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Effects of topography and woody plant canopy cover on near-ground solar radiation: Relevant energy inputs for ecohydrology and hydropedology

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[1] The emerging interdisciplinary approaches of ecohydrology and hydropedology are sensitive to variation in soil-surface energy inputs, which are primarily modified by topography and woody plant canopies. Yet a synthesis of the interactive effects of these two modification types is lacking. We systematically estimated near-ground surface solar radiation inputs as modified by key attributes of topography (aspect and slope) and tree cover (degree of openness) using solar radiation modeling based on hemispherical photographs. For south aspects, reductions in annual transmission were dominated by canopy cover rather than topography, even when canopy cover was low, whereas for north aspects, canopy effects dominated the reduction in annual transmission for slopes of up to 10° at low canopy cover and up to 30° at high canopy cover. Our results provide a synthetic perspective of the nonlinear, interactive, and temporally dependent effects of slope, aspect, and amount of canopy cover on near-ground solar radiation.

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1. Introduction

[2] Environmental changes related to climate change and land use are driving the emergence of the interdisciplinary interfaces of both ecohydrology, which focuses on interrelationships of the water budget with vegetation [*Rodriguez-Iturbe*, 2000; *Newman et al.*, 2006], and hydropedology, which focuses on interrelationships of the water budget with soils [*Lin et al.*, 2005; *Kutilek and Nielsen*, 2007]. Both interfaces are largely affected by incoming near-ground solar radiation, or insolation, which is a fundamental driver of not only of relevant hydrological processes but also of relevant pedological [*Geiger et al.*, 2003; *Rasmussen et al.*, 2005] and ecological [*Huxman et al.*, 2005] processes. Insolation can be greatly affected by both topography—through slope orientation (degree of slope and aspect), elevation, and the presence of other topographical obstructions such as nearby mountains and vegetation cover through degree of openness, which is determined by the amount, spatial variation and clumping of the plant canopy [*Martens et al.*, 2000; *Breshears et al.*, 1997; *Chen et al.*, 1997; *Leblanc et al.*, 2005].

[3] Previous studies have largely focused on reductions in incoming solar radiation due to either the effects of topography or changes in plant canopy cover on insolation and localized water budget, but generally not on the interactive effects of both topography and canopy cover (but see *Kittredge* [1948]). Topographical attributes of slope and aspect have been shown to cause general, predictable trends in insolation and associated diurnal cycles [*Weiss et al.*, 1988; *Whiteman et al.*, 1989a, 1989b; *Matzinger et al.*, 2003]. Similarly, heterogeneous vegetative cover imposes substantial and predictable reductions in near-ground insolation yielding strong relationships between insolation and potential evaporation of soil water that are relevant for ecological and pedological processes [*Breshears et al.*, 1997; *Breshears et al.*, 1998; *Scholes and Archer*, 1997; *Martens et al.*, 2000; *Huxman et al.*, 2005]. For example, vegetation type and amount vary in response to trends in insolation along topographic gradients [*Whittaker and Niering*, 1975], while at the same time variation in vegetation cover produces finer-scale trends in near-ground insolation that affects the water budget and understory species [*Breshears*, 2006]. However, trends relevant to ecohydrology and hydropedology that need to be quantified include: (1) the amount of canopy cover beyond which there is minimal influence of topography, regardless of slope, (2) how vegetative cover interacts with topography—particularly slope orientation (slope and azimuth), and (3) how the interactive effects of vegetative cover and topography on energy inputs vary seasonally. Here we systematically quantify the interactive and relative influences of topography and vegetation on near-ground insolation using hemispherical photography and controlled measures of surface orientation using a study system of a piñon-juniper woodland at 35° north latitude. We discuss how the two land-surface factors—topography and canopy cover—determine energy inputs along a grassland to forest continuum for a diverse set of topographic gradients, and the relevance of these findings to a diverse suite of applied issues in ecohydrology and hydropedology.

2. Methods

[4] We characterized near-ground solar radiation transmittance as affected by obstructions surrounding a given location, topography and canopy cover using hemispherical photography and relevant solar radiation algorithms, similar to the approach of others [*Rich*, 1990; *Clark et al.*, 1996;

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Battaglia et al., 2002; *Yirdaw and Luukkanen*, 2004]. We focused on trends associated with (1) topographical variation in slope and aspect (ignoring for now the effects of elevation and of neighboring obstructions such as nearby mountains), and (2) amount of canopy cover (ignoring for now spatial variation in canopy architecture such as clumping that might be interdependent with slope and aspect). Our approach is related to but differs from other modeling approaches that evaluate surface radiation trends using topographic and canopy surfaces in that hemispherical photos capture variations in canopy architecture. We characterized near-ground solar radiation transmittance using hemispherical photographs taken along a 100-m long transect that varied in canopy cover from relatively open to relatively closed, with dominant overstory species being *Pinus edulis* and *Juniperus monsperma*. This range in canopy cover of individual locations is relevant for considering variation both within a given site and for a general gradient of increasing woody plant canopy cover comprising a continuum from grassland to forest. The hemispherical photographs were taken 1.0 m above the ground along a transect at ~2000 m elevation within the Mesita del Buey study site in northern New Mexico (35.84, −106.35) (see *Breshears et al.* [1997] for additional details on the site and acquisition of the photographs). Images were analyzed using canopy analysis software (HemiView 2.1, Delta-T Devices, Cambridge, UK [*Rich et al.*, 1999]) to calculate the proportion of near-ground insolation relative to above the canopy (direct site factor, DSF). Sun and zenith angles were calculated using the following equations [*Gates*, 1980; *Rich*, 1989]:

$$\beta = \arcsin(\sin ø \cdot \sin \delta + \cos ø \cdot \cos \delta \cdot \cos h), \text{and}$$
$$\alpha = 2 \arctan((\cos \delta \cdot \sin h)/(\cos ø \cdot \sin \delta - \sin ø \cdot \cos \delta \cdot \cos h - \cos \beta)),$$

where β is the elevation angle (the compliment of the zenith angle), ø is the latitude, δ is the solar declination for a given date, h is the hour angle, and α is the azimuth angle. Path length for a ray varies with secant of the zenith angle for angles greater than 80°:

$$S\theta = S_0\ \Gamma^{m(\theta)},$$

where $S\theta$ is the radiation flux from direct sunlight when the sun is at a given zenith angle θ, S_0 is the radiation flux outside the atmosphere, Γ is the atmospheric transmittance, and m is the optical air mass. Images were then grouped into those with DSF values of high canopy cover (0.2–0.3), medium canopy cover (0.55–0.65), and low canopy cover (0.8–0.9). Ten images were randomly selected from each group. Direct solar radiation near the ground surface (DirBe, MJ m^{-2} [*Rich et al.*, 1999] at 1 m height in this case) was re-calculated at ten slopes (0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45°) and for two aspects (north and south) for each image. The baseline solar radiation (direct radiation without any sky obstruction on a flat surface at the same research site) was calculated using a hemispherical photo in which all obstructions were digitally erased. Near-ground solar radiation under all other conditions was standardized with this baseline radiation to reflect individual or interactive effects of topography and canopy cover. We calculated these ratios for the maximum summer month (June), the minimum winter month (December) and the annual total. We expressed results as transmission of direct radiation, which were expressed as a ratio between the actual amount of incoming solar radiation received under the canopy and the maximum radiation above the canopy at the same location. To evaluate the relative contributions of topography and of canopy cover to reduction in transmission, we normalized the below-canopy values of solar radiation to the amount of insolation associated with the slope receiving the maximum insolation.

3. Results

3.1. Interactive Influence of Topography and Canopy Cover

[5] Near-ground solar radiation, expressed as transmission of direct radiation, varied systematically with aspect, slope, and cover, producing trends that are most effectively evaluated from different perspectives: (1) by aspect as a function of slope over a range of canopy cover (Figure 1), and (2) by slope as a function of canopy cover for contrasting aspects (Figure 2). In the summer, near-ground solar radiation transmittance consistently decreased with increasing slope in both north and south aspects, but any difference due to aspect was muted by high overstory canopy cover (Figure 1a). The presence of even low canopy cover reduced transmittance by 10%, and the presence of a high canopy cover reduced transmittance by nearly 80%. In the winter season, the lower sun angle resulted in a substantial increase in the transmittance beyond the 100% baseline for south aspect locations as increasing slope allowed the ground surface to be more perpendicular to the sun (Figure 1b). This led to a significant divergence in the transmittance between north and south aspects with increased slope; however, this divergence was muted by the increase in canopy cover. When summed across an entire year, maximum transmittance occurred at an intermediate slope of approximately 30° for the south aspect, reflecting the net result of the contrasting effects of increasing slope in summer versus winter months (Figure 1c). Increasing slope on the north aspect resulted in a consistent decrease in transmittance; however, the difference between aspects was again muted by increasing canopy cover.

[6] As expected, increasing canopy cover reduced transmittance, regardless of season or aspect (Figure 2). Furthermore, the divergence in transmittance due to topography was greatest under open conditions and was muted at medium canopy cover. High canopy cover completely overwhelmed all influence due to slope for both north and south aspects during the summer but less so in the winter (Figures 2a and 2b versus Figures 2c and 2d). During the winter, transmittance was more sensitive to increased canopy cover on the south aspect than the north, as seen by the more negative slopes. The annual sums of transmittance again reflected the net result of the contrasting effects of increasing canopy cover across a range of slopes (Figures 2e and 2f).

3.2. Relative Influences of Topography and Canopy Cover

[7] Normalized values of the reduction in transmission due to topography and to canopy cover quantify how the

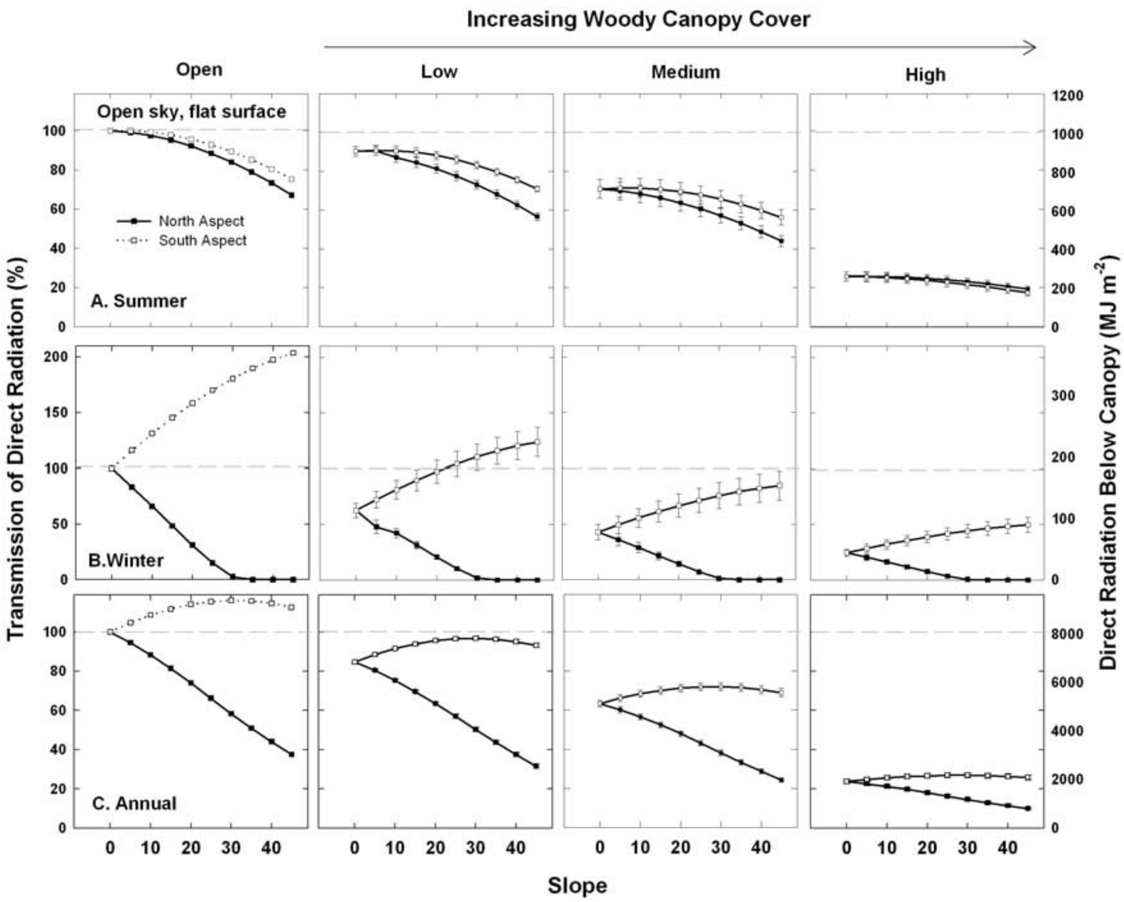

Figure 1. Trends in transmission of direct radiation (left axes) and direct radiation below canopy (right axes) highlighting contrasts with aspect as a function of slope for canopy covers from open to high canopy cover. Transmission is calculated as the percentage of direct radiation measured at 1 meter height above ground to that measured at open sky and flat surface (slope = 0 degree). Canopy cover levels are based on direct site factors (DSF): Open = 1.0, Low = 0.85, Medium = 0.63, and High = 0.24. Trends are shown for (a) month of June, the summer maximum; (b) the month of December, winter minimum; and (c) the annual total.

relative influence of these two types of insolation modifications vary (Figure 3). Within the north aspect, increased slope consistently resulted in a reduction in transmission of direct radiation, therefore contribution from slope continued to increase regardless of season or amount of canopy cover (Figures 3a, 3c, and 3e). During the summer, increasing slope on the north and south aspects resulted in a very similar reduction in transmission (Figures 3a and 3b). However, in the winter, increased slope had nearly an opposite effect on direct solar radiation reduction between the two aspects (Figure 3c versus Figure 3d). Furthermore, the effect of increased slope overwhelmed any influence of canopy cover beyond a 30° slope in the winter month (Figure 3c). Increasing slope on the south aspect led to a greater reduction in transmission in the summer, while an increase in slope limited the reduction of transmission in the winter (Figure 3b versus Figure 3d). This seasonal contrast in the effect of increased slope on the southern aspect resulted in a curvilinear relationship between annual transmission reduction and slope (Figure 3f). The contribution of slope to annual reduction of transmission for a south aspect, 30° slope is zero because this slope had the maximum isolation on an annual basis and therefore any reduction in transmission was all due to canopy cover (Figure 3f). In general, for south aspects, reductions in annual transmission were dominated by canopy cover rather than topography, even when canopy cover was low, whereas for north aspects, canopy effects dominated the reduction in annual transmission for slopes of up to 10° at low canopy cover and up to 30° at high canopy cover (Figure 3).

4. Discussion

[8] Our results highlight the complex ways in which topographic variation in surface orientation (slope and aspect) interacts with changes in the amount of woody plant canopy cover to influence patterns of near ground solar radiation. These results are consistent with and build upon our understanding of how insolation is modified by surface orientation and woody plant cover. However, our results are novel in that they provide a synthetic perspective of how these two major factors interact, yielding quantitative relationships and trends that were not readily apparent lacking such a systematic investigation. Our results differentiate

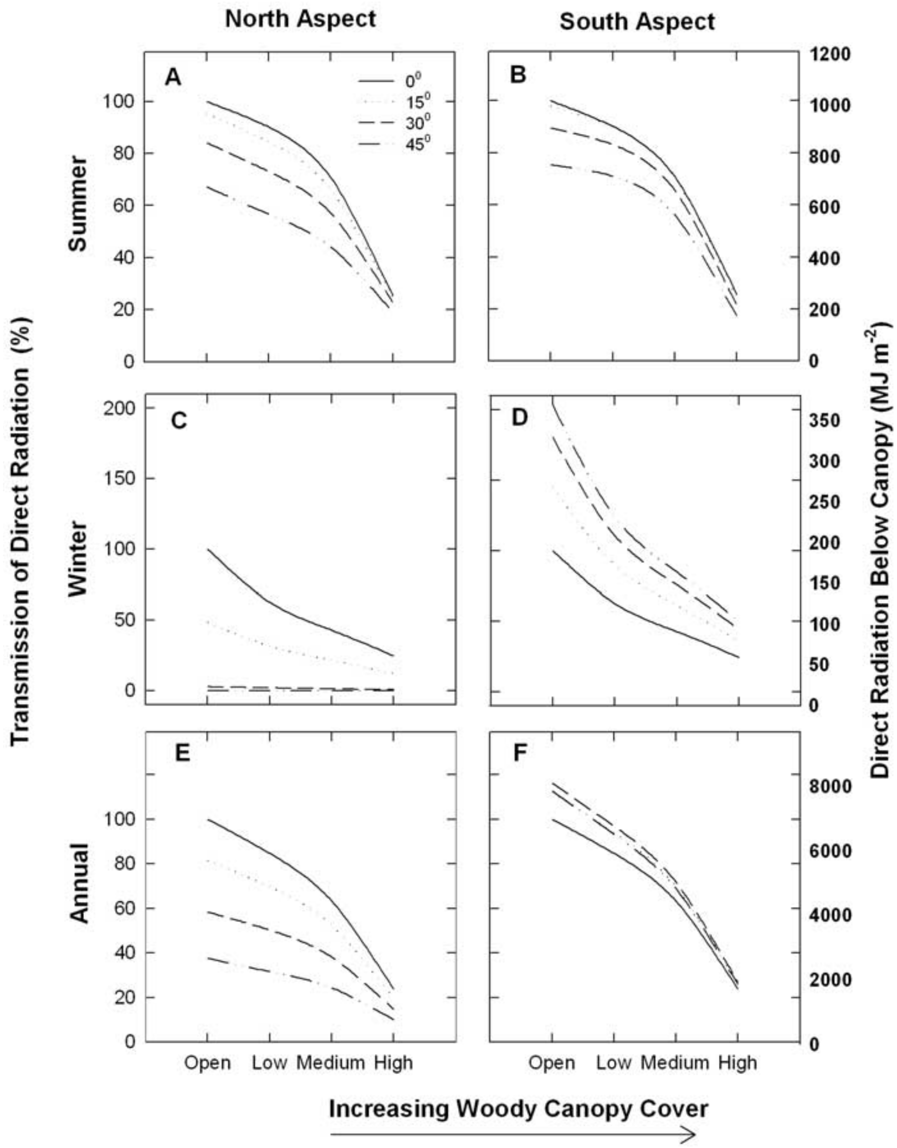

Figure 2. Trends in transmission of direct radiation (left axes) and direct radiation below canopy (right axes) highlighting contrasts with slope as a function of increasing canopy cover as a function of aspect (North vs. South) and time period (month of June, the summer maximum; the month of December, winter minimum; and the annual total). Transmission is calculated as the percentage of direct radiation measured at 1 meter height above ground to that measured at open sky and flat surface (slope = 0 degree). Canopy cover levels are based on direct site factors (DSF): Open = 1.0, Low = 0.85, Medium = 0.63, and High = 0.24.

cases for which changes in canopy cover will have important effects on near-ground insolation and associated ecohydrological and hydrological process versus cases for which they will not, and how this dichotomy varies with slope, aspect and amount of canopy cover. Ecosystem water budgets are driven by topography and vegetative canopy cover due to their influence on insolation [*Geiger et al.*, 2003], though often these two factors are studied independently of each other. For example, variation in solar radiation due to effects of slope alone greatly influenced soil water dynamics and soil evaporation rates of unvegetated plots adjacent to our study site [*Nyhan et al.*, 2001; *Nyhan*, 2005]. Variation in insolation due to the degree of canopy cover translates into large variations in soil temperature and soil evaporation rates [*Breshears et al.*, 1998] that affect soil moisture patterns [*Breshears et al.*, 1997; *Loik et al.*, 2004]. Further, insolation has been shown to be highly sensitive to changes in canopy cover, particularly at some intermediate (15–35%) values of woody cover [*Martens et al.*, 2000; *Breshears*, 2006].

[9] The interactions of slope, aspect and canopy cover can yield a variety of implications for ecohydrology and hydropedology. Notably, *Gutierrez-Jurado et al.* [2006] documented interactions among canopy cover presence/absence and canopy type, root zone water fluxes, and soil development. Their findings suggest that variations in water fluxes reinforce the development of $CaCO_3$ horizons present in the soil profiles, leading to a feedback between vegetation

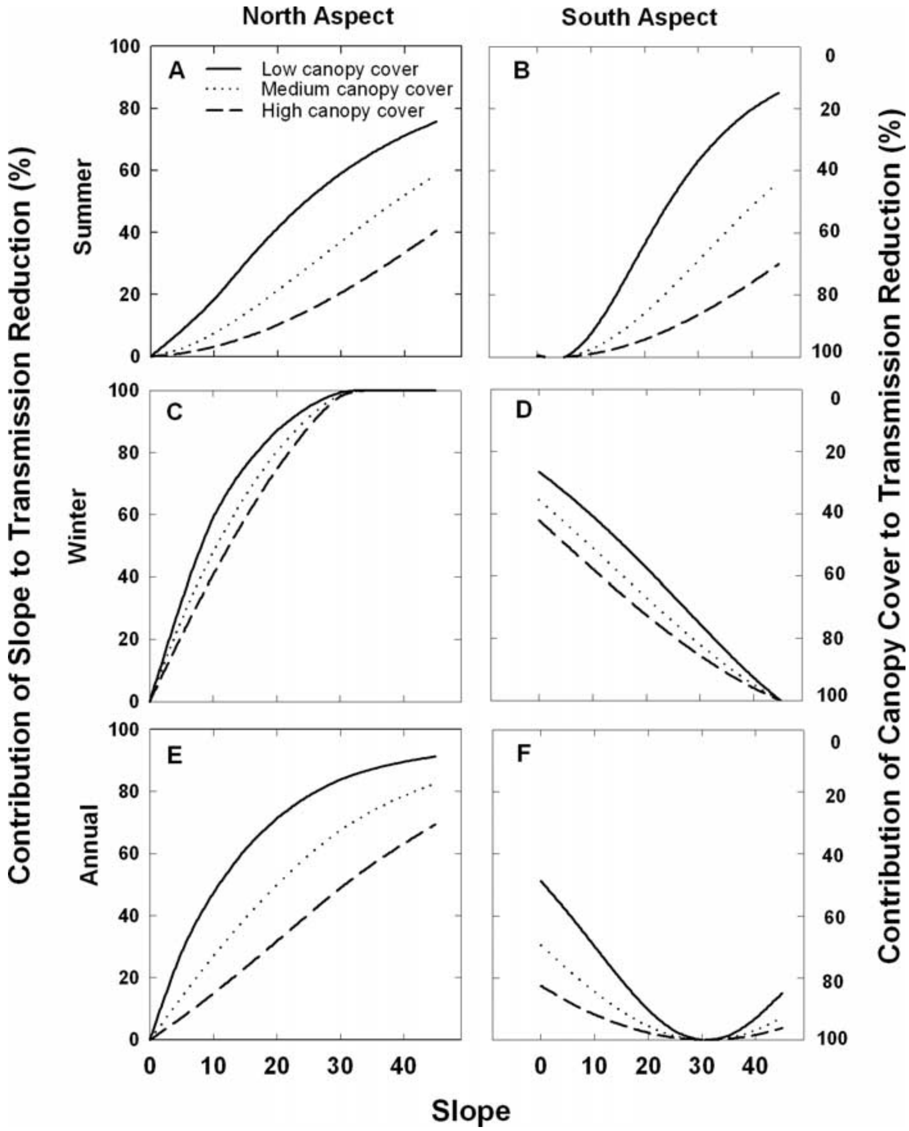

Figure 3. Relative contributions of topography (left axes) and woody canopy cover (right axes) to reduction in transmission, normalized to the maximum value of direct radiation across slopes of 0–45° of a given aspect (North or South) during the period of interest: (a, b) month of June, the summer maximum; (c, d) month of December, winter minimum; and (e, f) the annual total.

establishment, soil water fluxes and geomorphic processes in the catchment. Our work supports these insights into such important trends (and early watershed management research [*Kittredge*, 1948]) and extends them to allow for consideration of how changes in woody canopy cover spanning a spectrum of values from a grassland to a forest interacts with variation in slope and aspect in a seasonally-dependent manner to produce varying insolation. For example, our work is relevant to ecological studies of changes in canopy cover in piñon-juniper woodlands that consider rates of canopy cover expansion as a function of site topography and associated microclimate, including the potential acceleration of infilling beyond a minimum value of canopy coverage [*Weisberg et al.*, 2007].

[10] In conclusion, our systematic evaluation of how topographical variation in slope and aspect interact with variation in canopy cover in a seasonally dependent manner provides a synthetic assessment of a fundamental driver for both ecohydrological and hydropedological processes. Although it has been well known that topographical surface orientation influences insolation, we have illustrated how the influences of topography due to slope and aspect are systematically muted through shading as a function of season. These effects are of particular importance at relatively open locations, which are important for issues such as woody encroachment. There are also seasonal consequences of these differences that are important for water budgets in winter snowmelt periods versus summer monsoonal periods. Our results are reflective of the vegetation type and geographical location of our study and do not account for other potential factors such as plasticity in tree canopy architecture that may occur in association with variation in slope and aspect. Additional research is needed to determine how other features of topography, including elevation and the presence of sky obstructions and other variation in canopy architecture such as slope-dependent branch clumping,

modify the broad trends that we quantify here. In summary, our results provide generalizable relationships that are of fundamental relevance to ecohydrology and hydropedology in that they quantify the relative roles of topography and canopy cover in determining energy inputs relevant for a diverse set of topographic gradients and a continuum from grassland to forest.

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