transpiration [Tnc]), thereby affecting the way evapotranspiration is partitioned between major components of soil evaporation (Esoil) and plant transpiration (Ttot).

Figure 3
Canopy cover has been shown to directly influence the dynamics of evapotranspiration (ET) drivers via effects on (a) surface energy availability (modified from figure 2 in Royer et al. [2012] for pinon juniper systems by averaging values reported for July, the middle of growing season); (b) surface soil temperature (modified from Royer et al. [2012]), which, holding other drivers constant, translates directly into (c) canopy cover effects on near-ground potential ET (PET; modified from Royer et al. [2012]). Plant canopies not only affect near-ground energy balance, but also affect (d) wind dynamics, and therefore surface roughness, via modifications in surface flow around them (Breshears et al. 2009). These effects of canopy cover can be muted or more pronounced in response to (e) plant architectural attributes (shown as DSF, an index indicative of near ground energy availability [Villegas et al. 2010a]).
case, total ET relative to LAI should decrease as a result of the significant change in ratio of E and T. Thus, an increase in T occurs concurrent with a reduction in E from neighboring intercanopy patches. In such a case, relative T (the ratio between T to total ET) increases more than a corresponding per unit increase in canopy cover (Huxman et al. 2005; Breshears 2006), resulting in a positive deviation from the 1:1 line relating woody canopy cover and T/ET and reflecting a net negative deviation of relative E from the 1:1 line, referred to as “apparent E suppression” (figure 4a). The magnitude of this deviation can vary, particularly at intermediate levels of cover where canopy heterogeneity is more pronounced (Martens et al. 2000) in response to canopy attributes (such as foliar density), to the availability of soil moisture near the surface, to soil exploration by roots, and/or to atmospheric demand for water. Although we hypothesize proportional decreases in E with increases in vegetation cover (assuming constant root dynamics), there also could be potential decreases in relative T for additional increases in tree cover due to self-shading and modifications on boundary layer properties. These effects would influence amount of T per unit canopy cover, T/ET, and likely become important at higher levels of cover than the values that affect soil water flux, depending on canopy structural and biophysical characteristics. This response would be reflected by a net negative deviation from the 1:1 line relating canopy cover to T/ET, referred to as “apparent T suppression” (figure 4b). The magnitude of this deviation likely depends on characteristics such as canopy density, energy availability, and soil moisture potentially available for T, as well as ecophysiological attributes of vegetation, including the spatial structure of stomatal conductance throughout the canopy. It is important to note that deviation from the 1:1 T/ET line can also occur due to differences in the nature of the supply of water to a transpiring canopy (e.g., if plants significantly extract water from intercanopy spaces or preferential flow through roots results in greater percolation of water to depths that are primarily lost to the atmosphere via T).

The processes that influence apparent net suppressions on E and T likely vary along a continuum of canopy cover, producing a potential for co-occurrence of both effects for gradients of vegetation cover (figure 4c). When cover is low, a change in canopy cover is more likely to affect energy balance at neighboring intercanopy patches than other vegetated areas, thus exerting a greater influence over E; conversely at higher cover values, a change in canopy cover is more likely to influence the fraction of vegetation shaded on a neighboring vegetated area, affecting the dynamics of T (figure 4c). However, when energy is not limiting (e.g., high temperatures), the atmospheric demand for water is high, and soil surface is exposed directly to the atmosphere (no litter layer [Villegas et al. 2010b]), shading effects are expected to be insufficient to cause E suppression; therefore changes in T dynamics will likely be very biome specific. Changes in T due to canopy cover shifts are likely also amplified to a greater extent when near-surface soil moisture supply to E is limited. In addition, less dense canopies at much lower average LAI (that often occur in warmer/drier climates) should induce less pronounced heterogeneity in near-ground solar radiation between canopy and intercanopy patches (Villegas et al. 2010a; Royer et al. 2012). These ideas are intended initially to apply to canopies that are randomly distributed across the landscape. However, in water-limited systems spatial distribution of canopies may also result from combinations of clustering and randomness, which, in concert with other architectural attributes, may lead to differential dominance of either apparent E or T suppression processes (Scanlon et al. 2007; Martens et al. 2000). In summary, in heterogeneous systems the interactive effects between canopies and the environment at the plot scale can be determinant on the ways in which ET fluxes are partitioned between E and T components, potentially in nonlinear ways, explained by the effects of canopies in the drivers of both E and T.

**COMPARING THE CONCEPTUAL FRAMEWORK TO LIMITED AVAILABLE DATA**

Although few datasets on ET partitioning explicitly report data on canopy cover and/or consider a range of canopy cover values, we identified three relevant studies for gradients of canopy cover that span diverse range of conditions: (1) a controlled greenhouse study (Wang et al. 2010), (2) a set of field observations (Raz-Yaseef et al. 2010a), and (3) a controlled small-scale educa-
tional laboratory study associated with our research (Villegas et al. 2009).

First, in a controlled study that quantified ET partitioning using both isotopic and lysimetric measurements in mesquite tree (Prosopis chilensis) arrangements at five levels of canopy cover and LAI, Wang et al. (2010) found an ET partitioning relationship dominated by a positive deviation from the 1:1 line relating the component fluxes to the total, until canopy cover was high (75% canopy cover), at which point the data trend back toward a negative deviation from the 1:1 line (figure 5a, redrawn from Wang et al. [2010]).

The greater effect of an increase in canopy cover on the relative increase in T compared to E for low canopy covers, up until a threshold at much higher values where proportional shifts return to a balance, is related to the structural characteristics of the canopies that have low foliar density but effectively extend toward neighboring intercanopy patches. The low foliar density of these trees limits self-shading, thereby reducing their influence over the relative growth in T with canopy cover except at very high values.

Second, in a field study, Raz-Yaseef et al. (2010a) monitored three years of ET partitioning in a semiarid pine (Pinus halepensis) forest. Building from data in their table 3 and figure 7, we estimated ET partitioning between soil E and T, assuming that what they refer to as excess water could go either to T (figure 5b, upper line) or to runoff (lower line), leaving a region of potential ET partitioning between them. Similar to the previous case, ET partitioning in this semiarid forest is dominated by an apparent smaller proportional change in E at low canopy covers, up to a threshold where the proportional changes in E and T return to balance each other. The difference in this threshold value from our first example is likely due to the structural attributes (foliar density and height to lower foliage) of conifers that make them more effective at shading both the ground and other canopies at lower levels of cover (Royer et al. 2010; Villegas et al. 2010a).

Third, we used a suite of small-scale measurements that were part of an educational program: small pots with and without plants in matrices of varying proportions (Villegas et al. 2010c). We made the simplifying assumptions that (1) water loss was only via E or T (reasonable given no observed seepage from the pots) and (2) that E from the soil in pots with plants is negligible (reasonable given that plants almost completely covered the soil surface). Evaporation and T from unvegetated and vegetated pots, respectively, were measured using a lysimetric approach. Four cases differed in two factors expected to influence ET partitioning: foliar density (low: Eucalyptus spp. seedlings; intermediate: Capsicum spp.; and high: Antirrhinum majus and Thymus vulgaris) and temperature, a proxy for near-ground energy availability (low average daily temperature: ~15°C (~59°F); intermediate average daily temperature: ~25°C (~77°F); and high average daily temperature: ~30°C (~86°F)).

The observations highlight a range of potential responses in ET partitioning with changes in proportion of vegetation cover and variations in temperature and foliar density (figure 5c). The results suggest an apparent prevalence of the lower cover dynamics we have seen in other data sets with respect to the fractional change in E relative to T (particularly in cases 2 and 3 and in case 4 at lower amounts of plant cover), with some apparent T suppression (case 4 for greater amounts of plant cover). Further, contrasts between cases (1 vs. 2 and 3 vs. 4) suggest that increases in foliar density (therefore increases in LAI) drive the occurrence of apparent T suppression and that this effect is more pronounced when energy availability is higher, as plant canopy effects on each other are more evident.

**TOWARD IMPROVING EVAPOTRANSPIRATION PARTITIONING**

This hypothesized conceptual framework provides a means for improving understanding of how the components of ET may change with vegetation heterogeneity and could be used as a tool to link hydrological processes to other phenomena within ecosystems. Our framework builds on previous studies that have evaluated how canopy cover influences surface energy balance, and it hypothesizes that both E and T components of ET are influenced by canopy cover. The inclusion of canopy cover into the fundamental approach for ET partitioning is a concept that, while not yet quantitatively developed with respect to aspects such as canopy attributes, climate, and soils, nonetheless merits further consideration for inclusion in both empirical and modeling studies addressing surface-atmosphere exchanges at landscape scales and for improvements in water conservation in heterogeneous landscapes that represent a large portion of the terrestrial biosphere.

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