

THE PARTITIONING OF EVAPOTRANSPIRATION ALONG THE GRASSLAND-  
FOREST CONTINUUM: ECOHYDROLOGICAL IMPLICATIONS OF  
MICROCLIMATIC TRENDS AND RESPONSE TO AMOUNT OF WOODY PLANT  
COVER

by

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A Dissertation Submitted to the Faculty of the  
SCHOOL OF NATURAL RESOURCES AND THE ENVIRONMENT

In Partial Fulfillment of the Requirements  
For the Degree of

DOCTOR OF PHILOSOPHY  
WITH A MAJOR IN NATURAL RESOURCES

In the Graduate College

THE UNIVERSITY OF ARIZONA

2010

THE UNIVERSITY OF ARIZONA  
GRADUATE COLLEGE

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## ACKNOWLEDGMENTS

I want to express my gratitude to all the people who have aided in the development of this dissertation. I would like to thank my wife, who with her unconditional love has been a tremendous support through all these years; to my family, both present and gone, who have been provided me with their example of discipline, responsibility, passion, solidarity and love. I would also like to thank my home institution, the Universidad de Antioquia in Medellín, Colombia, for the academic and economic support. I would like to express my gratitude to my dissertation director, Dr. David D. Breshears for his support and his example of academic excellence and integrity. Special thanks to my committee members: Dr. Travis Huxman, Dr. Shirley Kurc, Dr. Laura Lopez-Hoffman and Dr. Brian Enquist. I would also like to thank my lab mates and colleges who supported and contributed to my research.

Funding for my doctoral studies and this dissertation came from a DNP/Fulbright/Colciencias scholarship, commission from the Universidad de Antioquia, University of Arizona Water sustainability program, University of Arizona Biosphere 2 EarthScience via Philecology Foundation

## DEDICATION

A vos, mi sol, mi tierra, mi nube, mi agua, a los ojos limpios que llevan dentro a la Flora que siempre he amado.

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## ABSTRACT

Evapotranspiration dominates the water budget in drylands, exerting important controls not only on the dynamics of water, but also on the amount and distribution of vegetation on a landscape. The spatial and temporal variability of vegetation cover imposes constraints on key ecohydrological processes that feedback to the dynamics of evapotranspiration and, most importantly, its partitioning between direct evaporation and transpiration from plants, one of the most significant ecohydrological challenges. Yet, lacking are systematic evaluations of how variations in woody plant cover—a fundamental vegetation attribute of landscapes that can vary spatially with amount of cover and temporally with leaf phenology— influence the dynamics of soil microclimate and ultimately the partitioning of evapotranspiration into its components. This study presents the results of field experiments that systematically evaluated the effects of amount of canopy cover and its seasonality in both surface microclimate and soil evaporation. These field observations are complemented by controlled experiments that directly evaluate the relationship between amount of canopy cover and the partitioning of evapotranspiration, with an assessment of its larger-scale implications using a regional land surface–atmosphere model. Finally, this study presents a classroom-adaptation of the evapotranspiration partitioning experiment that was used to effectively translate new scientific concepts and information into k-12 classrooms. Overall, the results from this

study provide a comprehensive understanding about the interactive ways in which canopy cover, canopy structure attributes and plant phenology influence soil surface microclimate—characterized by near-ground solar radiation and soil temperature—and soil evaporation. More specifically, the results illustrate how the main control of deciduous-woody vegetation on soil evaporation is the addition of litter to the surface. However, in absence of litter, attributes of woody cover influence soil evaporation variably with season and phenology. Further, The results from this study illustrate how the partitioning of evapotranspiration exhibits a non-linear response to amount of woody canopy cover. Notably, when incorporated into a regional surface-atmosphere model, this non-linearity strongly affects water fluxes, highlighting the potential implications for ecological, hydrological, and atmospheric processes associated with the partitioning of evapotranspiration, providing important insights for natural resource management.

## INTRODUCTION

Evapotranspiration compromises the majority of the water budget in arid and semiarid ecosystems, often accounting for >95% of the annual water budget (Branson et al., 1981; Wilcox et al., 2003; Williams et al., 2004; Huxman et al., 2005). Although most research has focused on evapotranspiration as an aggregated process, more recently emphasis has been placed on the importance of distinguishing between and quantifying the two major components of evapotranspiration (after accounting for evaporation of water intercepted by the canopy): (1) evaporation from the soil and (2) transpiration from plants (Dugas et al., 1996; Williams et al., 2004; Huxman et al., 2005; Lauenroth and Bradford, 2006). This distinction between unproductive (soil evaporation) vs. productive (plant transpiration) water losses from the ecosystem is one of the most fundamental ecohydrological challenges in drylands (Newman et al., 2006). The accurate prediction of the partitioning of evapotranspiration is relevant not only for improving current understanding and predictive capabilities around the dynamics of the water budget, but, more importantly, for improving the ability to quantitatively represent the critical role that biological processes play within the biogeochemical dynamics associated with ecohydrological processes in drylands (Rodriguez-Iturbe et al., 1999), particularly those related to vegetation dynamics, ecosystem productivity, the coupling of water with carbon/nutrient cycles and atmospheric processes related to evapotranspiration (Raupach, 1998; Rodriguez-Iturbe, 2000; Eagleson, 2002; Newman et al., 2006; D'Odorico et al., 2007; Moran et al., 2009). Such a fundamental description of the role of biological processes in the hydrologic cycle can provide key tools for more effective assessment of

the larger scale effects of current and predicted ecosystem changes such as shrub encroachment, desertification, non-native species invasion, altered disturbance regimes and widespread vegetation die-off, leading to processes-based management practices that effectively address the challenges associated with these changes (Moran et al., 2009). However, despite the ecological, hydrological and biogeochemical relevance of characterizing the partitioning of evapotranspiration, lacking is a mechanistic description of how a fundamental land-surface variable such as woody plant cover systematically influences the overall partitioning of evapotranspiration and the effects of this characterization in the predictions of surface-atmosphere models.

Water limitations in drylands, which in part are evidenced by the magnitude of evapotranspiration in the water budget, constitute one of the most important controls on the production of biomass and the spatial distribution of vegetation. As a consequence, vegetation cover is often incomplete and spatially heterogeneous (Noy-Meir, 1973; Eamus, 2003; Loik et al., 2004; Breshears 2006; Caylor et al., 2006) such that, depending on the structural characteristics of dominant vegetation, most landscapes can be described as some stage within a continuum of woody plant cover between grasslands and forests (Belsky and Canham, 1994; Breshears, 2006). This “grassland-forest continuum” perspective provides a useful framework for systematically studying and interpreting trends and ecohydrological dynamics of both individual ecosystems and landscape gradients that span the continuum (Kittredge, 1948; Geiger, 1965; Martens et al., 2000; Bonan, 2002; Breshears, 2006; Zou et al., 2007; Veatch et al., 2009). Along the continuum, both the presence/absence of woody plant canopies at a location as well as

the overall woody canopy density in the landscape have been recognized to influence the dynamics of soil-plant-water interactions (Shreve, 1924; Breshears et al., 1997; Breshears et al. 1998; Martens et al., 2000; Eamus, 2003; Huxman et al., 2005; D'odorico et al., 2007; Zou et al., 2007; Breshears and Ludwig, 2009).

One specific way in which woody plant cover influences ecohydrological processes is via its effects on near-ground microclimate through the attenuation of incoming solar radiation and the modification of soil temperature regimes (Evans and Coombe, 1959; Anderson, 1964; Geiger, 1965; Breshears et al., 1998; Martens et al., 2000; Baldocchi and Xu, 2007). These microclimatic effects of woody plant cover are evidenced not only at locations directly covered by a canopy, but also at open locations where they are associated with the overall overstory cover related to the surrounding vegetation mosaic. Consequently, quantifying these microclimatic patterns requires consideration of not only canopy heterogeneity, but also canopy connectivity through which woody plants influence neighboring intercanopy and canopy patches beyond the extent of their above-ground canopy structure (Breshears, 2006), highlighting the importance of quantifying both the mean effect of canopies and the spatial variability of these effects.

A general way in which woody plant cover influences microclimate at a site is through an overall decrease in near-ground solar radiation availability. Several recent studies have assessed these trends along gradients of increasing canopy cover (Rich et al., 1994; Schulze et al., 1995; McPherson, 1997; Breshears et al., 1998; Martens et al., 2000; Roberts, 2000; Fu and Rich, 2002; Zou et al., 2007; Zou et al., 2009), using multiple

approaches that include both models and field-based estimates of near-ground radiation availability. The results from modeling approaches do not account for variation in foliar density, but rather treat woody plants as compact ellipsoids, suggesting a linear decrease in near-ground solar radiation in response to increases in canopy cover (Martens et al., 2000). However, field-based estimates of near ground energy availability for gradients of cover with different architectural attributes highlight the sensitivity of these relationships to differences in canopy architecture, including variation in overall height, height to lowest foliage, foliar density, and other aspects of canopy architecture (Breshears and Ludwig, 2009; Zou et al., 2009). Most of these studies have been developed in systems dominated by evergreen woody plants, where woody-plant canopy cover and foliage density vary in space, but remain relatively constant throughout the year (Breshears et al., 1998; Martens et al., 2000; Lebron et al., 2007; Adams, 2007). However, lacking are systematic evaluations of the microclimatic effects of woody plant cover in extensive deciduous-dominated drylands, where woody cover not only varies spatially in terms of amount of cover but also temporally because of seasonally-dependent changes in leaf phenology.

The spatial and temporal variability in surface cover associated with the phenological dynamics of woody plants in deciduous-dominated drylands likely alters relative importance of the physical processes that drive soil evaporation —and consequently the partitioning of evapotranspiration in drylands. In particular, variations in the amount and seasonality of woody plant cover have been demonstrated to affect radiation availability, temperature, wind, soil and vegetation characteristics (Kondo et al.

1992; Baldocchi et al., 2000; Baldocchi et al., 2002; Small and Kurc, 2003) both at the individual patch and the overall vegetation mosaic scales. At the individual patch scale, woody plants influence the dynamics of soil evaporation by locally reducing the amounts of solar radiation reaching the ground (Breshears et al., 1998; Martens et al., 2000; Fu and Rich, 2002; Zou et al., 2007; Breshears and Ludwig, 2009) and by the addition of litter to the ground beneath the canopy (Facelli and Pickett, 1991; Lafleur, 1992; Kelliher et al., 1998; Wilson et al., 2000; Throop and Archer, 2007). At the vegetation mosaic scale, characterized by the overall amount of woody-plant canopy cover and its spatial distribution, woody plants can have an effect on soil evaporation via attenuation of radiation, modification of wind dynamics, and alteration of soil microclimate (Geiger, 1965; Bonan, 2002; Warner, 2004; Breshears et al., 2009). Collectively, these issues highlight that lacking is a systematic evaluation of how the changes in surface cover imposed by the seasonal dynamics of deciduous vegetation, both at the vegetation mosaic and patch scales, influence the dynamics of soil evaporation. Such an evaluation is critical for improving our understanding of ecohydrological dynamics in semi-arid ecosystems and particularly to address one of the main ecohydrological challenges in drylands: the effects of woody plant cover in the partitioning of evapotranspiration into transpiration and evaporation (i.e. water that is productive, vs. water that is not).

The precise field quantification of the partitioning of evapotranspiration remains a theoretical, empirical and instrumental challenge (Williams and Albertson, 2004; Huxman et al., 2005; Breshears, 2006; Moran et al., 2009) Current estimations of evapotranspiration partitioning—which are often derived from the integration of

observations performed at multiple spatial and temporal scales—can inheritably replicate errors associated with both measurement techniques and the scaling relationships used to derive them (Harley and Baldocchi, 1995; Herbst et al. 1996; Wilson et al., 2001; Williams et al., 2004; Lawrence et al., 2007). Notably, the insufficient field characterization of evapotranspiration and its major components has precluded the correct parameterization of key ecological, hydrological and atmospheric in land surface-atmosphere models, which have traditionally parameterized the partitioning of evapotranspiration as a linear function of vegetation cover (Lawrence et al., 2007). However, as noted above, the influence of woody plant cover on some of the major drivers of evapotranspiration likely produce a non-linear effect of canopy cover in the partitioning of evapotranspiration (Huxman et al., 2005; Breshears et al., 2006; Lawrence et al., 2007), which can have important consequences for the predictions of land-surface atmosphere models that link the dynamics of major ecological, hydrological and biogeochemical processes (Zavaleta et al., 2003; Scanlon et al., 2005; IPCC, 2007; Jackson et al., 2009). In consequence, a more robust set of observations is required to better characterize the dynamics of the partitioning of evapotranspiration in response to basic land surface variables, such as woody plant cover, and to evaluate the potential consequences of these dynamics at broader spatio-temporal scales, leading to more accurate predictions of the environmental effects of current and predicted changes in climate and vegetation cover.

## **PRESENT STUDY**

The methods and design of this study, along with detailed results and discussion, are presented in the papers appended to the dissertation. Given that each individual paper is a stand-alone scientific product that covers a portion of the study, some common introductory concepts and discussion points concur in multiple publications. However, each of them constitutes an important part of the overall study, for which the most important findings are presented below.

Evapotranspiration dominates the water budget in arid and semi-arid ecosystems, such that it exerts important controls not only on the dynamics of water, but also in the amount and distribution of vegetation in the landscape. However, the distinction between the two major components of evapotranspiration (soil evaporation and plant transpiration) that discriminates between water that is ecologically productive vs. water that is not remains one of the most fundamental ecohydrological challenges and has important ecological, hydrological and biogeochemical consequences associated with the role of evapotranspiration in ecosystem productivity, carbon and nutrient cycling, as well as consequences associated with the effects of widespread vegetation changes resulting from processes such as shrub encroachment, desertification, exotic invasions, modified disturbance regimes and vegetation die-off . The first part of this document (Appendices A, B and C) explores the spatio-temporal effects of woody plant cover on soil microclimatic characteristics and its potential effects on the dynamics of soil evaporation fluxes. The second part of the document (Appendices D and E) reports the use of two experimental approaches for quantifying the effects of woody canopy cover in the

partitioning of evapotranspiration and discusses the potential implications of this quantification in the predictions of land surface-atmosphere models at the regional scale. In addition, the continental-scale effects of modified regimes of evapotranspiration at the regional scale are assessed, and a new framework for characterizing atmospheric hydrological connectivity is proposed (Appendix F). Finally, the third part of the dissertation (Appendices G and H) presents the results of translating key-scientific concepts associated with ecohydrological processes, in particular the partitioning of evapotranspiration, into the k-12 education curriculum, highlighting the importance of translating state-of the art environmental science into general education.

Appendix A presents a quantification of soil temperature trends and their implications for potential soil evaporation in a gradient spanning evergreen piñon-juniper woodland (5 to 65% canopy cover). The results document that soil temperature generally decreased with increasing woody canopy cover for intercanopy as well as canopy patches, indicating coalescing influence of individual canopies on their neighboring areas. Intercanopy patches were 10°C cooler and reduction in potential soil evaporation were at least two-fold higher- compared to low-density sites. Notably, the results of this work highlight the ecohydrological consequences of density-dependent shading by evergreen woody plants through their amelioration of intercanopy temperature, which in turn can affect potential soil evaporation, with key implications for a more mechanistic understanding of the partitioning of evapotranspiration along the grassland-forest continuum.

Appendix B evaluates season-dependent changes in soil microclimate along a deciduous grassland-forest continuum of mesquite (*Prosopis velutina*) using repeated hemispherical photography and continuous soil temperature measurements at 5-cm deep. Both near-ground solar radiation and soil temperature decreased with increasing canopy cover, even during the leafless season. However, the trends varied substantially among seasons, with differences between canopy and intercanopy patches readily evident only during the period of full leaf-out, during which correlation between near-ground solar radiation and soil temperature was strongest. The results from this work provide a comprehensive understanding about the interactions of canopy cover, canopy structure attributes and plant phenology that produce seasonally pulsed heterogeneity in soil surface microclimate, adding a new dimension to the moisture “pulse dynamics” perspective commonly applied to dryland ecohydrology. Notably, the results from this work provide a systematic approach that can be useful for understanding the coupling between key ecological and hydrological processes which can be particularly useful for assessing the effects of current and predicted changes in climate, vegetation cover and vegetation seasonality.

Appendix C presents an experimental assessment of the interactive ecohydrological controls on soil evaporation along a gradient of mesquite cover (*Prosopis velutina*), with respect to two characteristics of vegetation cover: (1) a hierarchical structure of vegetation cover spanning from the presence or absence of litter, through canopy patches of woody plants and intercanopy patches separating them, up to the overall vegetation mosaic characterized by density of woody plant cover in the

landscape; and (2) the changes in cover associated with the seasonality/phenology of vegetation in a seasonally-deciduous grassland-forest continuum. The results from this assessment indicate that the presence of litter on the soil surface exerts a dominant control on soil evaporation, independent of seasonality; in absence of litter, both patch and mosaic attributes influence soil evaporation variably with season/phenology, suggesting that energy limits evaporation in many cases, although other factors such as wind may potentially influence hierarchical and seasonal/phenological combinations. Overall, the results from this assessment highlight the need to account for both hierarchical vegetation structure and seasonal/phenological variability to improve ecohydrological predictions of soil evaporation.

Appendix D presents the results of the assessment of a new technique for quantifying the partitioning of evapotranspiration into soil/canopy evaporation and plant transpiration within an experimentally manipulated gradient of woody plant cover s a laser-based isotope analyzer for continuous measurement of near-surface variations in the stable isotopic composition of water vapor ( $\delta^2\text{H}$ ) and the Keeling plot approach. The applicability of the technique was verified by confirming an expected increase in transpiration relative to total evapotranspiration as woody plant cover increased. Additional development and deployment of the technique could enable field characterization of evapotranspiration partitioning across diverse woody-plant cover gradients, needed to address major dryland ecohydrological challenges.

Appendix E experimentally evaluates the relationship between amount of woody canopy cover and the partitioning of evapotranspiration on its two major components:

soil evaporation and plant transpiration and assesses the potential region-scale effects of this relationship using a land surface-atmosphere model. Understanding the partitioning of evapotranspiration into evaporation and transpiration has been identified as one of the most fundamental ecohydrological challenges in drylands and has fundamental implications for key ecological, hydrological and atmospheric processes. This study used the logistical capabilities of Biosphere 2 to develop an experiment that simulated different levels of woody canopy cover by establishing regular 10 x 10 grids with different proportions of containers with either bare soil or a planted mesquite tree. Containers with bare soil were sources of evaporation, while containers with trees were sources of evapotranspiration, for which transpiration was discriminated using sap flow sensors in the trees. The results from this experiment show that there is a non-linear relationship between woody canopy cover and the partitioning of evapotranspiration. Notably, when incorporated into a regional land surface-atmosphere model, the modest non-linearity that resulted from the experiment has a strong influence in the model's predictions not only in overall evapotranspiration from the region (which decreased by ~40% in some areas during the monsoon season of a wet year) but most importantly, in the overall proportion of evapotranspiration that corresponds to soil evaporation (which increased by ~200% in both wet and dry years). Collectively, the results from this study illustrate the importance of a fundamental ecohydrological relationship that had been previously overlooked and/or omitted due to both technical and theoretical constraints and that has that has profound ecological, hydrological and biogeochemical implications.

Appendix F explores regional to continental scale hydrologic connectivity via atmospheric pathways and assesses the cross-regional effects of modified evapotranspiration regimes within the North American monsoon region. In particular, this study uses a Lagrangian analytical model to track the trajectory of atmospheric moisture originated in the North American Monsoon region for different hydrologic conditions: pre-drought, drought, and drought-transition periods. The results of this study illustrate how moisture originating as evapotranspiration from the North American Monsoon can account for ~15% of the total precipitation in nearby regions of the North American continent, with this amount decreasing by 45% during the period of regional drought in the Southwestern U.S. Overall, this study highlights the importance of considering atmospheric pathways when accounting for hydrologic connectivity and cross-regional effects of hydrologic regimes.

Appendix G presents the materials and procedures for conducting a scientific experiment conducted in middle, high school and undergraduate science classrooms, studying the relationship between changes in vegetation cover and the processes of evaporation and transpiration. This procedure has been tested with middle and high school students in the United States and Australia and the results of its impact in the students learning and understanding of this key ecohydrological process is presented in appendix H.

Appendix H presents the results from a one-week long experiment was conducted by Grade 6 students (N=82) in classrooms in Oro Valley, Arizona exploring the effects of changes in landscape vegetation cover on evapotranspiration, the major component of the

water budget. Students completed pre- and post- experiment tests designed to assess their general understanding of the water budget, the components of evapotranspiration

For Appendices B, C, E, G and H Juan Camilo Villegas Palacio's role as lead author was to make the majority of the contributions to the overall development and design of the studies; to conduct all data collection, process and analysis; and to develop and lead the subsequent peer-reviewed manuscripts and publications. For Appendices A, D and F, Juan Camilo Villegas Palacio's role as supporting author was to make significant contributions to the study design and data analysis, as well as writing the subsequent peer-reviewed manuscript. More specifically, for Appendix A, Juan Camilo Villegas Palacio provided guidance on the experimental design, which was adapted from the design in one of the experiments where Juan Camilo is the lead author (Appendix B), as well as contributing to the data analysis with calculations of soil evaporation and overall organization of the manuscript; in Appendix D, a collaborative project with researchers from Princeton University, all data collection was performed on Juan Camilo's experimental design, who also contributed with supporting data for the experiment, and provided key insights in the preparation and revision of the peer-reviewed manuscript. Finally, in Appendix F, Juan Camilo worked closely with the formulation and development of the research question, participated in the data analysis phase with the NARR suitability assessment and worked closely with the other authors on the preparation, submission and revision of the peer-reviewed manuscript.

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APPENDIX A

DENSITY-DEPENDENT EFFECTS OF EVERGREEN WOODY PLANTS IN  
RANGELANDS: ECOHYDROLOGICAL IMPLICATIONS FOR SOIL  
MICROCLIMATE AND POTENTIAL SOIL EVAPORATION

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Document type: In review as of January 19<sup>th</sup> 2010 for *Agriculture, Ecosystems & Environment*

**Abstract:** The dynamics of many fundamental environmental processes of rangelands are driven in large part by microclimate and associated ecohydrological processes, one of the most important of which is the soil evaporation component of evapotranspiration that dominates dryland water budgets. Previous studies have assessed spatial variation of ecohydrological attributes within an ecosystem (e.g., under vs. between woody plants) or across ecosystems (e.g., areas with different amounts of woody canopy cover), but generally lacking are assessments accounting systematically for both. Here, building on recently quantified trends in near-ground solar radiation associated with a gradient spanning evergreen piñon-juniper woodland (5 to 65% canopy cover), we quantified the

soil temperature trends and their implications for potential soil evaporation. We document that soil temperature generally decreased with increasing woody canopy cover for intercanopy as well as canopy patches, indicating coalescing influence of individual canopies on their neighboring areas. Intercanopy patches could be 10°C cooler and reduction in potential soil evaporation could be at least two-fold higher- compared to low-density sites. Our results highlight the ecohydrological consequences of density-dependent shading by evergreen woody plants on intercanopy temperature and potential soil evaporation and may also have more general relevance for other rangeland ecosystems within the grassland-forest continuum.

### **Introduction**

Many key environmental processes in rangelands and other agroecosystems are strongly affected by ecohydrological relationships between vegetation and hydrology (Rodriguez Iturbe and Poporato, 2004; Wilcox and Newman, 2005). Semiarid ecosystems in particular are inherently water limited because annual potential evapotranspiration exceeds precipitation, and consequently evapotranspiration can dominate the water budget and have important ecological and hydrological effects (Wilcox et al., 2003). A predominant component of overall evapotranspiration is soil evaporation, which can significantly reduce water availability for species (Huxman et al., 2005). Therefore, improved estimates of microclimate and potential soil evaporation are needed for more effective land management (Wilcox and Newman, 2005; Huxman et al., 2005; Newman et al., 2006). Furthermore, information about soil evaporation is also important for understanding how the soil surface beneath woody plants (i.e., canopy

patches) and the grass-dominated areas between crowns of woody plants (i.e., intercanopy patches) contribute to evapotranspiration.

Canopy cover of woody plants (hereafter referred to as “woody canopy cover”) is an important architectural attribute in rangeland agroecosystems that strongly influences ecohydrological processes. Woody canopy cover affects *vertical* water fluxes, such as interception (Owens et al., 2006), evaporation and transpiration (Breshears et al., 1998; Kurc and Small, 2004; Huxman et al., 2005), sublimation (Veatch et al., 2009), infiltration and soil moisture (Bhark and Small, 2003; Zou et al., 2008; Lebron et al., 2007; Madsen, 2008), and recharge (Loik et al., 2004, Seyfried et al., 2005); and *horizontal* water fluxes, such as baseflow, overland flow, run off, and lateral redistribution (Brooks et al., 2002; Ludwig et al., 2005; Newman et al., 2010). Perhaps most importantly in an ecohydrological context, woody canopy cover influences the contribution of evaporation to overall evapotranspiration (Huxman et al., 2005; Breshears, 2006).

Previous studies of the amount of woody canopy cover have revealed systematic relationships with variation in microclimate at the stand scale (Martens et al., 2000; Veatch et al., 2009; Breshears and Ludwig, 2010; Villegas et al., 2010b; Zou et al., 2010), and have highlighted how variation in microclimate differs between canopy and intercanopy patch types (Breshears et al., 1998; Kurc and Small, 2004; Lebron et al., 2007; Newman et al., 2010). These studies have generally shown that as woody plant density increases, near-ground solar radiation, soil temperature, and potential soil evaporation decreases. Importantly, these studies have not accounted for the role of

woody canopy cover in determining trends within a given ecosystem. The magnitude of microclimate differences between canopy and intercanopy patches differs at low vs. high amounts of woody canopy cover (Breshears et al., 1998; Loik et al., 2004; Ludwig et al., 2005; Lebron et al., 2007; Villegas et al. 2010b). Understanding the role of woody canopy cover is necessary because the proportion of woody plant cover can span a broad range: from sparse, as in grasslands with few woody plants, to approaching total canopy closure, as is the case for high-density shrublands, woodlands, or forests (Breshears, 2006). Further, the effects of woody plants on herbaceous plants and site hydrology are topics of debate in rangeland management (Breshears 2006).

In this study, our overall objective was to address the role of the amount of woody canopy cover in affecting potential soil evaporation, focusing on piñon-juniper woodlands as a model evergreen system. We assessed how canopy and intercanopy patches individually and collectively influence soil temperature through their effects on near-ground solar radiation, and consequently potential soil evaporation. We also evaluated ecohydrological implications with respect to potential soil evaporation, including density-dependent differences in potential soil evaporation at the patch scale. We focused on a piñon-juniper gradient ranging from 5 to 65% woody canopy cover. More specifically, we assessed 1) spatiotemporal variation in near-ground solar radiation, soil temperature and potential soil evaporation (PE) across the gradient, 2) near-ground solar radiation and soil temperature trends specific to canopy and intercanopy patches within and across the gradient, and 3) implications for potential soil evaporation based on field-derived temperature data. We discuss observed systematic relationships between

total cover and canopy presence/absence within the entire cover gradient and their more general ecohydrological implications.

## **Materials and Methods**

### *Study site*

Our study site was located in semiarid piñon-juniper woodland at a previously established series of 50-m transects in northern Arizona (approximately 60km north of Flagstaff Arizona: 35.535° N, 111.853° W; Villegas et al. 2010b; Royer et al., in review). The transects spanned a gradient of increasing cover by woody plants at levels of 5, 15, 25, 35, 45, 55 and 65% canopy cover.

### *Near-ground solar radiation*

Along each of the transects, hemispherical photographs were previously obtained at 1-m intervals at a height of 1 m and processed using Hemiview Canopy Analysis (version 2.1, Delta-T devices, 1999, Cambridge, UK) to estimate near-ground solar radiation (Villegas et al., 2010b; Royer et al., in review). Near-ground potential solar radiation (hereafter referred to as “near-ground solar radiation”) was expressed as Direct Site Factor (DSF)—ranging from 0 for a completely covered location to 1 for a completely open one—and as energy input (i.e.  $\text{W m}^{-2}$ ). The estimates correspond to clear-sky conditions and do not vary with weather conditions. For this study, based on instrumentation constraints, we used an 18-m subset of each transect that had approximately the same woody canopy cover as the overall 50-m transect for soil temperature measurement. The average woody canopy cover of the subset transect was within 3% of that for the whole 50-m transect. We re-evaluated the trend in near-ground

solar radiation for each 18-m subset of locations within each transect to verify that relationships were similar to those found for the full 50-m transects.

*Soil temperature and potential soil evaporation*

We measured soil temperature at 5 cm, a depth intermediate between the soil surface and an assumed evaporative depth of 10 cm, at every 1 m interval along each of the 7 subset of transects every 2 h for 1 year, using Thermochron temperature sensors (Maxim Integrated Products, Inc.; Sunnyvale, CA 94086). Sensors in canopy patches were placed at 5 cm below the approximate litter/soil surface interface, based on visual observation and similar to a related study (Breshears et al., 1998). All sensors were installed in August 2007. They were retrieved for data downloading at two intermediate dates (October 2007 and April 2008). We summarized soil temperature data for average minimum, average daily, and average maximum temperatures during each of four months (February, April, August, and November) for comparison with near-ground solar radiation estimates.

To assess stand-level potential soil evaporation across the transects, we used the Hargreaves (1975) equation, which uses average monthly minimum, maximum, and average soil temperature data to estimate monthly potential soil evaporation (PE). We also conducted an experimental analysis to assess differences in potential soil evaporation between canopy and intercanopy patches in response to the observed differences in soil temperature, as well as soil textural characteristics associated with the presence of a litter layer at canopy patches. Soil cores were randomly selected from intercanopy and canopy locations (n=5 each) along a transect with intermediate woody canopy cover (35%). The

soil samples were collected in polyvinyl chloride (PVC) tubes (10cm depth by 10cm diameter) by driving PVC tubes serrated edges of into the soil profile, digging around the core sample, and capping the bottom before removal, such that soil profiles and soil composition remained intact and relatively undisturbed; soils were subsequently stored in the laboratory at  $\sim 23^{\circ}\text{C}$  prior to the potential soil evaporation measurements.

The potential soil evaporation measurements were conducted in a controlled growth chamber (E7/2, Conviron, Pembina, ND U.S.A). Soil cores were dried, initially weighed, wetted to saturation, allowed to drain overnight, reweighed, and then dried at temperatures corresponding to maximum daily temperatures in August, and soil water loss was calculated gravimetrically at 2, 4, 7, 12, 25, 36, and 48 h. We chose maximum daily August temperatures to approximate maximum differences in potential soil evaporation corresponding with variations in temperature. We focused on two key comparisons in potential soil evaporation: (1) canopy vs. intercanopy rates of potential soil evaporation at intermediate (35%) cover, and (2) intercanopy rates of potential soil evaporation at low (5%) vs. high (65%) canopy cover. For these comparisons, we measured soil water loss from both patch types under different temperature regimes (canopy at 35% and intercanopy at 35% for the first, and intercanopy at 5% and at 65% for the second) and then paired the appropriate temperature and soils data for the two comparisons of interest.

#### *Data analysis*

To assess the relationship between solar radiation and soil temperature we calculated average daily maximum, average, and average daily minimum seasonal

temperature values for each of the 7 levels of canopy cover (5-65% cover) and regressed them with near-ground solar radiation values for four months (February, April, August and November). To assess canopy and intercanopy temperature differences, we calculated mean values for incoming energy and temperature for both patch types, and regressed them with percent cover for the same months. All statistics were obtained using jmp 5.1 statistical software (SAS Institute, Carry, NC, USA). Results were considered significant at an alpha level of 0.05.

## **Results**

### *Overall trends with woody canopy cover in microclimate and potential soil evaporation*

The 18-m transects used in this study, which were selected to have similar amounts of woody canopy cover to that of the previously studied 50-m full transects, exhibited trends in near-ground solar radiation similar to the full 50-m transects (Fig. 1). Near-ground solar radiation estimated for cloudless conditions decreased as expected with increasing woody canopy cover. The decrease was by a factor of 2 or more for most months, with the reduction being greatest in summer months (Fig. 2a). Associated soil temperature dynamics—which reflect near-ground solar radiation (Fig. 2a), modifications in cloudiness and air temperature, as well as variation in soil water content—exhibited a similar decrease with increasing canopy cover (Fig. 2b); the temperature measurements were obtained much more frequently than the monthly near-ground solar radiation estimates and exhibit a high degree of temporal variability. Soil temperature differed between low and high amounts of woody plant canopy cover sometimes by as much as a

factor of 2. Potential soil evaporation estimated from soil temperature data similarly decreased with canopy cover, again by as much as a factor of 2 in some cases (Fig. 2c).

*Seasonal correlations between near-ground radiation and soil temperature*

For subsequent more detailed analyses, we limited our focus to relationships in four months throughout the year, one for each season (February, April, August, and November), which was deemed sufficient for gaining insight into predominant patterns occurring over an annual cycle (given the clear annual patterns highlighted in Fig. 2). Overall, monthly soil temperatures (minimum, average, maximum) were directly correlated with near-ground solar radiation and inversely correlated with woody canopy cover (Fig. 3); an exception occurred during the coldest season (February), when minimum temperature decreased in response to increasing near-ground solar radiation. Correlations were stronger when temperatures were warmer, as for maximum and average temperatures of warmer months (April had  $R^2=0.80$  and  $0.88$ , respectively, and August had  $R^2=0.87$  and  $R^2=0.90$ , respectively; all  $p<0.01$ ), and even for minimum temperature in the warmest month (August:  $R^2=0.82$ ,  $p<0.01$ ). Correlations were weaker for intermediate temperatures (for October, maximum temperature with  $R^2=0.71$ ,  $p=0.02$  and average temperature with  $R^2=0.67$ ,  $p=0.02$ ). Soil temperature was not correlated with near-ground solar radiation at cooler times, except for under the coldest conditions, when the correlation had a negative slope (minimum February temperatures,  $R^2=0.80$ ,  $p<0.01$ ).

*Seasonal heterogeneity in canopy and intercanopy microclimate and potential soil evaporation*

Near-ground solar radiation decreased with woody canopy cover within intercanopy as well as canopy patches (Fig. 4, upper panels). In contrast to differences found between canopy and intercanopy patches in the full 50-m transect, in the 18-m transects we were able to detect overall significant patch differences only for April, although patch differences for other months were nearly significant ( $p = 0.8 - 0.13$ ); we expect this difference in results is related to a difference in sample size. Differences in soil temperature-woody canopy cover relationships were detected in the 18-m transect between canopy and intercanopy patches under warmer conditions (April,  $p = 0.01$ ; August,  $p=0.02$ ; Fig. 4, lower panels). Under cooler temperatures, there was a significant interaction between patch type and cover (November and February, both  $p < 0.03$ ; test for interaction-non-zero slope); temperature decreased under canopy relative to intercanopy patches with each unit increase in woody canopy cover, by  $0.2^{\circ}\text{C}$  for November and by  $0.08^{\circ}\text{C}$  for February (Fig. 4, lower panels). Notably, the effect of amount of woody canopy cover on intercanopy patches of a given transect was evident in diurnal patterns of near-ground solar radiation and soil temperature, and was particularly pronounced during warmer months (Fig. 5).

There were greater rates of potential soil evaporation from intercanopy soils compared to canopy soils at all temperatures (Fig. 6; all  $p$ -values  $< 0.01$ ; based on soil cores from the intermediate site with 35% woody canopy cover). Potential soil evaporation was more than 3 times greater for intercanopy than canopy soils when we matched each patch type to its' respective maximum August temperature over 48 hours (Fig. 6c, derived from Fig. 6a-b). Notably, the difference in potential soil evaporation

rate for intercanopy soils (at intercanopy temperatures) from the low (5%) vs. high (65%) canopy cover sites (Fig. 6f, derived from Fig. 6d-e) was of the same magnitude as the previous canopy-intercanopy comparison (Fig. 6c) and consistent with diurnal differences in temperature (Fig. 5).

## **Discussion**

### *Spatiotemporal trends in microclimate across the continuum*

Our results document clear trends in microclimate in response to woody canopy cover, consistent with findings for a variety of woody plant architectures (Villegas et al., 2010b). The decrease in near-ground solar radiation with increasing woody canopy cover in piñon-juniper woodland documented previously (Villegas et al., 2010b; Royer et al. in review) and focused on here (Fig. 1) formed the basis for assessing other trends in microclimate, beginning with average site temperature and potential soil evaporation as a function of woody canopy cover (Fig. 2). Notably, the effects of woody canopy cover on near-ground solar radiation translated into soil temperature patterns during warmer months (Fig. 3) in contrast to systems with woody plants with less foliar density, such as mesquite (Villegas et al. 2010a).

The effect of increasing amount of woody canopy cover on microclimate at the patch scale was most evident in the diurnal responses of intercanopy patches: at 5% canopy cover, diurnal curves were largely unaffected but at 65% cover the curves were sharply dampened (Fig. 5). This finding is similar to those of others evaluating effects of neighboring trees (Breshears et al., 1988; Naumburg and DeWald, 1999; Forseth et al.,

2001; Drezner, 2006; Drezner, 2007; Lebron et al., 2007) but extends those findings to a broad gradient of woody canopy cover.

The effects of woody canopy cover influence both site conditions across the gradient and patch heterogeneity within it (Fig. 7). Several trends occur concurrently along the grassland-forest continuum from low to high woody canopy cover: overall site soil temperature decreases, canopy patches are cooler than intercanopy patches, and the relative influence of intercanopy patches decreases while that of canopy patches increases. Interestingly, the difference between intercanopy soil temperatures at low vs. high density is comparable to an intercanopy patch having a microclimate similar to that of a canopy patch (Fig. 7). These results build on other studies of trends in near-ground solar radiation along the continuum (Martens et al., 2000; Roberts, 2000; Fu and Rich, 2002; Zou et al., 2007; Villegas et al., 2010a; Villegas et al., 2010b) and extend them to soil temperature. Importantly, they indicate overall woody canopy cover needs to be accounted for in addition to site-specific differences microclimate associated with canopy/intercanopy patch type (Breshears et al., 1998; Lebron et al., 2007; Newman et al., 2010).

#### *Ecohydrological implications*

The differences in microclimate along the gradient and with respect to patch type have important ecohydrological implications. Our simplified potential soil evaporation estimates indicate large differences in rates at multiple scales: for canopy vs. intercanopy patches within a site, for intercanopy patches at low vs. high density, and in overall soil evaporation along the gradient. These results not only contrast potential soil evaporation

regimes between patch types at a site or between two sites but also, and most importantly, have key implications for a more mechanistic understanding of the partitioning of evapotranspiration along the continuum (Breshears et al., 1998; Kurc and Small, 2004). Use of intercanopy water by woody plants is another important process that connects canopy and intercanopy patches in addition to the connections through shading that we quantify here (Newman et al., 2010). The differences in potential soil evaporation that we have assessed here have important implications for soil water content and other components of the water budget in addition to evapotranspiration (Lebron et al., 2007; Madsen et al., 2008; Newman et al., 2010).

In conclusion, we evaluated trends in microclimate within and across sites along an continuum of woody canopy cover that ranged from 5% cover in juniper-*piñon* savannas to 65% in dense *piñon*-juniper woodland, collectively spanning much of a grassland-forest continuum. We documented expected decreases in near-ground solar radiation, soil temperature, and potential soil evaporation of as much as a factor of 2 or more with increasing canopy cover. Similar to the response for near-ground solar radiation, soil temperature at the patch scale generally decreased with woody canopy cover for intercanopy as well as canopy patches, indicating coalescing influence of individual canopies on neighboring areas. Intercanopy patches were as much as 10°C cooler at high- compared to low-density sites, yielding a potential soil evaporation difference that rivaled that between canopy and intercanopy patches at a lower density sites. Our results highlight the ecohydrological consequences of density-dependent shading by evergreen woody plants through their amelioration of intercanopy

temperature, which in turn can affect potential soil evaporation. These relationships may also have more general relevance for other rangeland ecosystems within the grassland-forest continuum.

***Acknowledgements*** Support was provided by USDA CSREES NNF (PDR and DDB), NSF Drought Impacts on Regional Ecosystem Networks (DIREnet), DOE National Institute for Climate Change Research (DDB), Arizona Water Institute (PDR and DDB), the Arizona Agricultural Experimental Station (DDB, CBZ, and SAK), the Oklahoma Agricultural Experimental Station (CBZ), and the University of Arizona Biosphere 2 (JCV).

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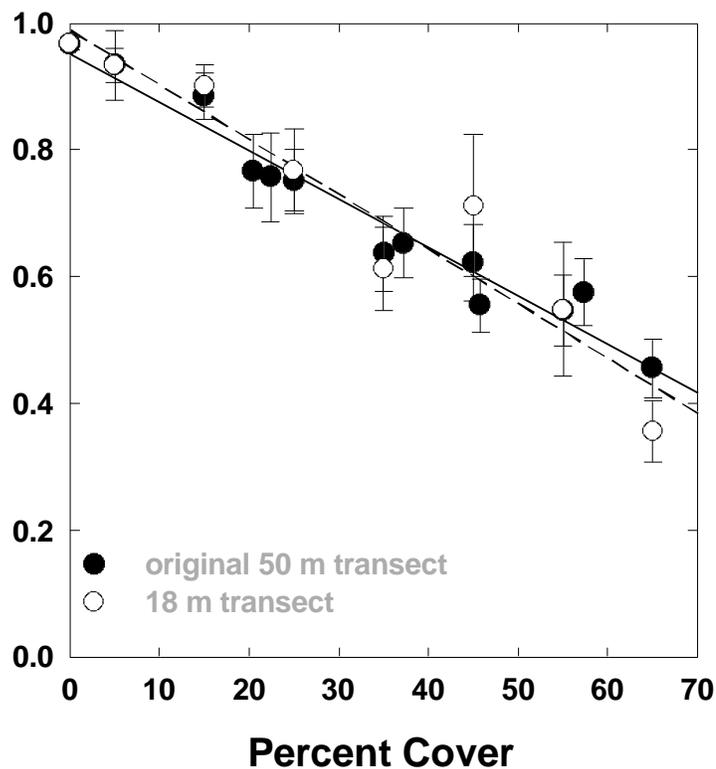
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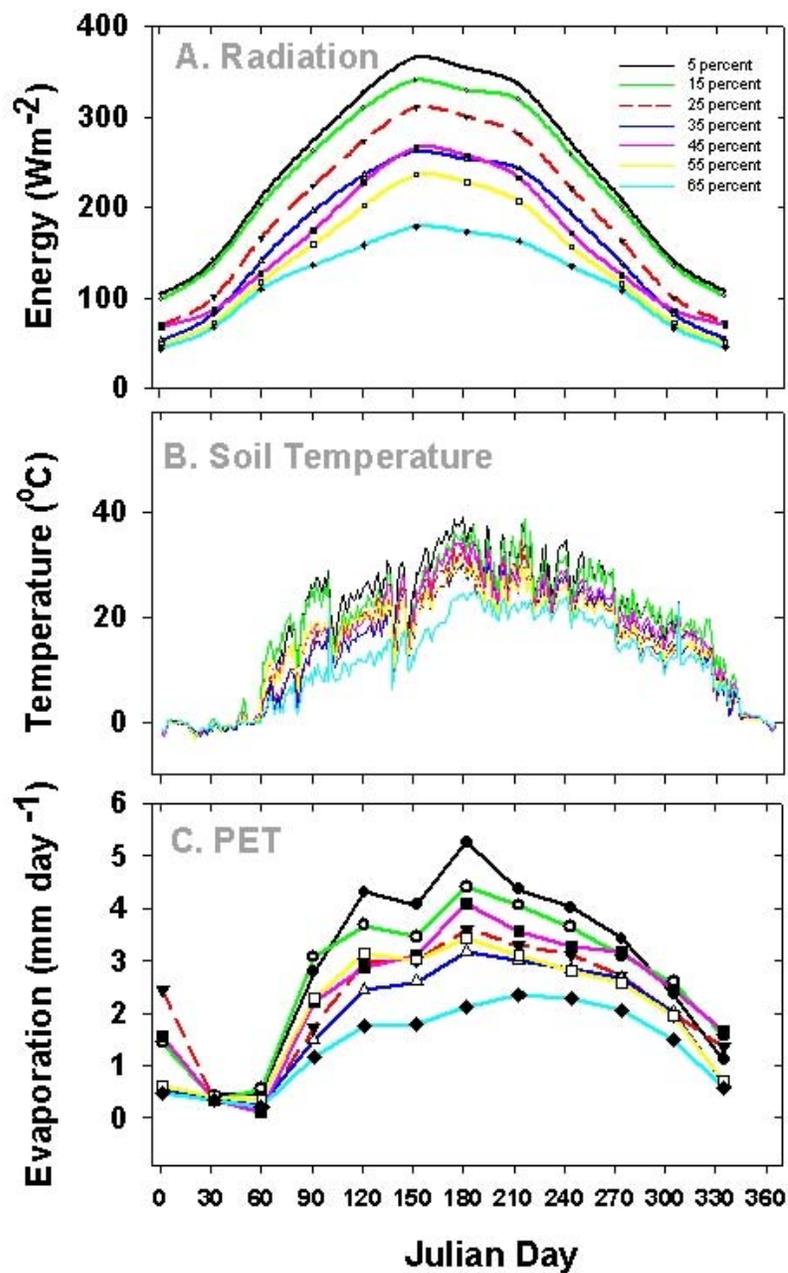
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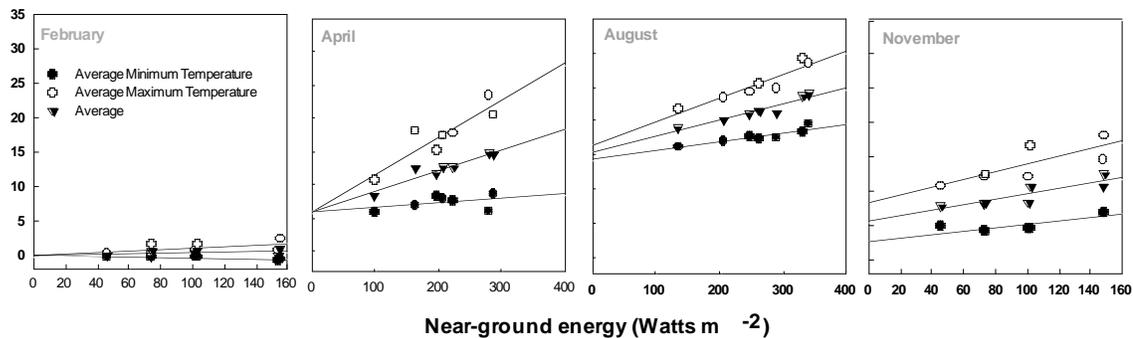
## Figures



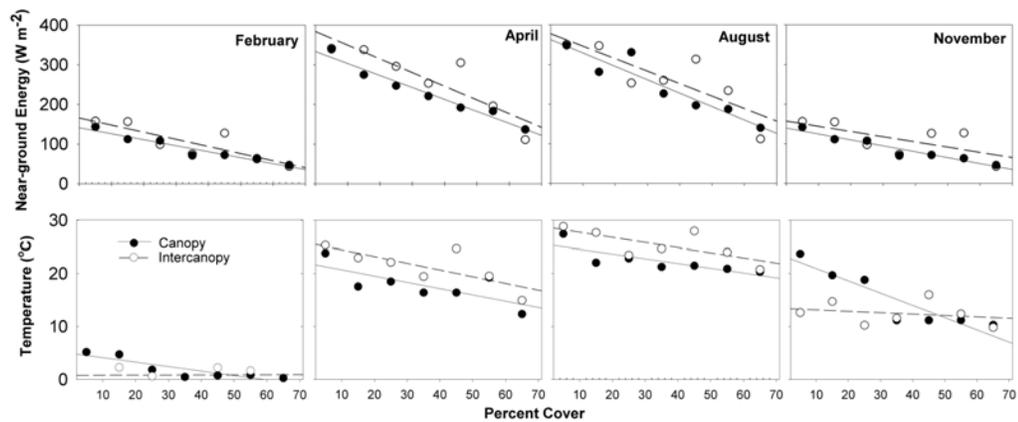
**Figure 1.** Comparison of incoming near-ground solar radiation trends, estimated as direct site factor (DSF), for original 50-m (solid circles and line) transects from Royer et al. (in Review), and 18-m transects used in the current study (open circles and dashed line) that were nested within the previous transects. Direct Site Factor is a dimensionless value between 0.0 and 1.0, indicating the amount of direct solar radiation throughout the year, correcting for surface orientation and global location.



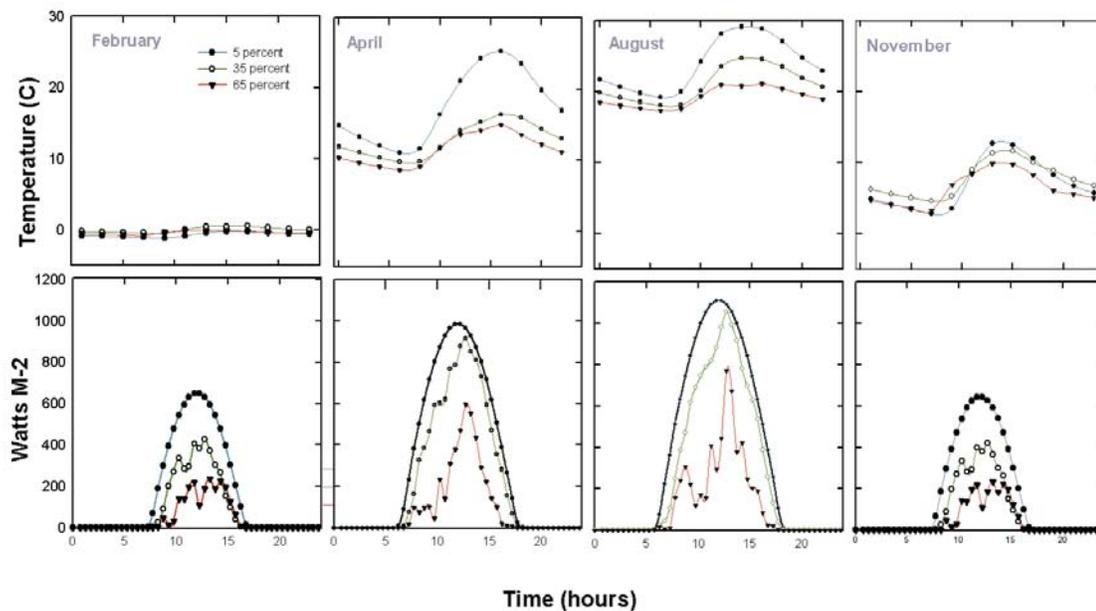
**Figure 2.** Annual values in near ground radiation ( $W\ m^{-2}$ ), daily maximum soil temperature ( $^{\circ}C$ ) and potential evapotranspiration ( $mm\ day^{-1}$ ).



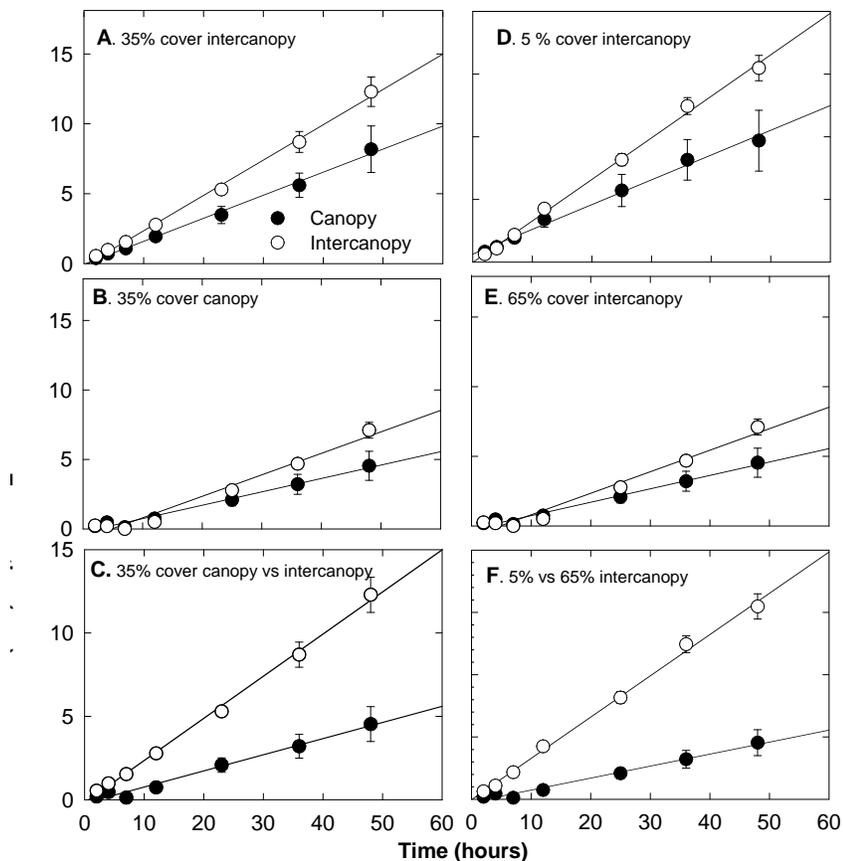
**Figure 3.** Trend derived functions correlating average minimum, average maximum and average soil temperature ( $^{\circ}\text{C}$ ) with near ground radiation ( $\text{W m}^{-2}$ ) for February, April, August and November.



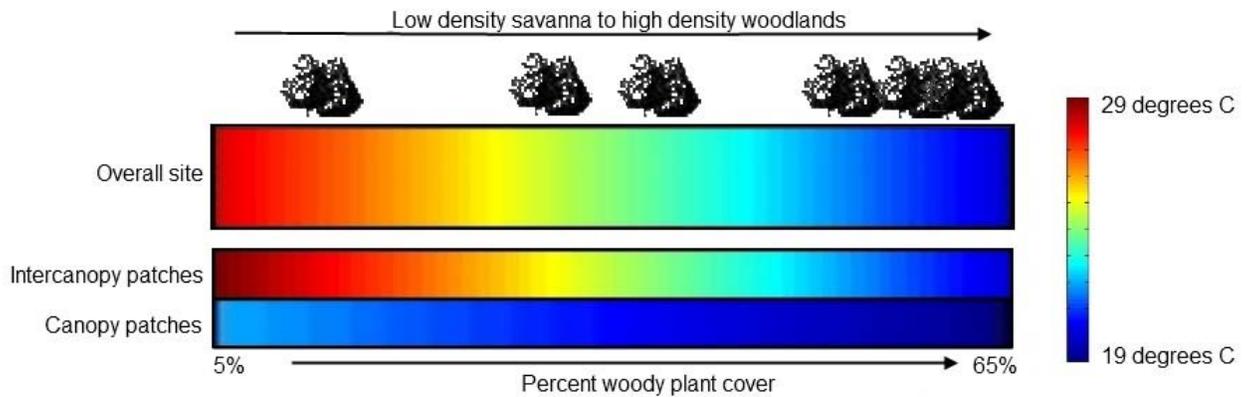
**Figure 4.** Trends in soil temperature (°C) and near-ground solar radiation (W m<sup>-2</sup>) for canopy (solid circles) and intercanopy (empty circles) along all gradients of woody canopy cover in February, April, August and November.



**Figure 5.** Diurnal values for near-ground solar radiation ( $\text{W m}^{-2}$ ) in intercanopy and soil temperature compared at 5, 35, and 65% woody canopy cover values.



**Figure 6.** Potential soil evaporation as a function of time at canopy (solid circles) and intercanopy (empty circles) soil types from drying experiments based on temperatures during August. For both canopy and intercanopy soil types the experiment temperatures reflect (A) intercanopy soil temperature for 35% woody canopy cover ( $\sim 25^{\circ}\text{C}$ ), (B) canopy soil temperature for 35% woody canopy cover ( $\sim 20^{\circ}\text{C}$ ) (C) the composite graph of intercanopy soils at intercanopy temperature and canopy soils at canopy temperature, (D) intercanopy soil temperature for 5% woody canopy cover ( $\sim 29^{\circ}\text{C}$ ), (E) intercanopy soil temperature for 65% woody canopy cover ( $\sim 20^{\circ}\text{C}$ ), and (F) the composite graph of intercanopy soils at temperatures for 5% and 65% woody canopy cover.



**Figure 7.** Synthesis of trends in soil temperature during August for overall site, and canopy and intercanopy patch type, all as a function of woody canopy cover. The temperature gradient ( $\sim 19$  to  $29$  °C) reflects the actual field derived values for the range of soil temperatures. Note that soil temperature for intercanopy patches at high amounts of woody canopy cover approximates that of canopy patches. Differences in soil evaporation between patch types would be further exaggerated due to soil texture and litter effects.

## APPENDIX B

SEASONALLY PULSED HETEROGENEITY IN MICROCLIMATE: PHENOLOGY  
AND COVER EFFECTS ALONG DECIDUOUS GRASSLAND-FOREST  
CONTINUUM

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Document type: Peer-reviewed publication in *Vadose Zone Journal*

**Abstract:** Much of the terrestrial biosphere can be viewed as part of a gradient with varying amounts of woody plant cover, ranging from grassland to forest—the grassland-forest continuum. Woody plant cover directly impacts soil microclimate through modifications of near-ground solar radiation and soil temperature, and these interactive effects are relevant for key ecohydrological processes such as soil evaporation. Trends in how increasing woody plant cover affect soil surface microclimate have recently been evaluated for gradients of evergreen woody plants, but analogous trends for deciduous plants, where phenology should be influential, are lacking. We evaluated season-dependent changes in soil microclimate along a deciduous grassland-forest continuum of

mesquite (*Prosopis velutina*) using repeated hemispherical photography and continuous soil temperature measurements at 5-cm deep. Both near-ground solar radiation and soil temperature decreased with increasing canopy cover, even during the leafless season. However, the trends varied substantially among seasons, with differences between canopy and intercanopy patches readily evident only during the period of full leaf-out, during which correlation between near-ground solar radiation and soil temperature was strongest. Our results provide a more comprehensive understanding about the interactions of canopy cover, canopy structure attributes and plant phenology that produce seasonally pulsed heterogeneity in soil surface microclimate. Notably, our results add a new dimension to the moisture “pulse dynamics” perspective commonly applied to dryland ecohydrology, highlighting seasonally pulsed heterogeneity in soil microclimate that could influence soil moisture dynamics in drylands.

## **Introduction**

Ecohydrological processes generally hinge on soil moisture, which integrates fundamental responses to the interactions between vegetation, climate, and soil characteristics (Rodriguez-Iturbe, 2000; Eagleson, 2002; Loik et al., 2004; Newman et al., 2006). The linkages between soil moisture and ecosystem dynamics are particularly important in drylands, where soil water availability is the key determinant of ecosystem function and productivity (Newman et al., 2006; Caylor et al., 2006). Drylands constitute a large proportion of the terrestrial biosphere and have been identified as being highly sensitive to land use and climate changes. One of the most general landscape-scale patterns that affect both ecosystem structure and function and their responses to land use

and climate is woody plant cover (Schlesinger et al., 1990; Archer et al., 1995; Scholes and Archer, 1997; Jackson et al., 2002; Breshears, 2006). The presence/absence of woody plant canopies and their density have been recognized to influence the dynamics of soil-plant-water interactions at the landscape scale (Shreve, 1924; Breshears et al., 1997; Breshears et al. 1998; Martens et al., 2000; Eamus, 2003; Huxman et al., 2005; D'odorico et al., 2007; Zou et al., 2007; Breshears et al., 2009; Villegas et al., 2010; Royer et al., in review). Notably, most landscapes can be viewed as intermediate within a continuum of woody plant cover between grasslands and forests (Belsky and Canham, 1994; Breshears, 2006). This perspective provides a useful framework for systematically studying and interpreting trends and ecohydrological dynamics of both individual ecosystems and landscape gradients spanning this conceptual continuum (Kittredge, 1948; Geiger, 1965; Martens et al., 2000; Bonan, 2002; Breshears, 2006; Zou et al., 2007; Veatch et al., 2009). In particular, a key way in which woody plant cover influences ecohydrological dynamics is via effects on near-ground microclimatic conditions through attenuation of incoming solar radiation and modification of temperature regimes (Evans and Coombe, 1959; Anderson, 1964; Geiger, 1965; Breshears et al., 1998; Martens et al., 2000; Baldocchi and Xu, 2007). These microclimatic effects are spatially heterogenous, particularly between canopy patches right under the overstory of woody plants and the intercanopy patches that separate them. In addition, these microclimatic effects also depend on differences in overall overstory cover associated with the vegetation mosaic of a site. Collectively, these patterns highlight the importance of considering not only canopy heterogeneity, wherein canopy and intercanopy patches differ, but also canopy

connectivity, through which woody plants influence neighboring intercanopy and canopy patches beyond the extent of their above-ground canopy structure (Breshears, 2006).

Quantifying these microclimatic patterns requires consideration of not only the overall mean condition for a given site or ecosystem, but also the spatial variability within that site.

Along the grassland-forest continuum, the most general and intuitive effect of increasing woody plant cover on microclimate is an overall decrease in near-ground solar radiation. In addition, spatial variability is likely greatest at an intermediate level of canopy cover rather than at either extreme of the continuum (Breshears, 2006). Several recent studies have assessed such trends along gradients of increasing canopy cover (Rich et al., 1994; Schulze et al., 1995; McPherson, 1997; Breshears et al., 1998; Martens et al., 2000; Roberts, 2000; Fu and Rich, 2002; Zou et al., 2007; Zou et al., in press). These studies have used different approaches to quantify near-ground solar radiation as a function of canopy cover, including modeling approaches and field-based estimates of near-ground energy availability using hemispherical photography along gradients of woody plant cover. The results from modeling approaches do not account for variation in foliar density, but rather treat woody plants as compact ellipsoids, suggesting a linear decrease in near-ground solar radiation in response to increases in canopy cover (Martens et al., 2000). However, field-based estimates of near ground energy availability for gradients of cover with different architectural attributes highlight the sensitivity of these relationships to differences in canopy architecture, including variation in overall height, height to lowest foliage, foliar density, and other aspects of canopy architecture

(Breshears and Ludwig, 2009; Royer et al., in review; Zou et al., in press). To date these relationships have been evaluated for evergreen woody plants, but not for deciduous woody plants in drylands, which are spatially extensive and for which foliar density can be low and vary seasonally.

The effects of woody plants on near-ground solar radiation will influence soil temperature. For locations or gradients where soil characteristics such as soil texture and soil water content remain constant, near-ground solar radiation will be the primary determinant of soil temperature dynamics (Hillel, 1998). Indeed, isolating the effect of variation in near-ground solar radiation on soil temperature will improve our understanding of soil water content dynamics on sites and gradients where soil characteristics generally change concurrently with woody plant cover. Notably, in an ecohydrological context, soil surface temperature is one of the key drivers of soil evaporation (Schulze et al., 1995), a major component of dryland water budget (Wilcox et al., 2003; Williams et al., 2004; Huxman et al., 2005). In addition to the existing knowledge gap in near-ground solar radiation studies, lacking are systematic evaluations of how the amount of woody plant cover affects soil temperature, particularly for deciduous woody plants for which the effects could vary with seasonally-pulsed changes in leaf phenology. Importantly, dryland landscapes dominated by deciduous woody plants span extensive portions of the terrestrial biosphere (Baldocchi, 1997) and are expected to change in phenology due to projected changes in climate (Swetnam and Betancourt, 1998; Smith et al., 2009), as well as to change in the amount of cover as a result of current changes in land use (Archer et al., 1995; Van Auken, 2000).

To address the knowledge gap associated with microclimate for deciduous woody plant gradients outlined above, we systematically evaluated how the spatial variability associated with canopy cover and temporal variability associated with woody plant phenology interact, under conditions of controlled soil characteristics, to influence the spatiotemporal dynamics of surface microclimate, as reflected in near-ground solar radiation and soil surface temperature. Our overall goal was to explore the variability in soil microclimate imposed by seasonal changes in vegetation cover both at the scale of individual patches (canopy vs. intercanopy), and scales related to the vegetation mosaic at a site, and how both of these vary along gradients of increasing canopy cover. Specifically, our first objective was to systematically describe the effects of canopy cover on near-ground solar radiation in a deciduous grassland-forest continuum in response to the phenological changes in vegetation. Our second objective was to define the extent to which such changes, under conditions of controlled soil characteristics, affect the dynamics of surface soil temperature. We discuss our results in the context of the current paradigm of the effects of canopy cover on soil microclimate and their implications for understanding the dynamics of the processes that mediate the ecohydrological coupling between hydrology, soil moisture and ecosystem dynamics in drylands.

## **Materials and Methods**

### *Study site*

Our study was conducted at the University of Arizona cell and adjoining pasture 9 at the Santa Rita Experimental Range (31.79° N, 110.84° W), about 50 km south of Tucson, Arizona, USA. Our research site is at approximately 1200 m in elevation with

soil that is a coarse-textured, sandy-loam developed on Holocene-aged alluvium. Slopes range between 5 and 8 %. Mean annual precipitation is 294 mm, with a bimodal distribution defined by the North American monsoon season and a winter precipitation regime (McClaran et al., 2002).

We established six 50-m transects oriented east-west that represented a gradient of velvet mesquite (*Prosopis velutina*) canopy cover that included 2%, 16%, 26%, 37%, 56%, and 73%, defined here as the level for the overall vegetation matrix. Transects were selected to be relatively uniform with respect to edaphic, topographic, and climatic conditions and were located within less than 200 m from one or more transects from this study. Mesquite apparently encroached into the study site during historical exclusion of cattle grazing that followed an initial period of intense grazing post 1880 (McClaran et al., 2002). Differences in canopy cover have resulted from the different phases of the encroachment process. Soil texture, one of the most important variables defining soil hydraulic characteristics is similar between patch types (canopy/intercanopy) and transects (Figure 1), thereby allowing us to more readily isolate the effects of woody plant canopy on microclimate. Values of canopy cover were calculated during the full leafout season as the fraction of ground covered by the vertical projection of the canopies of all trees in the 50 x 20 m rectangular plot that was centered on the transect. Since cover was calculated as the area under drip line, it would only change with branch growth and death and not with phenology, which only affects foliar density. Patch type (canopy or intercanopy) was manually recorded every 1 m along each transect by visual surveys. A canopy location is defined as having a dominant woody plant overstory directly above

it. These surveys were repeated for each of the four study seasons. Within each transect, the relative proportions of canopy and intercanopy locations did not vary among the four seasons.

We quantified near-ground solar radiation interception at each location on each transect for each of the four seasons using hemispherical photographs. More specifically, hemispherical photographs were taken during each of four main phenological seasons (fall intermediate senescence, winter leafless, spring intermediate green-up, and summer full leaf-out), between October 2006 and July 2007. Photographs were taken at 1.0 m above the ground using a horizontally leveled digital camera (CoolPix 5400, Nikon, Tokyo, Japan), with a fish-eye lens (FC-E9, Nikon, Tokyo, Japan). The 1.0 m height is pre-defined to capture only the influence of the mesquite-dominated canopy without recording any effect of the undergrowth. Photographs were taken during uniform sky conditions at dawn, ensuring correct contrast between canopy and sky (Rich et al., 1999; Quilchano et al., 2008). Images were analyzed using Hemiview canopy analysis software version 2.1 (1999 Delta-T Devices, Ltd., Cambridge, UK; Rich et al., 1999) to calculate the annual Direct Site Factor (DSF). The Direct Site Factor is the proportion of direct solar radiation reaching a given location over a year, relative to that in the same location with no sky obstructions under clear sky conditions. This approach accounts for obstructions imposed by plant canopies and surrounding topographic features, if present, over an entire course of a year, assuming clear sky conditions. In addition, to assess the annual progression of near-ground solar radiation, we calculated mean maximum

potential inputs (corresponding to clear sky conditions) of near-ground solar radiation flux ( $\text{W m}^{-2}$ ) for each month.

Soil surface temperature was measured using data-logging temperature sensors (I-button DS1921G, Maxim Integrated Products, Inc., Sunnyvale, CA) that were installed at 5-cm depth at 1-m intervals for the center 20 m of each transect. Temperature data were recorded every two hours for the period between October 2006 and November 2007 and then averaged across all measurement intervals for two sets of time intervals: (1) each of four three-month seasonal periods corresponding to phenological intervals listed above, and (2) monthly.

#### *Data analysis*

We summarized DSF and soil temperature data not only for each transect overall but also by patch type (canopy and intercanopy) within each. We also calculated variance across the spatial locations for each transect overall and for canopy and for intercanopy patch types within each. We evaluated the association of both near-ground solar radiation (expressed as DSF) and soil temperature with amount of canopy cover across all transects for each of the four seasonal periods (for the transect overall and for both canopy and intercanopy patches), using linear models of the form:  $DSF = a + b*cover$ , and  $Temp = a + b*cover$ . Each model was tested with and without a quadratic term, the later of which did not increase statistical significance in any case. Similarly, we evaluated these same associations as a function of canopy cover for the variance at each transect across the locations.

We used a one-way ANOVA test to identify differences in the mean values of DSF and temperature at the patch-scale. Mean monthly DSF and temperature values were used to characterize the changes in total incoming solar radiation in response to the changes in cover imposed by the phenological dynamics of vegetation. Linear models of the form  $Temperature = a + b*DSF$  were used to evaluate the significance of the associations between DSF and soil surface temperature at both patch- and vegetation mosaic- scales for all seasons. All statistics were performed in Matlab v.7.7.0.471. Results were considered significant at an alpha level of 0.05.

## **Results**

### *Seasonal trends of near-ground solar radiation as a function of canopy cover*

Mean values of DSF for near-ground solar radiation fluctuated along each transect as a function of amount of canopy cover and varied seasonally in response to leaf phenology (Figure 2, appendix table 4). Not surprisingly, mean DSF values were generally greatest for the leafless season and smallest for the full leafout season (Figure 2; appendix figure 4). Across the gradient of increasing woody plant cover, mean DSF values consistently decreased with increasing cover for the overall vegetation mosaic as well as for both canopy and intercanopy patches (Figure 3, left column). Mean DSF values at canopy locations were lower than intercanopy locations ( $p < 0.01$  for all seasons), with values of DSF for the overall vegetation matrix constrained between the two patch values and weighted by the proportion of canopy patches at a site. Notably, the greatest differential in DSF between canopy and intercanopy patches occurred during the full leafout season ( $p = 0.0011$ ). Linear models between vegetation cover and DSF ( $DSF = a + b*cover$ ) were

significant ( $p < 0.05$ ) for the overall vegetation mosaic as well as for both patch types for all seasons (Appendix Table 1; DSF values for the 56% canopy cover transect during the intermediate-leaf senescence season only were not considered in the analysis due to technical errors in the hemispherical photographs that were not fixable using image editing software). In addition, variance in DSF for the overall vegetation mosaic generally peaked at intermediate levels of canopy cover (except during the leafless season, when it increased with increasing canopy cover) as the result of differential responses in canopy and intercanopy patches to amount of canopy cover (Figure 3, right column; relationships reported in Appendix Table 1).

*Seasonal trends of soil temperature as a function of canopy cover*

Consistent with trends in DSF, seasonal values of mean soil temperature decreased with increasing canopy cover for both overall vegetation mosaic and for canopy and intercanopy patches (Figure 4, left column), with significant linear models of the form  $Temperature = a + b * cover$  for all patch types for all seasons (however,  $r^2$  values were  $> 0.5$  only during the full leafout and intermediate-green up seasons; Appendix Table 2). Mean soil temperature differed significantly between canopy and intercanopy patches only in the full leaf-out season ( $p = 0.05$ ). In addition, consistent with general trends for DSF, variance in soil temperature for the overall vegetation mosaic generally peaked at intermediate levels of canopy cover (except during the leafless season, when it increased with increasing canopy cover) as the result of differential responses in canopy and intercanopy patches to amount of canopy cover (Figure 4, right column; relationships reported in Appendix Table 2).

### *Near-ground solar radiation-temperature relationships*

The monthly mean near-ground solar radiation (expressed in  $\text{W/m}^2$ ) and monthly mean soil temperature for the overall vegetation mosaic varied over the course of a year, with the effect of increasing canopy cover on near-ground solar radiation being more pronounced during the full leafout season (Figure 5, top panel). The effect of canopy cover on soil surface temperature was less evident, although was still more pronounced during the full leaf-out season (Figure 5, bottom panel). In general, DSF was positively correlated with soil surface temperature for the overall vegetation mosaic, as well as for intercanopy patches, during both the full leaf-out and intermediate seasons; corresponding associations for canopy patches were less pronounced but still significant. (Figure 6, Appendix Table 3).

## **Discussion**

### *Seasonally-pulsed heterogeneity in soil microclimate and its ecohydrological implications*

Our results for a deciduous grassland-forest continuum provide insights on how microclimate varies spatially with amount of canopy cover. More specifically, they generally support current perspectives about the effect of increasing canopy cover on the mean and associated variance among locations for near-ground solar radiation (Lin et al., 1992; Rich et al., 1994; Breshears et al., 1998; Martens et al., 2000; Breshears, 2006; Zou et al., 2007; Breshears and Ludwig, 2009; Zou et al., in press; Royer et al., in review). Our results quantify how solar radiation decreases linearly with increasing canopy cover for both the overall vegetation mosaic and for both patch types. In contrast to gradients of

increasing cover by evergreen woody plants, our results for deciduous woody plants indicate that the seasonal variation in canopy architecture induced by leaf-phenological dynamics affects the slope of relationships between canopy cover and near-ground solar radiation, as well as the associated variance functions. In general, during times of the year when leaves are present, variance peaks at intermediate values of canopy cover that are close to 50%. During the leafless season, however, this peak disappears and variance increases with increasing canopy cover. We interpret this shift associated with the leafless season to be due to the reduction in foliar density, which produces an effective reduction in woody plant canopy cover. Soil surface temperature follows a similar trend to that for DSF, but the seasonal dynamics of soil surface temperature for the overall vegetation mosaic are less sensitive to changes in canopy cover. This is not surprising because unlike near-ground solar radiation, which depends primarily on how woody plant canopies obstruct incoming solar radiation, soil temperature is an integrative metric that can reflect combined effects of climate-induced variations in ambient temperature, wind dynamics, soil thermal conductivity, and soil water content (Hillel, 1998). Notably, we focused on minimizing differences in soil characteristics both between patch types and across the vegetation gradient, as reflected in soil texture (Figure 1). In addition, over the seasonal periods that were the focus of most of our study, spatiotemporal variation in soil water content may have had minor influences on soil temperature dynamics. However, precipitation inputs to the soil in the dryland system that we studied are rapidly lost (e.g., within a few days), such that soil water content in the surface soil (5 cm in depth) is likely to be low for the majority of any seasonal period (Loik et al., 2004; Villegas et al.,

in review). Consequently, spatiotemporal variation in soil water content arguably did not have a pronounced effect on the trends that we document here. Collectively, then, our results highlight the synergistic effects of two types of interrelated annual periodicities— intra-annual changes in incoming solar radiation that are amplified by phenological dynamics of woody plant foliar density. The net results of these interrelated periodicities are an enhanced seasonally pulsed heterogeneity in soil microclimate.

Importantly, the availability of energy at soil surface that we have quantified, described by soil microclimatic parameters such as near-ground solar radiation and soil temperature, constitutes one of the key-drivers of ecohydrological processes in general (Veatch et al., 2009) and soil evaporation as a component of evapotranspiration in particular (Kurc and Small, 2004; Baldocchi and Xu, 2007). Therefore, the seasonally pulsed heterogeneity in soil microclimate should affect soil evaporation dynamics. To explore the potential consequences of the seasonally pulsed heterogeneity that we quantified, we used our measurements of soil surface temperature data (mean daily temperature and mean monthly temperature range) to extrapolate to approximate mean monthly potential evapotranspiration (PET). We used the Hargreaves equation (Hargreaves, 1975) for this extrapolation because it requires only temperature data to approximate PET at the landscape scale (Shuttleworth, 1993). These extrapolations (Figure 7) highlight how, in general, the seasonally-pulsed heterogeneity in microclimate varies with canopy cover, such that lower levels of canopy cover (2% and 16%) have higher rates of PET than higher levels of canopy cover (37% and 73%), even though there is some finer-scale variation for sites with more similar cover (e.g. PET for the site

with 16% was projected to be greater than that for the site with 2% canopy cover). The difference in extrapolated PET between low and high canopy cover sites is greatest during full leafout.

More generally, our results add a new dimension to the current paradigm of plant-water relations in drylands. The current paradigm for drylands focuses on pulse-driven dynamics of soil moisture as a key driver of ecohydrological processes, a perspective that has been considered in a broader context more recently (Loik et al., 2004; Schwinning and Sala, 2004). Our results add to this perspective by highlighting how the synergistic effects of intra-annual changes in incoming solar radiation and phenological dynamics of woody plant foliar density add an additional dimension of seasonally pulsed heterogeneity to other intra-annual pulse dynamics in drylands.

*Generalized effects of canopy architecture and connectivity on soil microclimate*

Our study of deciduous woody plants complements previous studies that have evaluated how canopy architecture influences near-ground solar radiation (ElJai et al., 1995; Landry et al., 1997; Martens et al., 2000; Breshears and Ludwig, 2009; Veatch et al., 2009; Zou et al., in press; Royer et al., in review). Our results contrast with previous studies in that we focused on deciduous woody plants, and they expand current understanding by defining how the relationship between canopy cover and near-ground solar radiation changes seasonally with phenology. Considered in concert with results from previous studies, our results highlight the different ways in which canopy architecture influences near-ground solar radiation along gradients of woody plant cover (Figure 8). The degree to which woody plants affect near-ground solar radiation in

general depends on key aspects of canopy architecture and structure. These include foliar density (Martens et al., 2000; Veatch et al., 2009, Royer et al., in review), which can vary either with intrinsic foliar characteristics of the dominant species (e.g., evergreen, conifer dominated systems; Royer et al., in review), or with seasonal changes in leaf density (e.g., deciduous woody plants, as studied here); canopy thickness (Zou et al., in press); vegetation height differences (e.g., between shorter- and taller statured piñon-juniper and ponderosa pine systems; Royer et al., in review); and in height to lower levels of foliage (Breshears and Ludwig, 2009). The differences in woody plant canopy architecture directly affect the degree of connectivity among vegetation patches by influencing the degree to which woody plants shade neighboring intercanopy and canopy patches beyond the extent of their above-ground canopy structure (Breshears, 2006). Notably, the seasonally-pulsed heterogeneity in microclimate that we document for deciduous woody plants is interrelated with changes in the degree of canopy connectivity (Figure 9) and contrasts with less temporally dynamic relationships for evergreens.

In conclusion, our results, which are consistent with previous general frameworks describing the behavior of near-ground solar radiation in the grassland-forest continuum (Martens et al., 2000; Breshears, 2006), amplify the current understanding of the vegetation influence on soil surface microclimate by documenting seasonally-pulsed heterogeneity associated with deciduous vegetation. They also highlight the importance of considering canopy architecture along with its amount and seasonality. Notably, our results complement previous studies that incorporate different types of canopy architecture in the study of vegetation effects on near-ground solar radiation, and provide

a systematic approach that can be useful for understanding the coupling between key ecological and hydrological processes. Understanding these relationships can be particularly useful for assessing the effects of current and predicted changes in climate, vegetation cover, vegetation seasonality in the coupling between the physical and biological processes that determine ecosystem dynamics at multiple spatial and temporal scales.

***Acknowledgements.*** We thank Mitch McClaran and Mark Heitlinger at Santa Rita Experimental Range for logistical and technical support. We also thank Colleen Boodleman, Jason Field, and James Luo for assistance on initial experimental design, field site selection, plot establishment, and experimental support. Support was provided by DNP- Fulbright-Colciencias scholarship (JCV), University of Arizona Technology and Research Initiative fund 2007/2008 (JCV), B2 Earthscience at Biosphere 2 through the Philecology Foundation (JCV), USDA CSREER (PDR and DDB), NSF Drought Impacts on Regional Ecosystem Networks (DIREnet), DOE National Institute for Climate Change Research (DDB), Arizona Water Institute (PDR and DDB) and the Arizona Agricultural Research Station (DDB, CBZ).

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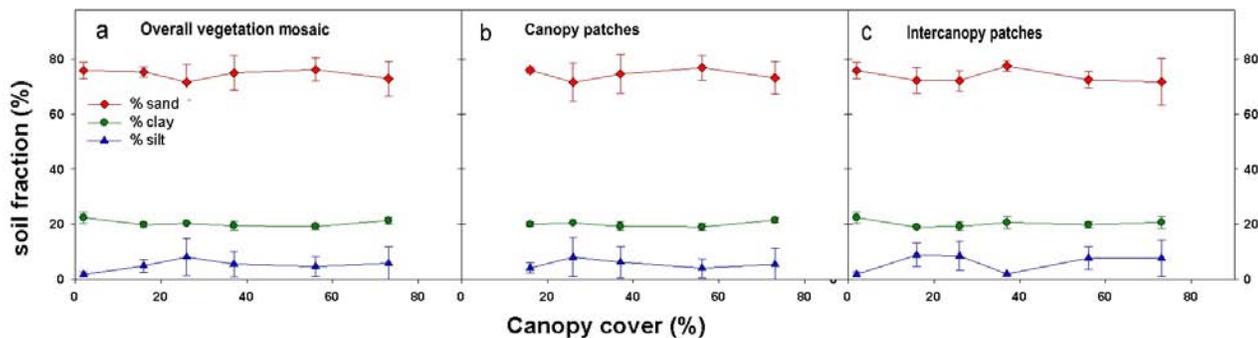
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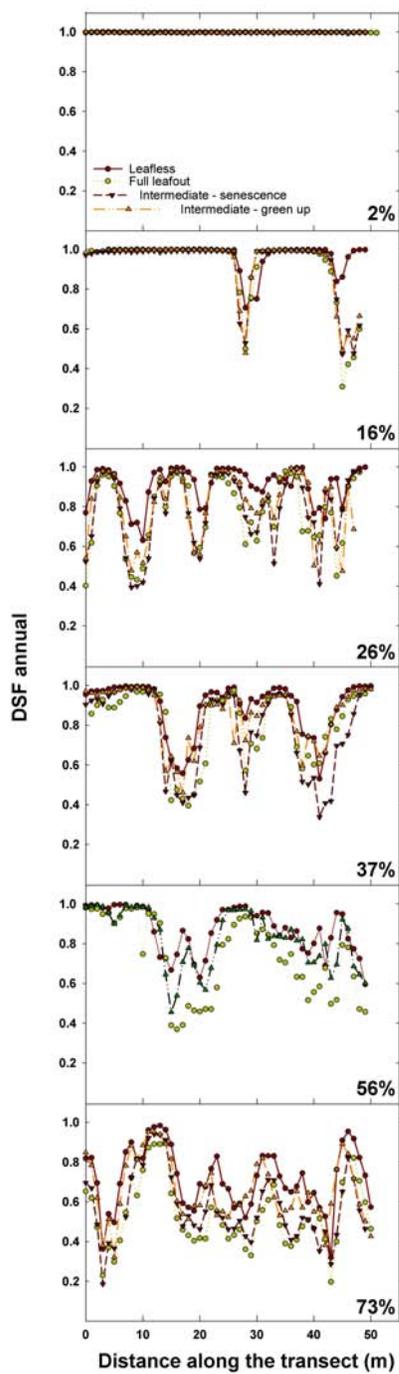
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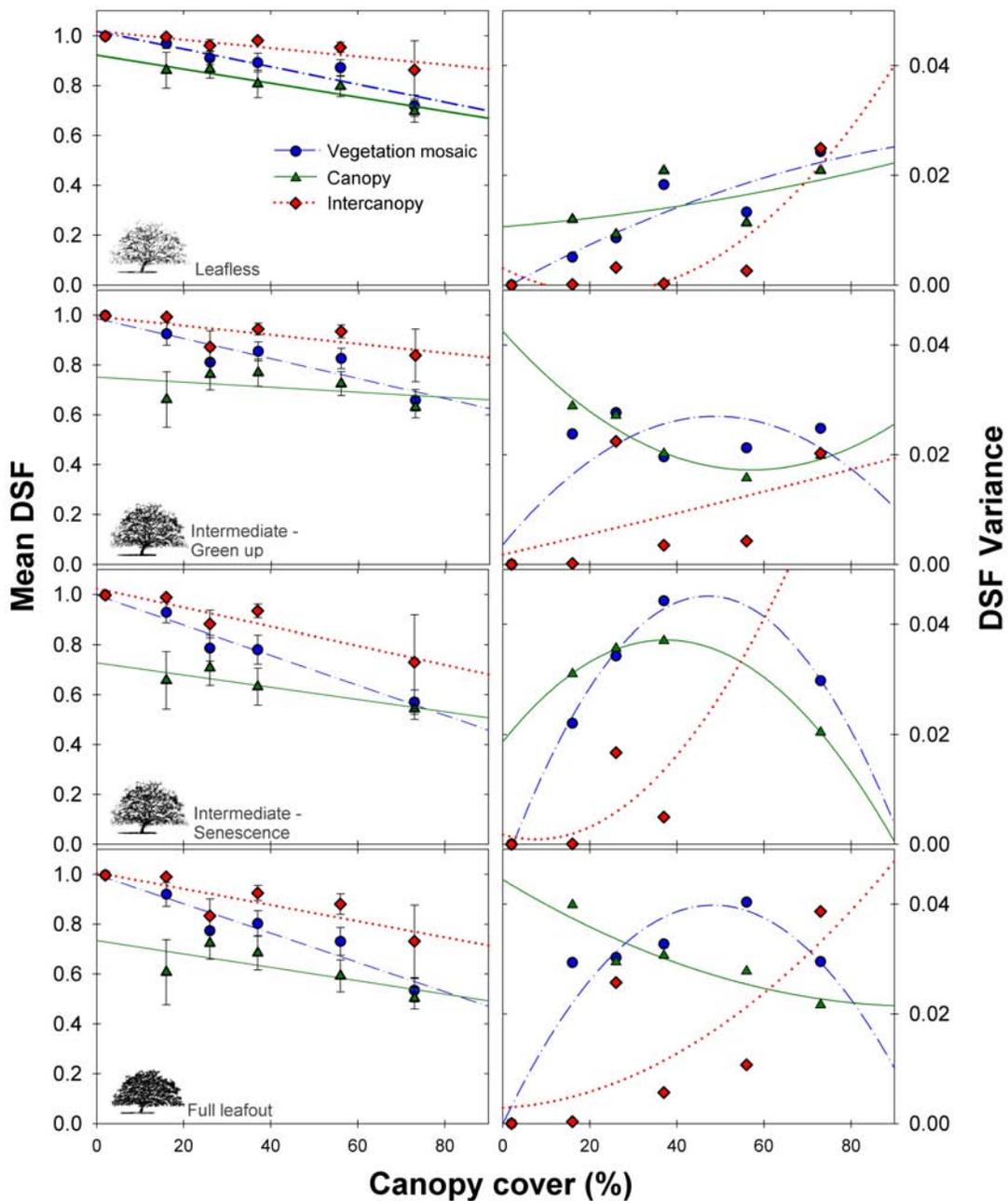
## Figures



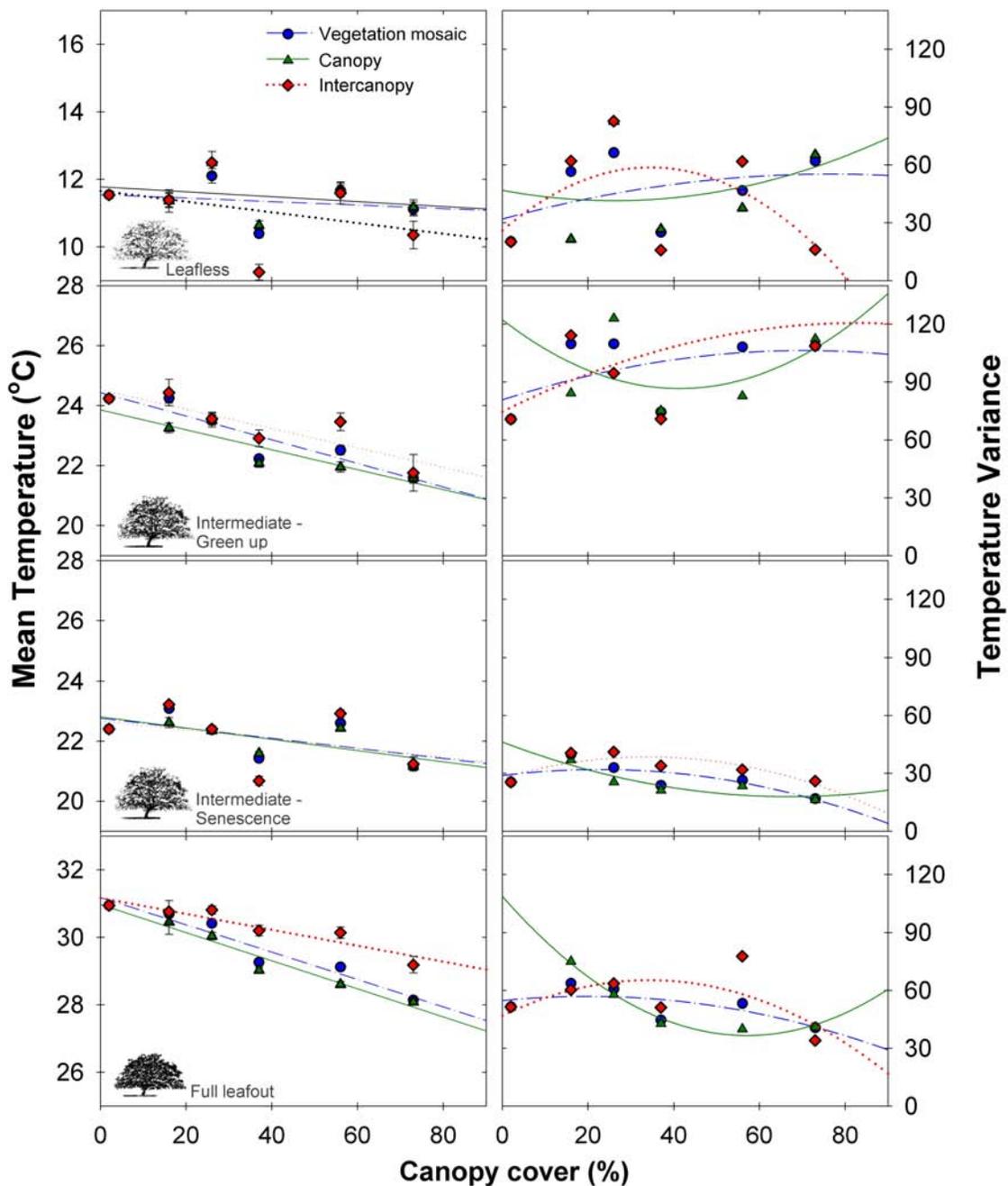
**Figure 1.** Soil textural characteristics represented by the fraction of sand (red diamonds), clay (green circles) and silt (blue triangles) for sites along a grassland-forest continuum of increasing canopy cover at the overall vegetation mosaic scale (a) and for canopy (b) and intercanopy (c) patches.



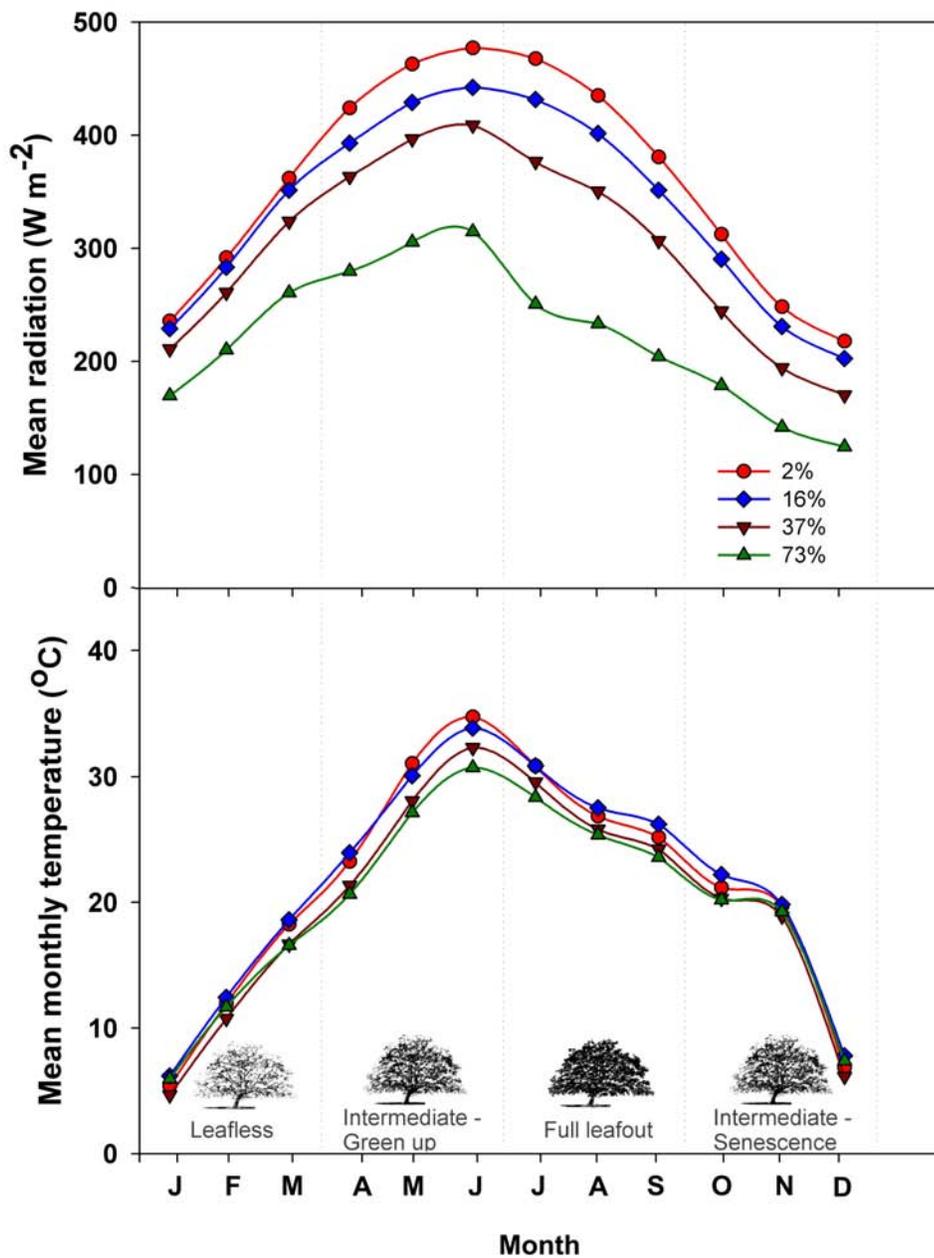
**Figure 2.** Seasonal variation of the fraction of near-ground solar radiation estimated as Direct Site Factor (DSF) along a gradient of mesquite-dominated transects spanning canopy covers that range between 2% and 73%



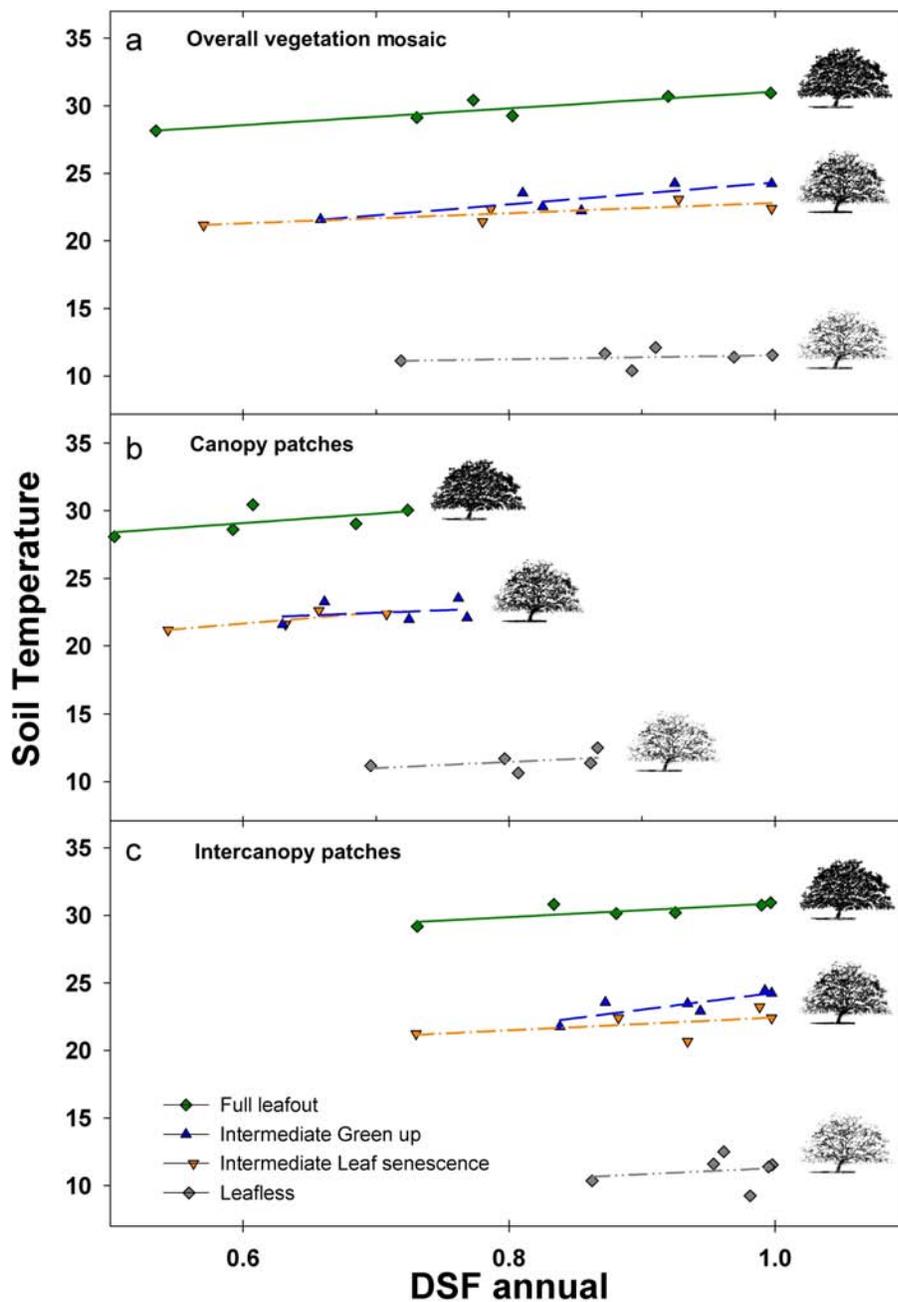
**Figure 3.** Seasonal trends in mean and variance Direct Site Factor (DSF) for sites along a grassland-forest continuum of increasing canopy cover at the overall vegetation mosaic scale (blue dash-dot line) and for canopy (green solid line) and intercanopy (red dotted line) locations.



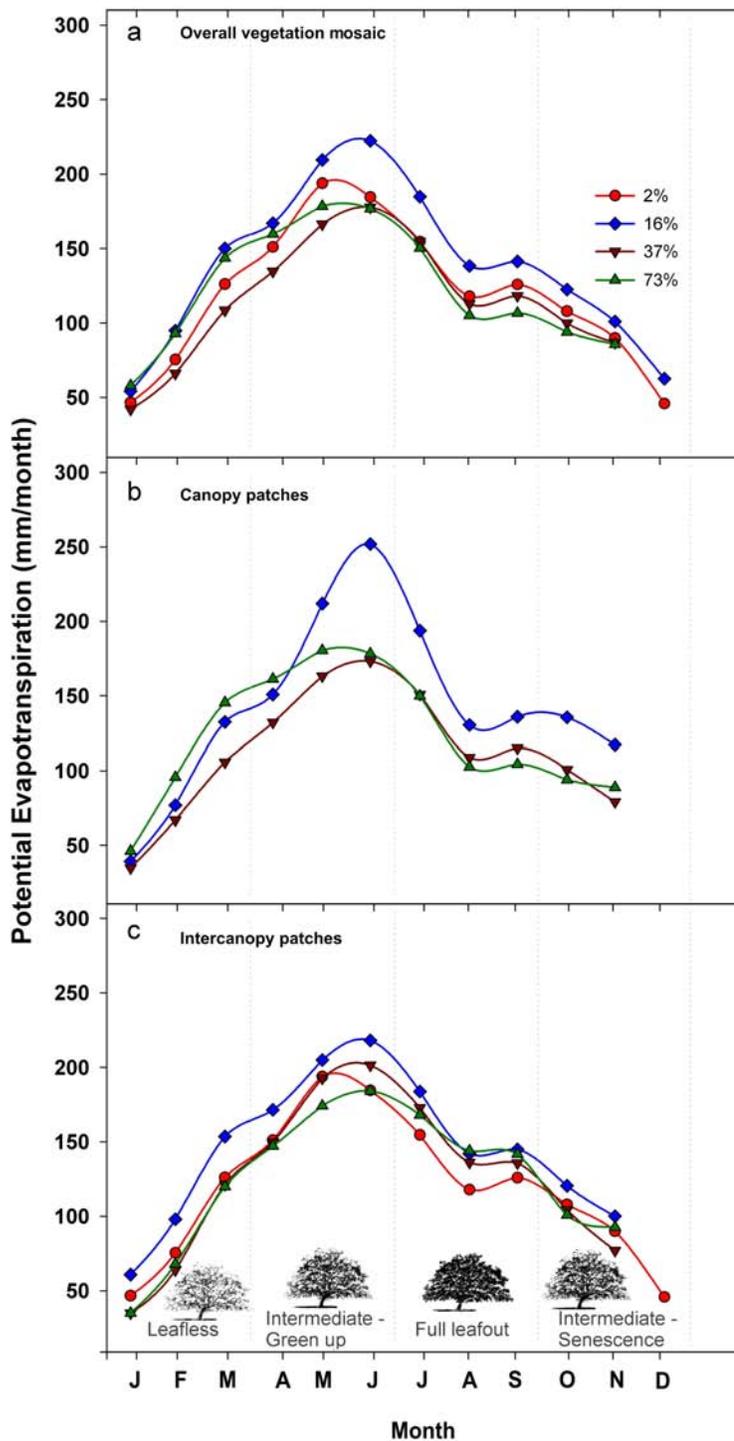
**Figure 4.** Seasonal trends in mean and variance soil temperature for sites along a grassland-forest continuum of increasing canopy cover at the overall vegetation mosaic scale (blue dash-dot line) and for canopy (green solid line) and intercanopy (red dotted line) locations.



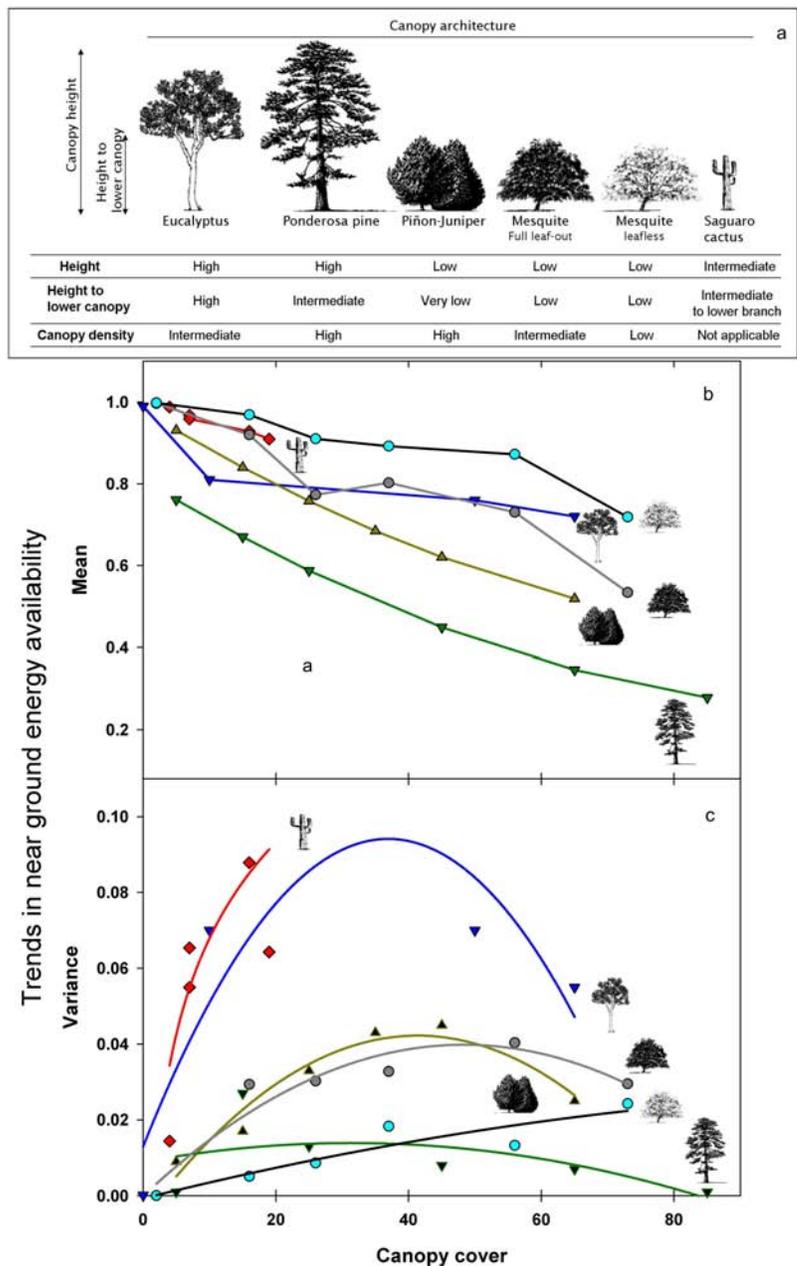
**Figure 5.** Monthly variation in near ground solar radiation (a), and soil temperature (b) for selected levels of canopy cover representing a deciduous-dominated grassland-forest continuum



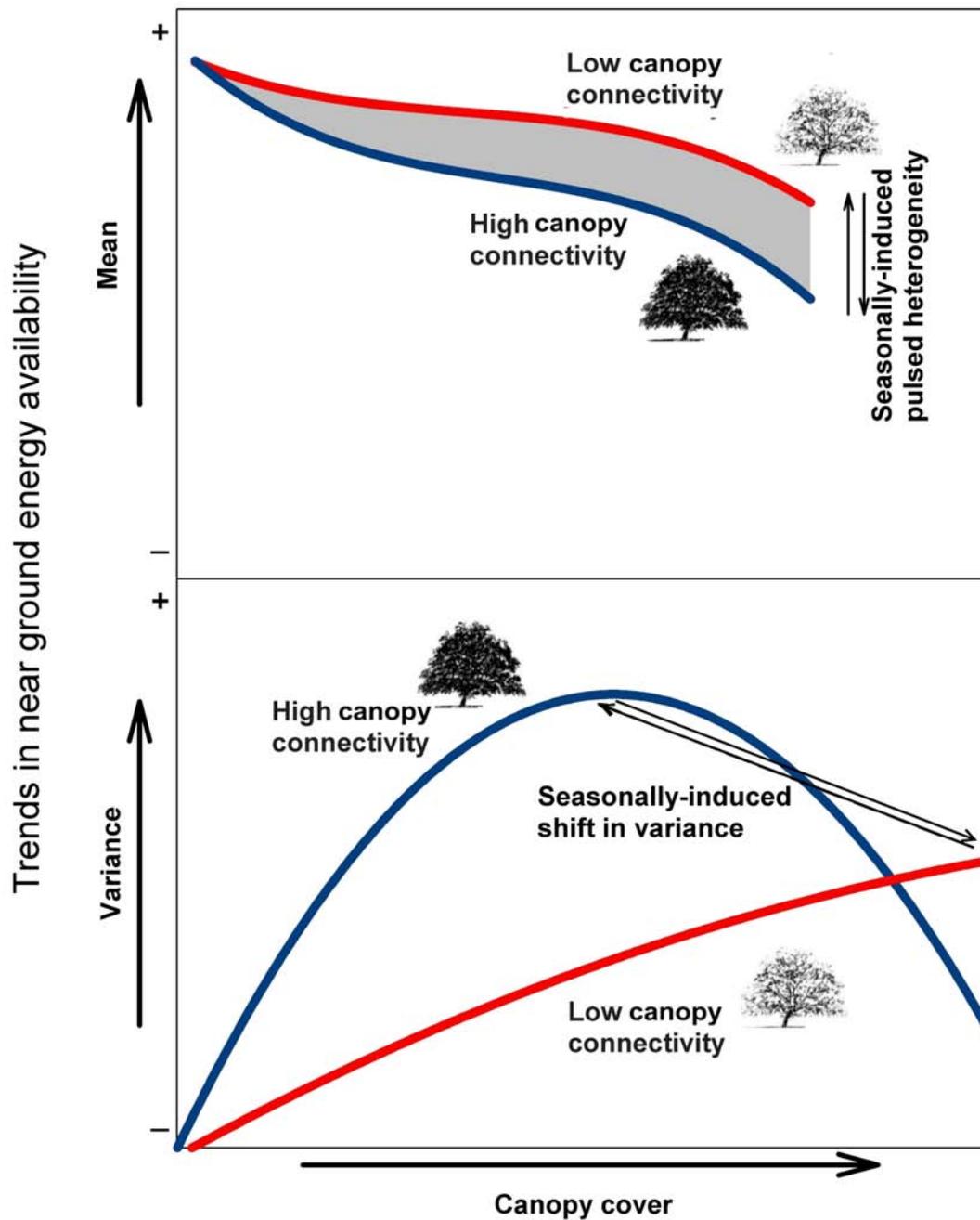
**Figure 6.** Seasonal variation in soil temperature as a function of near ground solar radiation, expressed as Direct site factor (DSF) for the overall vegetation mosaic (a), canopy (b), and intercanopy patch scales (c) during all four phenological seasons.



**Figure 7.** Seasonal variation of potential evapotranspiration (calculated with the Hargreaves equation using temperature observations) for selected transects along a deciduous-dominated grassland-forest continuum at the overall vegetation mosaic (a), canopy (b), and intercanopy patches (c).



**Figure 8.** Trends in near ground solar radiation along different grassland forest continuum types (including Eucalyptus-dominated, Breshears and Ludwig, 2009; Ponderosa pine and piñon-juniper, Royer et al., in review, mesquite-dominated, this study; and saguaro cactus-dominated, Zou, et al., in press), with different canopy architectural characteristics (a), corresponding to mean (b), and variance (c) values of Direct Site Factor (DSF).



**Figure 9.** Conceptual model of seasonally-induced pulsed heterogeneity in soil microclimate, as described by shifts in the patterns of mean and variance near ground energy availability along a deciduous grassland forest continuum. Such shifts in mean and variance are associated with the changes in patch-scale connectivity via canopy-imposed shading patterns imposed by the leaf phenological dynamics.

## Appendix tables

**Appendix Table 1.** Summary of regression parameters for linear regressions for canopy cover and mean Direct Site Factor ( $Mean\ DSF = a + b*canopy\ cover$ ) as well as canopy cover and Variance in Direct Site Factor ( $Var\ DSF = a + b*canopy\ cover + c*canopy\ cover^2$ ).

Mean DSF					
Season	Spatial scale	a	b	R2	
Leafless	Overall -vegetation mosaic	1.02	$-3.54 \times 10^{-3}$	0.90	
	Canopy patch	0.92	$-2.81 \times 10^{-3}$	0.89	
	Intercanopy patch	1.02	$-1.67 \times 10^{-3}$	0.76	
Intermediate - green up	Overall -vegetation mosaic	0.98	$-4.01 \times 10^{-3}$	0.83	
	Canopy patch	0.75	$-1.01 \times 10^{-3}$	0.14	
	Intercanopy patch	1.00	$-3.24 \times 10^{-3}$	0.70	
Intermediate - senescence	Overall -vegetation mosaic	1.00	$-5.99 \times 10^{-3}$	0.96	
	Canopy patch	0.73	$-2.45 \times 10^{-3}$	0.79	
	Intercanopy patch	1.02	$-3.8 \times 10^{-3}$	0.88	
Full leafout	Overall -vegetation mosaic	1.00	$-5.87 \times 10^{-3}$	0.91	
	Canopy patch	0.73	$-2.68 \times 10^{-3}$	0.51	
	Intercanopy patch	1.01	$-3.24 \times 10^{-3}$	0.70	
Variance DSF					
Season	Spatial scale	a	b	c	R2
Leafless	Overall -vegetation mosaic	$-7.26 \times 10^{-4}$	$4.37 \times 10^{-4}$	$1.66 \times 10^{-6}$	0.85
	Canopy patch	0.01	$6.36 \times 10^{-5}$	$7.31 \times 10^{-7}$	0.28
	Intercanopy patch	$3.09 \times 10^{-3}$	$-4.04 \times 10^{-4}$	$9.05 \times 10^{-6}$	0.84
Intermediate - green up	Overall -vegetation mosaic	$-9.33 \times 10^{-5}$	$1.65 \times 10^{-3}$	$-1.71 \times 10^{-5}$	0.90
	Canopy patch	0.04	$-4.79 \times 10^{-4}$	$2.49 \times 10^{-6}$	0.82
	Intercanopy patch	$2.86 \times 10^{-3}$	$4.59 \times 10^{-5}$	$5.04 \times 10^{-6}$	0.55
Intermediate - senescence	Overall -vegetation mosaic	$-4.91 \times 10^{-3}$	$2.12 \times 10^{-3}$	$-2.26 \times 10^{-5}$	0.99
	Canopy patch	0.02	$9.93 \times 10^{-4}$	$-1.32 \times 10^{-5}$	0.99
	Intercanopy patch	$-1.75 \times 10^{-3}$	$-2.22 \times 10^{-4}$	$-1.46 \times 10^{-5}$	0.93
Full leafout	Overall -vegetation mosaic	$3.55 \times 10^{-3}$	$9.61 \times 10^{-4}$	$-9.85 \times 10^{-6}$	0.61
	Canopy patch	0.04	$-8.85 \times 10^{-4}$	$7.74 \times 10^{-6}$	0.91
	Intercanopy patch	$1.78 \times 10^{-3}$	$1.84 \times 10^{-4}$	$1.28 \times 10^{-7}$	0.25

**Appendix Table 2.** Summary of regression parameters for linear regressions for canopy cover and mean soil temperature ( $Mean\ Temperature = a + b * canopy\ cover$ ) as well as canopy cover and Variance in soil temperature ( $Var\ Temperature = a + b * canopy\ cover + c * canopy\ cover^2$ ).

Mean Temperature					
Season	Spatial scale	a	b	r <sup>2</sup>	
Leafless	Overall -vegetation mosaic	11.55	$-5.21 \times 10^{-3}$	0.06	
	Canopy patch	11.77	$-7.29 \times 10^{-3}$	0.06	
	Intercanopy patch	11.66	-0.016	0.13	
Intermediate - green up	Overall -vegetation mosaic	24.44	-0.039	0.85	
	Canopy patch	23.86	-0.033	0.79	
	Intercanopy patch	24.53	-0.032	0.76	
Intermediate - senescence	Overall -vegetation mosaic	22.77	-0.017	0.36	
	Canopy patch	22.81	-0.019	0.48	
	Intercanopy patch	22.68	-0.015	0.16	
Full leafout	Overall -vegetation mosaic	31.18	-0.04	0.94	
	Canopy patch	30.97	-0.04	0.94	
	Intercanopy patch	31.16	-0.02	0.88	
Variance Temperature					
Season	Spatial scale	a	b	c	r <sup>2</sup>
Leafless	Overall -vegetation mosaic	31.92	0.61	$-3.98 \times 10^{-3}$	0.18
	Canopy patch	46.87	-0.41	$7.95 \times 10^{-3}$	0.08
	Intercanopy patch	25.99	1.89	-0.03	0.30
Intermediate - green up	Overall -vegetation mosaic	54.74	0.22	$-5.64 \times 10^{-3}$	0.49
	Canopy patch	108.82	-2.53	0.02	0.98
	Intercanopy patch	46.88	1.07	-0.01	0.39
Intermediate - senescence	Overall -vegetation mosaic	28.91	0.28	$-6.15 \times 10^{-3}$	0.58
	Canopy patch	46.26	-0.84	$-6.30 \times 10^{-3}$	0.80
	Intercanopy patch	27.66	0.64	$-9.42 \times 10^{-3}$	0.67
Full leafout	Overall -vegetation mosaic	80.78	0.73	$-5.15 \times 10^{-3}$	0.24
	Canopy patch	122.35	-1.73	0.02	0.16
	Intercanopy patch	74.65	1.11	$-6.68 \times 10^{-3}$	0.29

**Appendix Table 3.** Summary of regression parameters for linear regressions between DSF and soil temperature ( $Temperature = a + b*DSF$ ).

<b>Season</b>	<b>Spatial scale</b>	<b>a</b>	<b>b</b>	<b>r2</b>
Leafless	Overall -vegetation mosaic	10.07	1.45	0.06
	Canopy patch	4.06	1.57	0.39
	Intercanopy patch	6.63	4.66	0.04
Intermediate - green up	Overall -vegetation mosaic	16.23	8.08	0.70
	Canopy patch	8.48	2.93	0.35
	Intercanopy patch	11.74	12.53	0.68
Intermediate - senescence	Overall -vegetation mosaic	19.09	3.80	0.39
	Canopy patch	7.91	2.98	0.38
	Intercanopy patch	17.71	4.72	0.21
Full leafout	Overall -vegetation mosaic	24.84	6.20	0.83
	Canopy patch	10.98	3.82	0.36
	Intercanopy patch	25.79	5.09	0.62

**Appendix Table 4.** Seasonal DSF values for all locations within transects

Seasonal DSF for 2% canopy cover transect

Transect location: Lat = 31° 47' 16.3'' N; Long= 110° 50' 9.32'' W

Location (m)	Senescence	Leafless	Green-up	Leaf out
0	0.996983123	0.997057	0.996	0.999549
1	0.999073906	0.998475	0.996	0.999402
2	0.999377676	0.999122	0.997	0.99927
3	0.99918017	0.999616	0.995	0.998268
4	0.999240055	0.999345	0.998	0.996972
5	0.998535961	0.999217	0.998	0.997099
6	0.998659484	0.998589	0.996	0.998728
7	0.998081442	0.997976	0.997	0.994
8	0.998073839	0.997949	0.997	0.998851
9	0.99826129	0.99907	0.998	0.996813
10	0.998533535	0.998003	0.995	0.996975
11	0.997942377	0.997815	0.996	0.99866
12	0.996688706	0.998527	0.995	0.998155
13	0.998379246	0.998088	0.998	0.994575
14	0.997677718	0.999193	0.997	0.997841
15	0.997185213	0.998511	0.996	0.998247
16	0.998593643	0.997256	0.996	0.997301
17	0.998419357	0.997898	0.995	0.996394
18	0.994395349	0.997605	0.997	0.995803
19	0.998276877	0.997422	0.996	0.99752
20	0.998994746	0.998101	0.998	0.996826
21	0.998918393	0.998206	0.994	0.997311
22	0.997717401	0.998356	0.998	0.998546
23	0.99849118	0.998744	0.996	0.996985
24	0.995360581	0.99834	0.998	0.994684
25	0.995510526	0.997946	0.996	0.997951
26	0.996056497	0.999506	0.996	0.998992
27	0.995923559	0.997313	0.998	0.998634
28	0.998033248	0.999258	0.997	0.998178
29	0.994808058	0.997351	0.997	0.99656
30	0.996464128	0.999468	0.998	0.998028
31	0.996770071	0.996262	0.998	0.997925
32	0.99732901	0.997108	0.997	0.99846
33	0.99329337	0.997433	0.998	0.998955
34	0.996876541	0.997277	0.997	0.998111
35	0.998486808	0.997767	0.998	0.996179
36	0.996870248	0.996813	0.998	0.995789
37	0.996457728	0.997876	0.997	0.994579
38	0.99668735	0.996755	0.997	0.997052
39	0.996408433	0.997553	0.998	0.997718
40	0.997312847	0.998173	0.997	0.996222
41	0.998151827	0.996321	0.999	0.998907
42	0.997833876	0.997758	0.996	0.997418
43	0.997992161	0.997003	0.997	0.997646
44	0.997597097	0.998111	0.998	0.998909
45	0.997565388	0.998692	0.997	0.997626
46	0.99721696	0.996953	0.993	0.998841
47	0.997998582	0.996498	0.996	0.998387
48	0.99651137	0.998763	0.997	0.998096
49	0.997754765	0.997572	0.997	0.998603

Seasonal DSF for 16% canopy cover transect

Transect location : Lat = 31° 47' 13'' N; Long= 110° 50' 30'' W

Location	Senescence	Leafless	Green-up	Leaf out
0	0.971411		0.979	
1	0.978223		0.992	
2	0.988855		0.987	
3	0.988242		0.991	
4	0.988456	0.998878	0.992	
5	0.985917	0.998199	0.993	0.995882
6	0.989287	0.998738	0.997	0.996176
7	0.990492	0.998369	0.996	0.996869
8	0.986636	0.997954	0.995	0.998179
9	0.988942	0.999588	0.996	0.996755
10	0.990025	0.998764	0.997	0.99712
11	0.99326	0.997725	0.996	0.997591
12	0.992506	0.998921	0.998	0.996129
13	0.985564	0.996674	0.997	0.998312
14	0.989931	0.998668	0.999	0.996623
15	0.991007	0.999321	0.999	0.998557
16	0.992128	0.999325	0.999	0.997702
17	0.994855	0.999043	0.997	0.998156
18	0.989634	0.999255	0.997	0.997966
19	0.994874	0.999568	0.999	0.997083
20	0.992417	0.999457	0.997	0.9977
21	0.991533	0.999254	0.997	0.997559
22	0.993305	0.999047	0.997	0.997226
23	0.993297	0.997492	0.996	0.996884
24	0.992372	0.994796	0.996	0.995967
25	0.989721	0.995821	0.992	0.992828
26	0.979276	0.996661	0.983	0.960769
27	0.627565	0.892268	0.783	0.689288
28	0.528659	0.705406	0.499	0.478132
29	0.856539	0.752803	0.756	0.858725
30	0.990966	0.75047	0.911	0.989355
31	0.991789	0.938433	0.988	0.992256
32	0.989544	0.978568	0.995	0.995141
33	0.990528	0.992234	0.993	0.996668
34	0.992246	0.996933	0.997	0.995549
35	0.992312	0.998268	0.996	0.997437
36	0.994265	0.996884	0.996	0.99479
37	0.99351	0.997552	0.995	0.991868
38	0.99277	0.998278	0.995	0.995809
39	0.992125	0.998718	0.992	0.9952
40	0.99257	0.998132	0.989	0.989788
41	0.987956	0.997598	0.977	0.987883
42	0.980538	0.99774	0.946	0.972786
43	0.945683	0.977872	0.888	0.929309
44	0.748254	0.838077	0.732	0.661325
45	0.473734	0.860831	0.309	0.490985
46	0.592723	0.961672	0.421	0.56678
47	0.477153	0.992704	0.456	0.551221
48	0.616458	0.998225	0.599	0.664381
49		0.997928		

Seasonal DSF for 26% canopy cover transect

Transect location: Lat = 31° 47' 16'' N; Long= 110° 50' 27'' W

Location	Senescence	Leafless	Green-up	Leaf out
0	0.523148	0.769059	0.402	0.539243
1	0.651468	0.927692	0.618	0.839178
2	0.926572	0.985315	0.906	0.945721
3	0.972182	0.990578	0.96	0.978617
4	0.977167	0.983902	0.952	0.976395
5	0.938293	0.964359	0.903	0.96365
6	0.792473	0.916312	0.767	0.846011
7	0.542674	0.829253	0.535	0.649744
8	0.393767	0.711726	0.445	0.477132
9	0.400317	0.719209	0.431	0.568902
10	0.418607	0.630065	0.488	0.515146
11	0.538868	0.872906	0.656	0.637638
12	0.843202	0.971695	0.849	0.822357
13	0.911002	0.986872	0.921	0.94712
14	0.766495	0.925595	0.797	0.837301
15	0.968793	0.992577	0.952	0.98202
16	0.977236	0.996056	0.968	0.976633
17	0.968338	0.994447	0.936	0.924937
18	0.766783	0.973633	0.904	0.747815
19	0.619008	0.935411	0.565	0.568729
20	0.53718	0.785315	0.592	0.557713
21	0.717592	0.791894	0.695	0.765806
22	0.9617	0.918292	0.961	0.956093
23	0.962546	0.991439	0.952	0.975704
24	0.96726	0.991739	0.947	0.981855
25	0.966351	0.992338	0.917	0.970879
26	0.931073	0.988911	0.866	0.945332
27	0.894462	0.978926	0.795	0.921838
28	0.748032	0.961013	0.61	0.834456
29	0.662238	0.903116	0.721	0.791255
30	0.671738	0.88782	0.628	0.765449
31	0.805039	0.873759	0.773	0.82932
32	0.845952	0.93704	0.828	0.856858
33	0.514329	0.957968	0.698	0.741949
34	0.792054	0.924086	0.944	0.857644
35	0.910265	0.940507	0.978	0.954073
36	0.991325	0.902652	0.967	0.993004
37	0.989705	0.994441	0.951	0.990907
38	0.896386	0.995382	0.675	0.967409
39	0.744459	0.889363	0.678	0.920194
40	0.721584	0.764794	0.647	0.502292
41	0.410203	0.793504	0.655	0.620519
42	0.871906	0.739943	0.798	0.887593
43	0.837229	0.938096	0.769	0.897751
44	0.590002	0.941816	0.451	0.597126
45	0.792303	0.784581	0.616	0.475438
46	0.932834	0.902982	0.901	0.902817
47	0.979287	0.974079	0.942	0.686228
48	0.982265	0.992545	0.973	
49		0.997752		

Seasonal DSF for 37% canopy cover transect

Transect location: Lat = 31° 47' 18.5'' N; Long= 110° 50' 27.9'' W

Location	Senescence	Leafless	Green-up	Leaf out
0	0.904016	0.953511		0.971347
1	0.924003	0.970701	0.857	0.962147
2	0.930429	0.972398	0.9	0.951841
3	0.907413	0.972285	0.927	0.964916
4	0.946169	0.981685	0.888	0.965569
5	0.965591	0.99054	0.888	0.966821
6	0.981755	0.991176	0.916	0.976388
7	0.98735	0.996373	0.946	0.985013
8	0.98498	0.992957	0.979	0.989676
9	0.990733	0.995621	0.967	0.992696
10	0.989809	0.993824	0.968	0.989118
11	0.957149	0.992946	0.976	0.978306
12	0.982084	0.981141	0.975	0.950322
13	0.809976	0.920858	0.955	0.820702
14	0.466791	0.737712	0.866	0.568333
15	0.62589	0.624816	0.422	0.641124
16	0.449204	0.583597	0.475	0.563525
17	0.410091	0.557623	0.43	0.460127
18	0.435938	0.624688	0.395	0.735297
19	0.449404	0.683634	0.451	0.618931
20	0.68706	0.89521	0.516	0.787362
21	0.899323	0.94994	0.606	0.902844
22	0.931636	0.9665	0.914	0.898347
23	0.919529	0.96316	0.925	0.902396
24	0.90441	0.939078	0.924	0.879946
25	0.962377	0.985137	0.945	0.943838
26	0.948727	0.989694	0.975	0.70887
27	0.672527	0.903766	0.86	0.923594
28	0.460719	0.835096	0.571	0.722059
29	0.765162	0.93205	0.707	0.8627
30	0.748771	0.914351	0.681	0.845877
31	0.852042	0.943973	0.736	0.901344
32	0.909129	0.959144	0.931	0.944111
33	0.953445	0.985373	0.948	0.943363
34	0.958351	0.987697	0.958	0.948872
35	0.950206	0.981623	0.948	0.952059
36	0.851654	0.947222	0.891	0.865824
37	0.661091	0.918494	0.69	0.76685
38	0.515611	0.754324	0.582	0.596824
39	0.501995	0.741117	0.646	0.744875
40	0.535421	0.735426	0.601	0.718943
41	0.337854	0.529794	0.608	0.644692
42	0.407168	0.661072	0.741	0.668685
43	0.418143	0.802775	0.831	0.803184
44	0.696252	0.877034	0.779	0.889632
45	0.70681	0.942247	0.845	0.900477
46	0.751195	0.975609	0.929	0.941346
47	0.856884	0.991466	0.946	0.973119
48	0.955799	0.996406	0.949	0.97852
49	0.979025	0.995351	0.959	0.983764

Seasonal DSF for 56% canopy cover transect

Transect location: Lat = 31° 47' 19.1'' N; Long= 110° 50' 21.7'' W

Location	Senescence	Leafless	Green-up	Leaf out
0		0.99109	0.981	0.981033
1		0.994346	0.973	0.986671
2		0.992762	0.975	0.994428
3		0.979667	0.948	0.987635
4		0.977629	0.954	0.956746
5		0.995102	0.903	0.898396
6		0.995568	0.933	0.94198
7		0.996186	0.978	0.991127
8		0.975887	0.976	0.985252
9		0.991512	0.981	0.986756
10		0.987232	0.747	0.980462
11		0.969357	0.951	0.982046
12		0.859331	0.948	0.929254
13		0.73192	0.903	0.870673
14		0.725077	0.728	0.645236
15		0.666876	0.389	0.454888
16		0.74534	0.369	0.537445
17		0.865456	0.39	0.707261
18		0.82323	0.486	0.775641
19		0.696471	0.463	0.69113
20		0.629309	0.458	0.603338
21		0.713551	0.47	0.566856
22		0.852394	0.47	0.677639
23		0.918927	0.579	0.794692
24		0.970263	0.794	0.917325
25		0.971076	0.823	0.967745
26		0.981204	0.894	0.967345
27		0.987061	0.926	0.970793
28		0.987669	0.936	0.973347
29		0.939321	0.932	0.964497
30		0.940094	0.852	0.817611
31		0.956116	0.871	0.931607
32		0.95396	0.845	0.824223
33		0.887943	0.792	0.838006
34		0.841195	0.718	0.834484
35		0.879443	0.705	0.829098
36		0.829991	0.747	0.87186
37		0.863464	0.633	0.815282
38		0.773137	0.633	0.820922
39		0.752053	0.515	0.705116
40		0.800859	0.556	0.705266
41		0.877112	0.584	0.738097
42		0.689505	0.677	0.797416
43		0.82895	0.497	0.627469
44		0.955829	0.517	0.694625
45		0.948736	0.793	0.921766
46		0.824473	0.781	0.8766
47		0.773569	0.634	0.68524
48		0.724224	0.471	0.645545
49		0.595113	0.457	0.60141

Seasonal DSF for 73% canopy cover transect

Transect location: Lat = 31° 47' 18.1'' N; Long= 110° 50' 27'' W

Location	Senescence	Leafless	Green-up	Leaf out
0	0.696406	0.818439	0.652	0.84831
1	0.668309	0.821871	0.619	0.783766
2	0.487231	0.694901	0.472	0.619879
3	0.186791	0.362363	0.229	0.380353
4	0.392865	0.539502	0.372	0.511974
5	0.366128	0.496077	0.298	0.321468
6		0.691116	0.406	0.589537
7	0.524391	0.851158	0.546	0.782041
8	0.723195	0.899607	0.723	0.881541
9	0.8186	0.814486	0.632	0.812567
10	0.785653	0.819273	0.76	0.884413
11	0.923006	0.960805	0.873	0.951845
12	0.940507	0.976336	0.89	0.953598
13	0.936713	0.98378	0.891	0.93963
14	0.91215	0.962731	0.899	0.891116
15	0.725105	0.889257	0.642	0.815362
16	0.593409	0.74198	0.517	0.60453
18	0.528618	0.571671	0.431	0.513488
19	0.481873	0.55466	0.404	0.57826
20	0.462257	0.689624	0.417	0.582056
21	0.552281	0.675808	0.415	0.681958
22	0.685194	0.766809	0.572	0.744877
23	0.545569	0.829193	0.553	0.532615
24	0.519894	0.690101	0.483	0.55072
25	0.462547	0.665291	0.414	0.52253
26	0.465687	0.568647	0.433	0.589834
28	0.427206	0.51991	0.361	0.627757
29	0.396832	0.587831	0.33	0.65547
30	0.521102	0.732026	0.502	0.78951
31	0.654223	0.832153	0.559	0.820535
32	0.712172	0.831469	0.609	0.737568
33	0.709061	0.830932	0.685	0.621816
34	0.595542	0.728765	0.482	0.531435
35	0.482743	0.668288	0.39	0.555397
36	0.409247	0.650032	0.377	0.569252
37	0.429054	0.678098	0.409	0.651943
38	0.520311	0.744733	0.476	0.57157
39	0.513303	0.598641	0.508	0.644871
40	0.467057	0.646091	0.466	0.549809
41	0.352641	0.570714	0.516	0.561027
42	0.451025	0.526674	0.412	0.381978
43	0.286335	0.319978	0.197	0.590094
44	0.434148	0.762852	0.4	0.762874
45	0.651878	0.909554	0.698	0.890915
46	0.824172	0.954383	0.827	0.841628
47	0.71576	0.917591	0.821	0.71679
48	0.556955	0.822261	0.705	0.58714
49	0.463187	0.732747	0.598	0.501503

## APPENDIX C

ECOHYDROLOGICAL CONTROLS OF SOIL EVAPORATION IN DECIDUOUS  
DRYLANDS: HOW THE HIERARCHICAL EFFECTS OF LITTER, PATCH AND  
VEGETATION MOSAIC COVER INTERACT WITH PHENOLOGY AND SEASON

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Document type: Peer-reviewed publication in *Journal of Arid Environments*

**Abstract:** Soil evaporation, a critical ecohydrological process in drylands, can exhibit substantial spatiotemporal variation. Spatially, ecohydrological controls of soil evaporation may generally depend on a hierarchical structure spanning from the presence or absence of litter, through canopy patches of woody plants and intercanopy patches separating them, up to the overall vegetation mosaic characterized by density of woody plant cover in the landscape, although assessment of these factors in concert is generally lacking. Temporally, ecohydrological controls can be further complicated by not only seasonal climate, but also phenology, particularly in seasonally-deciduous drylands. We experimentally assessed interactive controls on soil evaporation along a gradient of

mesquite cover (*Prosopis velutina*) within the North American monsoon region, with respect to such hierarchical structure and seasonality/phenology. Our results indicate presence of litter exerts a dominant control on soil evaporation, independent of seasonality; in absence of litter, both patch and mosaic attributes influence soil evaporation variably with season/phenology. Correlations from related measures of incoming energy suggest energy limits evaporation in many cases, although other factors such as wind may potentially influence hierarchical and seasonal/phenological combinations. Our results highlight the need to account for both hierarchical vegetation structure and seasonal/phenological variability to improve ecohydrological predictions of soil evaporation.

## **Introduction**

Evapotranspiration dominates water fluxes in semiarid ecosystems, often accounting for >95% of the annual water budget (Branson et al., 1981; Wilcox et al., 2003; Williams et al., 2004; Huxman et al., 2005). Although most research has focused on evapotranspiration as an aggregated process, more recently emphasis is being placed on the importance of distinguishing between and quantifying the two major components of evapotranspiration (after accounting for evaporation of water intercepted by the canopy): evaporation from the soil and transpiration from plants (Dugas et. al., 1996; Williams et al., 2004; Huxman et al., 2005; Lauenroth and Bradford, 2006). This distinction is one of the most fundamental ecohydrological challenges in drylands (Newman et al., 2006) and has important implications not only for the water budget, but also for understanding potential feedbacks between vegetation dynamics and water as

well as other biogeochemical cycles (Raupach, 1998; Rodriguez-Iturbe, 2000; Eagleson, 2002, Newman et al., 2006; D'Odorico et al., 2007). In particular, determining the dynamics and drivers of soil evaporation in drylands is a fundamental step for improving estimates of the partitioning of evapotranspiration.

Soil evaporation is expected to exhibit a substantial spatiotemporal variability. Spatially, the vegetation-associated controls of soil evaporation are expected to respond to a hierarchical structure spanning from the presence of a litter layer on the surface (Facelli and Pickett, 1991; Vetaas, 1992; Joffre, 1993), through the canopy patches of woody plants and the intercanopy patches separating them (Breshears et al., 1998; Martens et al. 2000; Loik et al., 2004), up to the overall vegetation mosaic characterized by the density of woody plant cover (Geiger, 1965; Schulze et al., 1995; Breshears et al. 1998; Roberts, 2000; Baldocchi and Xu, 2007; Villegas et al., 2010). Many ecosystems, particularly drylands, are dominated by woody plants that not only vary spatially in terms of amount of cover but also temporally because of seasonally-dependent changes in leaf phenology. Such seasonal variations in plant cover associated with the deciduous nature of the dominant woody species significantly influence the dynamics of soil evaporation as well (Baldocchi et al., 1997; Wilson et al., 2000; Vivoni et al., 2008). However, previous studies of the effects of woody plants on soil evaporation and associated ecohydrological processes have largely focused on the effects of evergreen trees, where woody-plant canopy cover and foliage density remain relatively constant throughout the year (Breshears et al., 1998; Martens et al., 2000; Lebron et al., 2007; Adams, 2007).

Variation in the amount and seasonality of effective surface cover associated with the phenology of woody plant cover can modify the relative importance of the physical processes that drive soil evaporation, particularly radiation availability, temperature, wind, soil and vegetation characteristics at the different levels of the vegetation structure hierarchy (Kondo et al. 1992, Baldocchi et al., 2000; Baldocchi et al., 2002; Kurc and Small, 2004). At the individual patch scale, woody plants influence the dynamics of soil evaporation by locally reducing the amounts of solar radiation reaching the ground (Breshears et al., 1998; Martens et al., 2000;; Fu and Rich, 2002; Zou et al., 2007; Breshears and Ludwig, 2009) and by the addition of litter to the ground beneath the canopy (Facelli and Pickett, 1991; Lafleur, 1992; Kelliher et al., 1998; Wilson et al., 2000; Throop and Archer, 2007). At the overall vegetation mosaic scale, woody cover can influence soil evaporation through the general attenuation of solar radiation (which differs from the localized effects at canopy patches), the modification of wind dynamics, and the alteration of soil microclimate (Geiger, 1965; Bonan, 2002; Warner, 2004; Breshears et al., 2009; Villegas et al., 2010). In addition, the interactive nature of these effects likely varies in response to associated seasonality, vegetation phenology and climate. Collectively, these issues highlight that lacking is a systematic evaluation of how the changes in surface cover imposed by the seasonal dynamics of deciduous vegetation, both at the scales of individual patches and of vegetation mosaics, influence the dynamics of soil evaporation. Such evaluation is needed to improve our understanding of the water budget in semi-arid ecosystems and the potential feedbacks between the dynamics of vegetation and climate.

In this study we assess how the spatial and temporal variability in soil evaporation relates to the hierarchy of vegetation structure, specifically considering the effects of litter, patch, and vegetation-mosaic scales and how these effects are influenced by the temporal dynamics associated with seasonal climate and leaf phenology. We approached this problem by performing a series of field experiments with microlysimeters. Based on our results, we discuss the mechanisms associated with these dynamics in the context of the environmental drivers of evaporation, and more generally, propose a conceptual framework to synthetically describe the mechanisms that drive soil evaporation and their interaction with vegetation dynamics.

### **Materials and methods**

We measured the dynamics of soil microclimate and soil evaporation along a gradient of vegetation cover located in the North American monsoon region, where soil evaporation rates and their seasonal variability can be particularly high. We assessed the seasonal dynamics of evaporation by conducting experiments during the main phenological seasons (fall intermediate senescence, winter leafless, spring intermediate green-up, and summer full leafout).

#### *Study site*

Experiments were conducted at the University of Arizona pasture cell at the Santa Rita Experimental Range (31.79° N, 110.84° W), about 50 km south of Tucson, Arizona, USA. The area is approximately 1200 meters in elevation with a coarse textured, sandy-loam soil developed on Holocene-aged alluvium. Slopes range between 5 and 8 %. Mean annual precipitation is 294 mm, with a bimodal distribution. Approximately 60% of the

annual rain falls during the North American monsoon season, and the remaining precipitation mostly occurs during the winter (McClaran et al., 2002).

We established six 50-m transects that represent a gradient of canopy cover dominated by the seasonally-deciduous velvet mesquite (*Prosopis velutina*). Canopy cover levels in this gradient included: 2%, 16%, 26%, 37%, 56%, and 73%. Values of canopy cover were calculated during the full leafout season as the fraction of ground covered by the vertical projection of the canopies of all trees in the 50 x 20 m rectangular plot that was centered on the transect. Since cover was calculated as the area under drip line, it would only change with branch growth and death and not with phenology, which only affects foliar density. Transects were uniform with respect to edaphic, topographic and climatic conditions. In particular, soil texture, which is one of the most important variables defining soil hydraulic characteristics is not significantly different between transects (Villegas et al., 2010). On each transect, we randomly selected five canopy and five intercanopy locations, except for the 2% cover plot, where only the intercanopy locations were selected. Canopy locations fell directly beneath a canopy structure whereas intercanopy locations did not have a canopy directly above them. At each one of these locations we deployed two microlysimeters: one containing bare soil and the other with a litter layer on top of the soil surface, yielding four treatments: (1) canopy locations with a litter layer (C-L), (2) canopy locations without a litter layer (C-NL), (3) intercanopy locations with a litter layer (IC-L), and (4) intercanopy locations without a litter layer (IC-NL). For each level of canopy cover, a total of 20 individual microlysimeters (except at the lowest level of canopy cover, where only 10 are measured

due to the absence of canopy locations) were deployed at each experiment, resulting in a total of at least 5 replicates for each treatment at each level of canopy cover.

The microlysimeters were metal cylinders 12 cm high with a circular surface area of 254.5 cm<sup>2</sup>. Each microlysimeter was insulated with two layers of commercial insulation material to avoid temperature conductance between the soil inside and outside of the lysimeter and to prevent temperature fluctuation associated with the manipulation of the microlysimeter during the experiments. Each microlysimeter was placed in the soil using a plastic liner that was preinstalled in the soil for ease of access. All microlysimeters were packed with a homogenized mixture of in-situ soil to control for potential soil textural differences between them. The surface of each microlysimeter was leveled with the outside soil surface to minimize unnatural air flow at the near ground boundary layer. Litter bags were built using the design of Throop and Archer (2007) and were 20 x 20 cm in size and made of fine fiberglass window screen (~0.9 mm openings, Phifer Wire Products, Tuscaloosa, Alabama, USA). The litter was collected on site and was 1.5 cm thick in each bag corresponding to the mean thickness of the litter layer under the canopies in the 73% canopy cover transect. Each microlysimeter was equipped with a temperature sensor installed at 5-cm depth (I-button DS1921G, Dallas Semiconductor). These sensors recorded soil temperature every 30 minutes throughout the duration of the soil evaporation experiments.

A soil evaporation experiment was conducted during each of the four main phenological seasons. Full leafout (June 21 – June 29, 2007); leaf senescence (October 11 – October 24, 2007); leafless (February 27 – March 6, 2008), and leaf green-up (May

8 – May 15, 2008). Soil evaporation experiments were initiated with the addition of a pulse of moisture equivalent to 20 mm to each microlysimeter (mean moisture added = 19.78 mm; 95% C.I. = 19.38 – 20.18). This amount of water brings the soil to field capacity to a depth of 10 cm (where most of the evaporation activity is expected to occur — Newman et al., 1997) based on the physical characteristics of the local soils.

Experiments were started when no rainfall events had occurred at the site for at least three weeks, this condition, along with soil moisture measurements at the nearby weather station, allowed us to assume that soils were dry at the beginning of each experiment. The pulse of moisture was simulated by the addition of commercially available ice, which was applied to the microlysimeters the night before the start of evaporation measurements and covered with plastic to minimize moisture losses via sublimation or direct evaporation from the soil surface. The use of ice improves horizontal uniformity in the application of the pulse, slows infiltration rates, creates a more uniform wetting front in the soil profile, and lowers rates of direct evaporation from the surface (Breshears et al., 1997). Soil evaporation measurements began with the removal of the plastic cover approximately 16 hours after the application of moisture, when the ice was completely melted, and all moisture had infiltrated. This time was sufficient for soil temperature to equilibrate with the environmental temperature (data not shown), thereby avoiding the potential effects of soil temperature change on soil evaporation due to ice.

Soil evaporation from the microlysimeters was calculated as the change in weight measured with portable, battery-operated, electronic scales (H-11, American Weigh Scales, Charleston, South Carolina) with 0.5 g precision, capable of accurately measuring

a 0.05% change in gravimetric soil moisture content. Weight measurements were taken every 2 hours during the first 24 hours of the experiment, every 3 hours for the following 12 hours, and subsequently every 24 hours up to the point when mean change in moisture content was not greater than 0.1%, which marked the end of the experiment. Sampling intervals were selected according to previous observations of soil moisture depletion for a 20 mm pulse of precipitation at the site, for which the greater evaporative activity occurs during the first 12 – 15 hours, but continues through a period of more than 50 hours (data not shown). For every measurement, the electronic scale was taken to all locations where microlysimeters were weighed and returned immediately to the soil. Previous literature has described soil evaporation as a two stage function of time, controlled by atmospheric demand and soil supply, that can be described by a linear function of time during the atmosphere-limited phase and subsequently by a non-linear function during the soil-limited phase (Menziani et al., 1999). For further analysis we calculated mean soil evaporation rates (expressed as percent change in gravimetric soil moisture content per hour) for the first 48 hours of the experiments, which corresponded to the period of largest variation in soil moisture content and associated with the atmosphere-controlled period of evaporation.

Solar radiation indices at each location and season were quantified using hemispherical photography. Photographs were taken at 1.0 m above the ground—to capture only the influence of the mesquite-dominated canopy, avoiding any effect of undergrowth—using a horizontally leveled digital camera (CoolPix, 5400, Nikon, Tokyo, Japan), with a fish-eye lens (FC-E9, Nikon, Tokyo, Japan), with a 180° field of view.

Photographs were taken during uniform sky conditions at dawn, ensuring correct contrast between canopy and sky (Rich et al., 1999; Quilchano et al., 2008). Images were analyzed using Hemiview canopy analysis software version 2.1 (1999 Delta-T Devices, Ltd., Cambridge, UK — Rich et al., 1999). We calculated the Direct Site Factor (DSF), which is the proportion of direct solar radiation reaching a given location over a year, relative to that in the same location with no sky obstructions, under clear sky conditions. This approach accounts for obstructions imposed by plant canopies and surrounding topographic features, if present, over an entire course of a year, or for a particular month of the year, assuming clear sky conditions. In our analysis we used monthly values of DSF, which incorporate the variation in solar radiation input associated with the seasons.

Mean hourly meteorological data was recorded for each experiment using a standard weather station located close to the 2% canopy cover plot, approximately 200 m from the farthest cover plot (73% canopy cover). We obtained hourly averages of air temperature and humidity (CS500-L. Campbell Scientific, Logan, USA); wind speed, measured at 3 meters above the ground (034B wind sensor, Met One instruments, Inc, Grants Pass, Or, USA); and total incoming solar radiation (LI200X-L Li-Cor Inc. Lincoln, USA). Vapor pressure deficit (VPD) was calculated from temperature and relative humidity measurements.

#### *Data analysis*

To generally characterize the climate seasonality at the site, non-parametric Friedman's rank tests were performed for the meteorological variables (air temperature, wind speed, vapor pressure deficit and incoming solar radiation) recorded at the nearby

weather station. This test identifies differences in the mean values of the variables through pairwise comparisons of their values throughout the duration of the experiments.

We calculated soil drying curves as a function of time during the atmosphere-controlled period of evaporation for each patch type at each season (representing cumulative soil evaporation through time). Both linear and non-linear models for cumulative soil evaporation during the first 100 h of soil drydown were fitted, with the most significant fit always occurring with 2<sup>nd</sup> order polynomials. The resulting functions were all of the form: *Cumulative Soil Evaporation (mm) = at+bt<sup>2</sup>*, where *t* represents the hours of drying time.

To define the factors that influenced soil evaporation at each season, we performed stepwise multiple linear regression analyses with soil evaporation rate — expressed as the mean rate for the first 48 hours of the experiment— as the dependent variable and canopy cover, DSF, soil temperature, presence of a litter layer and patch type (canopy or intercanopy) as the independent variables. For each season we performed individual correlation analyses between canopy cover, DSF, temperature and soil evaporation rate for each treatment type. These analyses allowed us to evaluate the significance of specific relationships between variables that drive soil evaporation dynamics at all phenological stages. All correlations reported were significant at the P=0.05 level. All the analyses were performed using SPSS v. 11.0 and Matlab v.7.7.0.471.

## Results

Our Friedman's rank test analysis shows that air temperature and vapor pressure deficit varied significantly among experimental periods, except between leaf green-up and leaf senescence when they were similar. Wind speed was significantly lower during the full leaf out experiment, while having higher instantaneous values during the leaf senescence experiment. Solar radiation varied as expected through the experiments, although during leaf senescence, radiation was lower, likely due to cloudy conditions during the experimental period, making it not significantly different than incoming solar radiation during the leafless period (Table 1).

Monthly DSF values varied with season, in response to the seasonal variation of solar radiation, as well as to the phenological dynamics of *Prosopis*. The highest values of DSF occurred in the summer and decreased systematically with decreasing available energy (Figure 1A). Within each season, DSF values were higher at intercanopy locations. The difference between canopy and intercanopy locations was more pronounced during the full leafout season, when foliage was at its maximum. Soil temperature also varied systematically with season. However, there were no significant differences between treatments within season (Figure 1B). Soil evaporation rates of a given patch were consistently higher during the full leafout experiment at locations where litter was absent compared to when litter was present; but similar significant differences for other seasons were not detectable (Figure 1C).

We fitted soil drying curves for the initial 100 hours of drydown, corresponding to the atmosphere-limited period of evaporation, for each treatment at each season.

Regression models were significant at the  $p=0.001$  level, with  $r^2$  values greater than 0.96 in all cases. Regression analyses show that soil evaporation dynamics varied for each patch-type and season, but most importantly, between locations with a litter layer and those without one. Soil evaporation rates generally decreased with decreasing seasonal energy availability, with the highest rates of evaporation occurring during the full leafout season at *intercanopy-no litter* locations and the lowest rates at *canopy-litter* locations in leaf senescence and leafless seasons (Figure 2). It is worth noting that the best fit was obtained from a second order polynomial. However, the second order coefficients are very low, which concurs with previous theoretical descriptions of a linear decrease in soil moisture during the atmosphere-limited period of the soil evaporation curve (Menziani et al., 1999).

The results from our stepwise multiple linear regressions show that soil evaporation varied systematically with canopy cover, DSF, soil temperature, surface cover, presence of a litter layer on the soil and location (canopy/intercanopy locations) throughout the seasons (Table 2). Notably, for all seasons, the presence of a litter layer in the soil was the most important factor influencing soil evaporation. In particular, during the full leafout period, when no energy limitation is expected, only litter controls soil evaporation. In contrast, during the leafless season (the coldest, more energy limited season), an additional energy-associated limitation (temperature) follows the presence of a litter layer controlling soil evaporation. Finally, during the intermediate seasons (green up and leaf senescence), other energy-related variables are also instrumental on

controlling soil evaporation, specifically canopy cover and soil temperature for the green up season and temperature and patch type during the leaf senescence season (Table 2).

Our correlation analyses between individual variables associated with key drivers of soil evaporation suggest that the controls on soil evaporation vary among seasons and among levels of canopy cover (Appendix figure 1). For the full leafout period, soil evaporation was positively correlated with DSF and temperature for the *canopy-litter* treatment and there is suggestive evidence of a significant correlation with overall canopy cover for *intercanopy-litter*. During the green-up period, soil evaporation was negatively correlated with overall canopy cover for the *intercanopy-no litter* treatment and negatively correlated with temperature at the *intercanopy-litter* and *intercanopy-no litter* treatments. During the leaf senescence period, soil evaporation was negatively correlated with overall canopy cover at the *canopy-litter* treatment and positively correlated with temperature at the *intercanopy-no litter* treatment, where overall canopy cover was also negatively correlated with DSF, which in turn was positively correlated with temperature. Finally, during the leafless period, soil evaporation was positively correlated with temperature at all intercanopy locations, and negatively correlated with overall canopy cover at the *intercanopy-no litter* locations (Appendix figure 1).

## **Discussion**

Our design allowed us to experimentally assess interactive controls on soil evaporation with respect to a hierarchical structure spanning from the presence or absence of litter, up to the canopy patches of woody plants and the intercanopy patches separating them, through the overall vegetation mosaic characterized by density of woody

plant cover, as well as with respect to seasonality/phenology. Notably, we found that litter exerts a dominant control on soil evaporation—a result that was robust across seasons but amplified during the main precipitation seasons at the site (full leafout and leafless seasons; Table 2). The presence of a litter layer in the ground controls soil evaporation via two basic mechanisms: though the attenuation of radiation flux into and from the ground (Baldocchi et al., 2000; Wilson et al., 2000) and by increasing the resistance to water flux from the ground (Sakaguchi and Zeng, 2009). The combined effect of these two mechanisms produced by litter cover apparently provides such a strong control on soil evaporation that other components of hierarchical structure (patch and mosaic scales) are essentially overwhelmed and seasonality and phenology only modify the magnitude of this effect. However, in the absence of litter, both patch and mosaic attributes can influence soil evaporation when climate is moderate, and when phenology is at an intermediate stage (e.g., patch effect during leaf senescence and mosaic effect during green up; Table 2); in these cases the degree of control appears to be moderate and the causes are perhaps more complex, varying with season/phenology. Collectively, our results highlight that both hierarchical vegetation structure and seasonal/phenological variability can influence soil evaporation.

Our analysis of correlations from related measures of incoming energy (DSF and soil temperature), as well patch type and vegetation mosaic, suggests that energy limits evaporation in many cases. This insight is indicated most directly by correlations between soil temperature and evaporation rates (e.g., *intercanopy/no litter* during leaf senescence and leafless seasons; *intercanopy/litter* during leafless season, and

*canopy/litter* during full leafout; Appendix figure 1). The seasonal/phenological variability in these responses as a function of patch type are consistent with expected trends—when it is hottest, the effect of soil temperature is apparent only in the most covered locations (*canopy/litter*), while when it is cooler, the effect is apparent in the intercanopy locations. Under specific conditions (*intercanopy/no litter* during the leaf senescence season), a progression of correlations (canopy cover-DSF, DSF- temperature, temperature-evaporation) indicates that the effect of the vegetation mosaic (reflected in amount of canopy cover) on energy can also limit soil evaporation (Appendix figure). In the absence of litter during the hottest season, lack of correlations with energy metrics may be indicative of a lack of energy limitation (*canopy/no litter* and *intercanopy/no litter* during full leafout); conversely, lack of correlation with energy metrics during the coolest season may be indicative of dominant energy limitation (*canopy/litter* and *canopy/no litter* during leafless season). Although we focused in this study on the potential influence of energy on soil evaporation, using incoming near-ground solar radiation and soil temperature as proxies for energy, in several cases energy alone was insufficient to explain variation in soil evaporation. In several such cases, however, canopy cover is correlated directly with soil evaporation, yet other correlations that would indicate that this relationship was associated with limitations on energy (DSF-temperature and temperature-evaporation) are lacking (*intercanopy/litter* during leafout, *intercanopy non-litter* during green-up, *canopy/no litter* during leaf senescence, and *intercanopy/no-litter* during leafless), thereby requiring consideration of alternative hypotheses about controlling mechanisms. Although we lack data to resolve this

uncertainty, we speculate that this could be due to the other fundamental driver of evaporation besides energy—turbulence due to wind (McNaughton, 1986; Kurc and Small, 2004; Baldocchi and Xu, 2007); this speculation requires testing with additional research. Collectively, our results did not indicate a simple set of energy limitations, but rather, when considered in concert with recognition of both energy and wind as drivers of evaporation (McNaughton, 1986; Kurc and Small, 2004; Baldocchi and Xu, 2007), suggest a framework of hypotheses for further testing the relative controls on soil evaporation as related to hierarchical vegetation structure and season/phenology (Figure 3).

Regardless of the specific mechanisms and their relative roles in driving soil evaporation with respect to hierarchical vegetation structure and season/phenology, the spatiotemporal differences that we quantified potentially have important ecohydrological implications. Notably, in drylands, the presence of a litter layer in the soil, not only affects processes such as evapotranspiration and land surface-atmosphere interactions, but also has important implications for other critical ecosystem dynamics associated with biogeochemical processes involving carbon and nitrogen in the soil. The enhanced moisture retention in the litter, associated with lower evaporation rates and increased water holding capacity can potentially favor soil respiration and decomposition, often limited by moisture in this type of ecosystems (Mazzarino et al., 1991; Conant et al., 2004; Scott et al., 2006; Raiesi and Asadi, 2006; Throop and Archer, 2008; McIntyre et al., 2009). In conclusion, our results that discuss vegetation-imposed limitations on soil evaporation at multiple temporal and spatial scales highlight the need to account for both

hierarchical vegetation structure and seasonal/phenological variability to improve ecohydrological predictions of soil evaporation.

***Acknowledgments.*** We thank Mitch McClaran and Mark Heitlinger at Santa Rita Experimental Range for logistical and technical support. We also thank Henry Adams, Colleen Boodleman, Jennifer Davison, Jason Field, James Luo, Patrick Royer and Haiyan Wei for assistance on initial experimental design, field site selection, plot establishment, and experimental support. JCV was supported by the DNP/ Fulbright/Colciencias scholarship, by the University of Arizona Technology and Research Initiative fund 2007/2008 and by B2 Earthscience at Biosphere 2 through the Philecology Foundation. DDB was supported by Arizona Agricultural Experiment Station.

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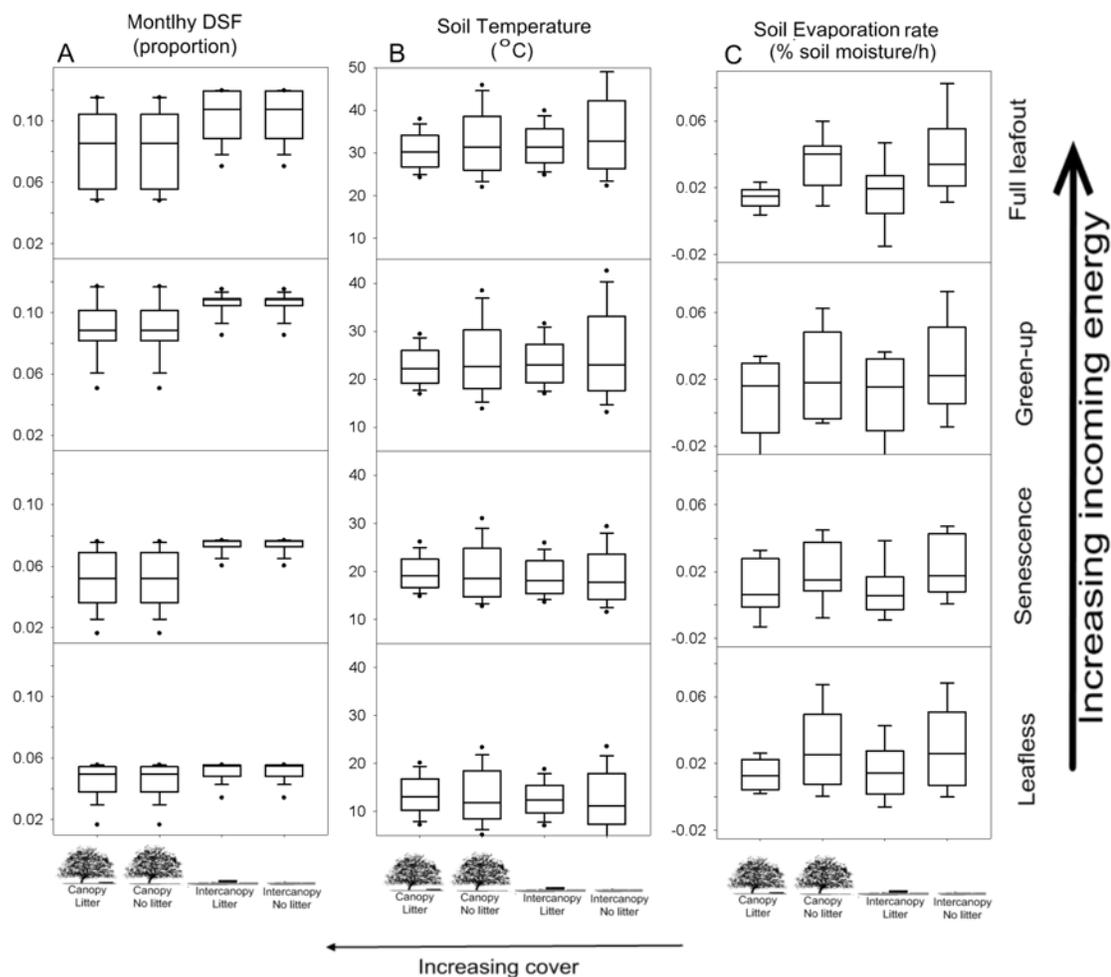
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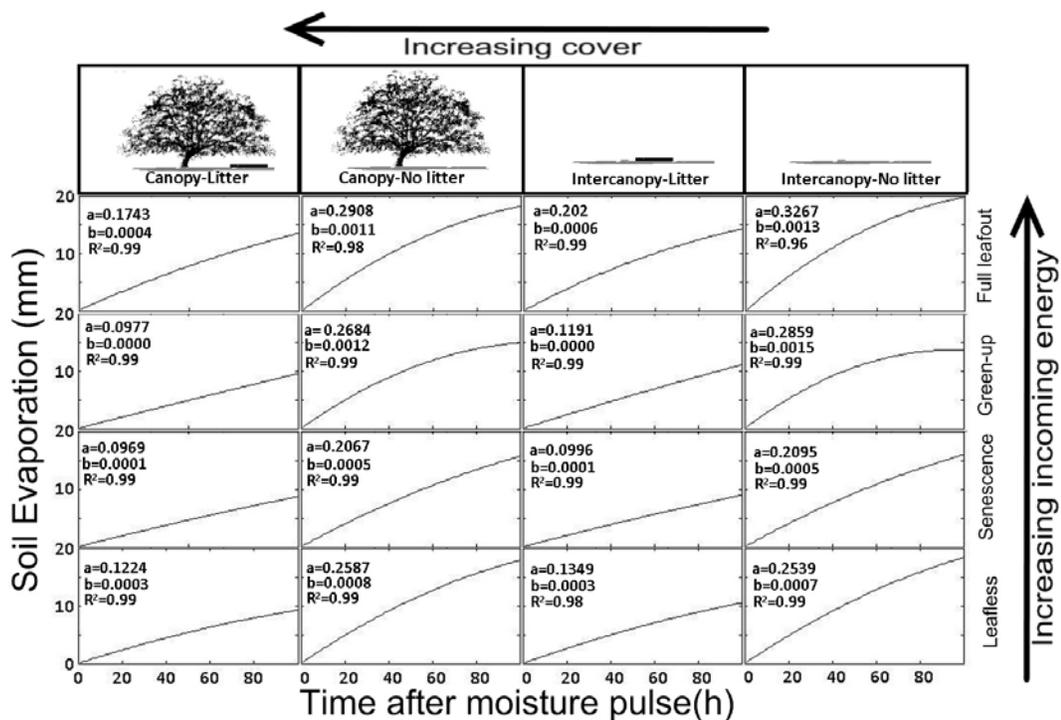
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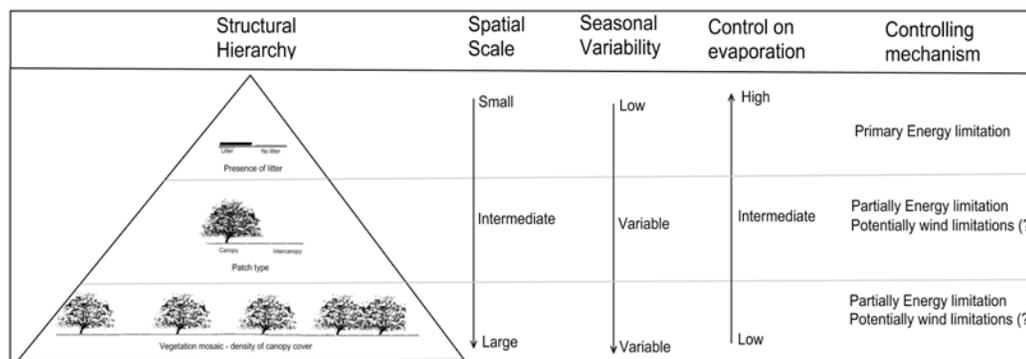
## Figures



**Figure 1.** Distribution of (A) mean monthly values of direct site factor (DSF), (B) soil temperature ( $^{\circ}\text{C}$ ), and (C) soil evaporation rates (% gravimetric/h – for the first 48 hours of drydown), for each patch type during soil evaporation experiments performed at the full leafout, green up, leaf senescence and leafless phenological seasons.



**Figure 2.** Soil evaporation (mm) curves as a function of time (h) for all patch types and seasons. Equations are of the form  $Soil\ Evaporation\ (mm) = at_1 + bt_2^2$ . Values of  $a$  and  $b$  parameters and  $r^2$  for each condition are presented above the curve. All regression models are significant at  $p=0.001$  level.



**Figure 3.** Control and hypothesized controlling mechanisms of soil evaporation at the hierarchical structure of vegetation cover (including litter, patch and vegetation mosaic scales) in response to season/phenology dynamics.

## Tables

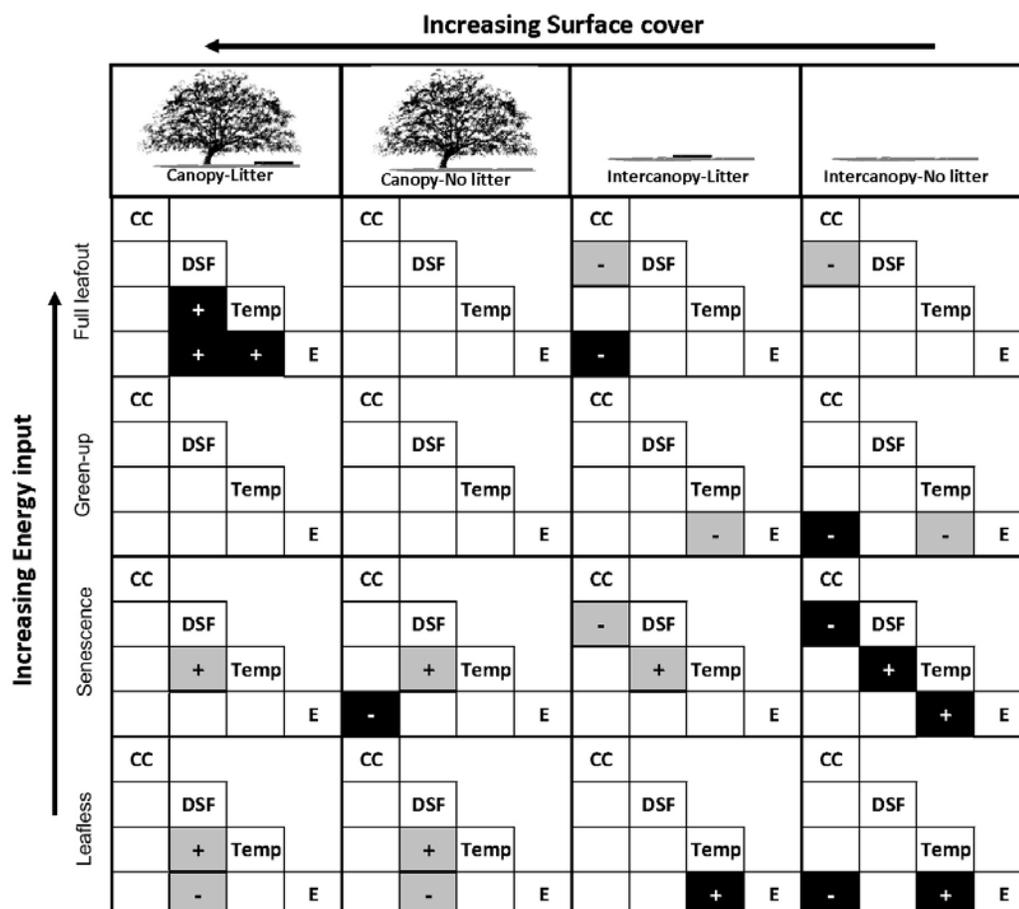
**Table 1.** Results from Friedman's rank test analysis, used to characterize the variation in mean meteorological conditions at the site during the experimental periods . Shaded cells indicate significant differences between seasons at an alpha level of 0.05.

	<b>Leaf senescence</b>	<b>Leafless</b>	<b>Leaf green-up</b>
<b>Air temperature</b>			
<b>Leafout</b>	p<0.0001	p<0.0001	p<0.0001
<b>Leaf senescence</b>		p<0.0001	0.05<p<0.10
<b>Leafless</b>			p<0.0001
<b>Wind speed</b>			
<b>Leafout</b>	p<0.0001	p<0.0001	0.0001<p<0.0005
<b>Leaf senescence</b>		p>0.20	p>0.20
<b>Leafless</b>			p>0.20
<b>VPD</b>			
<b>Leafout</b>	p<0.0001	p<0.0001	p<0.0001
<b>Leaf senescence</b>		p<0.0001	0.05<p<0.10
<b>Leafless</b>			p<0.0001
<b>Solar Radiation</b>			
<b>Leafout</b>	0.005<p<0.01	0.025<p<0.05	p>0.20
<b>Leaf senescence</b>		p>0.20	0.025<p<0.05
<b>Leafless</b>			0.10<p<0.20

**Table 2.** Results from stepwise regression analyses indicating the main environmental drivers of soil evaporation for each season. Shaded cells indicate variables that were significant in explaining the variation of soil evaporation using a stepwise regression model. Numbers indicate the importance of each variable on explaining the behavior of soil evaporation.

	<b>Vegetation mosaic</b>	<b>Patch type</b>	<b>DSF</b>	<b>Temperature</b>	<b>Litter layer</b>	<b>R<sup>2</sup></b>	<b>p- value</b>
Leafout					1	0.43	0.0001
Leaf senescence		3		2	1	0.48	0.0001
Leafless				2	1	0.62	0.0001
Leaf green-up	2			3	1	0.61	0.0001

## Appendix Figure



**Appendix Figure.** Correlation matrixes between surrounding vegetation cover (CC), direct site factor (DSF), soil temperature and soil evaporation for all patch types and seasons. Black squares indicate significant correlations ( $p=0.05$ ), with the sign indicating the direction of the correlation. Gray squares indicate correlations that although significant, are not readily attributable to soil evaporation and/or their sign does not reflect an expected physical process influencing soil evaporation.

## APPENDIX D

## PARTITIONING EVAPOTRANSPIRATION ACROSS GRADIENTS OF WOODY PLANT COVER: ASSESSMENT OF A STABLE ISOTOPE TECHNIQUE

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Document type: Accepted in press in *Geophysical Research Letters* (May 2010)

**Abstract:** In water-limited ecosystems, partitioning ecosystem-scale evapotranspiration fluxes between plant transpiration and soil/canopy evaporation remains a theoretical and technical challenge. We used the Biosphere 2 glasshouse to assess partitioning of evapotranspiration across an experimentally manipulated gradient of woody plant cover using continuous measurements of near-surface variations in the stable isotopic composition of water vapor ( $\delta^2\text{H}$ ). Our technique employs a newly-developed laser-based isotope analyzer and the Keeling plot approach for surface flux partitioning. The applicability of the technique was verified by comparison to separate, simultaneous lysimeter and sap flow estimates of *ET* partitioning. The results showed an expected increase in fractional contribution of transpiration to evapotranspiration as woody cover increased—from  $T/ET=0.61$  at 25% woody cover to  $T/ET=0.83$  at 100%

cover. Further development of this technique may enable field characterization of evapotranspiration partitioning across diverse woody cover gradients, a central issue in addressing dryland ecohydrological responses to land use and climate change.

### **Introduction**

In water-limited ecosystems, evapotranspiration (*ET*) losses can account for more than 95% of all water inputs (Wilcox and Thurow, 2006). It is essential to partition *ET* between transpiration and evaporation in drylands for at least three reasons: 1) Dryland ecosystem dynamics depend on plant water use and plant water use efficiency, which can only be measured at landscape scales by separating transpiration fluxes from soil/canopy evaporation; 2) Dryland regional water scarcity and demographic pressures necessitate quantifying processes that control the relative magnitude of unproductive (e.g., bare ground evaporation) vs. productive water losses (e.g., transpiration) (Rockstrom et al., 2009) in both managed and natural ecosystems; and 3) Determining relative amounts of evaporation and transpiration is necessary to resolve critical uncertainties regarding the coupling of water and carbon/nutrient cycles in drylands (Austin et al., 2004; Breshears, 2006). However, partitioning of *ET* at landscape scales within drylands across different amounts of woody plant cover remains both an observational and theoretical challenge (Huxman et al., 2005; Caylor et al., 2006; Moran et al., 2009), mainly due to the lack of methodologies available to quantify large-scale evaporation or transpiration in an easy and reliable way. For example, estimates of the percentage of annual evapotranspiration attributable to transpiration at similar sites in the Sonoran desert range from 7% (Sammis and Gay, 1979) to 80% (Liu et al., 1995).

Common methodologies for the estimation of field-scale transpiration rates include use of individual-tree sap flux (Jackson et al., 2000), whole tree chamber observations (Wullschleger et al., 1998), and paired soil lysimeters (Scanlon et al., 2005); each of these methods suffer from poor spatial representation. More recently, researchers attempted to partition daily-scale evapotranspiration using time series of soil surface temperature (Moran et al., 2009). Although this method can be applied over large spatial scales, it depends on consistency in the relationship between soil moisture and transpiration over the entire growing season.

Stable isotopes of water vapor hold great potential for resolving transpiration and evaporation fluxes from patch (*e.g.*, 100 m<sup>2</sup>) (Newman et al., 2010) to landscape scales (Walker and Brunel, 1990). The process of evaporation is accompanied by a high degree of isotopic fractionation that leads to evaporated water with an isotopic composition depleted in heavy isotopes (Craig and Gordon, 1965). Isotopic composition is denoted using  $\delta$  notation, where  $\delta = (R/R_{vsmow} - 1) \times 1000$ , where  $\delta$  is measured water vapor isotope composition ( $\delta^{18}\text{O}$  or  $\delta^2\text{H}$ ),  $R$  and  $R_{vsmow}$  are the heavy/light isotope ratios of samples and the international standard (*VSMOW*). At the same time, the rapid turnover of water in transpiring leaves means that the signature of transpiration is usually similar to the isotopic composition of plant source water, especially during midday (Ehleringer and Dawson, 1992). While some isotopic enrichment can occur in the leaf due to the same kinetic and diffusive effects that lead to evaporative fractionation in soils (Flanagan et al., 1991), these non-steady-state leaf-scale effects usually occur only during early morning hours (Flanagan et al., 1991). Therefore, the isotopic composition of

transpiration ( $\delta_T$ ) is always much heavier than the isotopic composition of evaporation ( $\delta_E$ ) (e.g., Craig and Gordon, 1965) and the distinct isotopic signature of these two fluxes can be used to partition total  $ET$  into relative rates of evaporation and transpiration in landscapes.

Traditionally, researchers use cold-trap methods for water vapor sample collection, which attempts to completely condense water vapor contained within an air sample for laboratory analysis. The difficulty regarding collection and analysis of water vapor samples using cold traps has limited most studies to either chamber scales (Yepez et al., 2005), or to temporally coarse observations (Williams et al., 2004). Recently, laser-based isotope instruments began to make direct and continuous water vapor  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  measurements possible, with precision similar to traditional cryogenic based isotope methods (Wang et al., 2009).

In this study, we develop and evaluate a new technique for evapotranspiration partitioning that is targeted towards field-scale application. The method uses a recently developed laser-based isotope analyzer and a Keeling-plot approach to determine the partitioning of evapotranspiration across a gradient of fractional woody cover obtained through experimental manipulation in the Biosphere 2 facility. This new technique provides, for the first time, evapotranspiration partitioning for across a range of fractional woody cover, and provides important experimental data regarding the effect of woody cover on evapotranspiration partitioning in drylands. We verify the applicability of the technique using independent lysimeter and sap flow measurements (Villegas et al., in preparation).

## Materials and Methods

### *Experimental Setup*

Our evapotranspiration experiments were performed within the Biosphere 2 glasshouse in Oracle, Arizona between September and October 2008. The advantage of Biosphere 2 is that the Biosphere 2 facility allows for more control of environmental variables such as temperature, relative humidity, and air circulation; details on the size, environmental control, and gas exchange of the biome can be found elsewhere (Barron-Gafford et al., 2007). In addition, the experimental framework of altering woody cover would be much more difficult to conduct in a non-greenhouse facility, where logistics of moving and weighing large potted tree containers would be very difficult. Most importantly, this facility ensures the source water for *E* and *T* are the same and that rainfall does not contribute to the water balance during the experiments. The measurements were taken over vegetation arrangements that were comprised of a 10 × 10 grid of containers (each 60 × 60 cm with depth of 80 cm). Each container was occupied by either bare soil or planted with a 2 meters tall single mesquite tree (*Prosopis chilensis*) on the same soil. Soils were sandy loam texture and were taken from local Sonoran desert soils. We evaluated four arrangements that contained 25%, 50%, 75% and 100% woody plant canopy cover (the remaining canopy windows corresponded to bare soil containers). For each vegetation arrangement, all containers were saturated with tap water and allowed to drain for 16 hours to reach field capacity.

*Continuous measurements of  $\delta_{ET}$ ,  $\delta_E$ , and  $\delta_T$*

We measured  $\delta_{ET}$  (the  $\delta^2\text{H}$  composition of the evapotranspiration flux) using the “Keeling plot” approach [e.g., Keeling, 1958; Lee et al., 2007] applied to data from the period during which water vapor concentration and  $\delta^2\text{H}$  were most variable and corresponding to when plants were most active (10 am-7 pm). We sampled gas at heights of 0.5, 1.0 and 2.0 m at the center of the container arrangement into a ring-down cavity infrared spectrometer designed for water vapor isotope and water vapor concentration analysis (WVIA, Los Gatos Research Inc., CA), which was covered by a tarp to avoid direct solar radiation and provide temperature stability. The WVIA was calibrated before and after each measurement period using the procedure described in Wang et al. (2009). The WVIA recorded  $\delta^2\text{H}$  and water vapor concentration (ppm) measurements every 2 s during each 90 s measurement interval. Each measurement interval was buffered before and after the sample by a 30 s interval to avoid transient effects of switching among sampling locations, and measurements for each height were repeated every 15 min.

An estimate of  $\delta_E$  for soil evaporation was obtained using the Craig-Gordon

model (Craig and Gordon, 1965): 
$$\delta_E = \frac{\alpha\delta_L - \delta_A h - \varepsilon_K - \varepsilon^*}{(1 - h) + 10^{-3}\varepsilon_K} \quad (1),$$
 where  $\delta_E$  is the

isotopic composition of water evaporated from the soil;  $\alpha$  is the temperature-dependent equilibrium fractionation factor, which can be calculated based on soil temperature

(Majoube, 1971);  $\delta_L$  is the isotopic composition of liquid water at the evaporating front;

$\delta_A$  is the isotopic composition of the background atmospheric water vapor;  $\varepsilon^*$  is

calculated as  $(1-\alpha) \times 1000$ ;  $\varepsilon_K$  is the kinetic fractionation factor for hydrogen (16.4‰ for

non-turbulent conditions and 10.9‰ for turbulent transport (Cappa et al., 2003)); and  $h$  is the relative humidity normalized to the soil temperature. The  $\alpha$  value was 0.9393 based on Biosphere 2 temperature data (39°C) and following equilibrium equations of Majoube (1971). We estimated  $\delta_L$  by measuring the isotope composition of irrigated water using a Los Gatos Research liquid water analyzer at the University of Arizona. A value of 16.4‰ was used for  $\epsilon_K$ , which corresponds to laminar conditions (Cappa et al., 2003). The  $\delta_A$  was measured using WVIA. The  $h$  values (0.25-0.30) were obtained from the Biosphere 2 humidity monitoring data.

To directly estimate  $\delta_T$  for plant transpiration from water vapor, we used two direct approaches, which contrasts with previous approaches that indirectly estimate  $\delta_T$  from measurements of extracted liquid leaf water or from leaf water enrichment calculations for non-steady state conditions (e.g., Yopez et al., 2005). Our first approach was to measure transpiration within a customized leaf chamber subjected to a 100% di-nitrogen atmosphere. Leaves used to determine the isotopic signature of transpiration were sealed inside the chamber, which had a small mixing fan, air temperature corresponding to that inside the glasshouse, and was flushed and purged with ultra-high purity nitrogen. Two sets of 20-min (at 0.5 Hz) measurements of  $\delta^2\text{H}$  (600 samples total) were obtained from each of two different branches; data were averaged by branch. Our second approach was to obtain measurements from branches within a LICOR-6400 standard leaf chamber (6400-02B) exposed to ambient air that had been passed through Drierite. We estimated  $\delta_T$  of plant transpiration for averages of three different 5-min

sampling periods (450 samples total). All chamber measurements of the isotopic composition of transpiration were obtained under sunny conditions between 1 and 3 pm.

*Evapotranspiration partitioning calculations*

Assuming a simple 2-source model of total evaporation, the fractional contribution of transpiration ( $F_T$ , [0-1]) to total evapotranspiration can be quantified

as  $F_T = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} = \frac{T}{ET}$  (2), where  $\delta_{ET}$ ,  $\delta_E$  and  $\delta_T$  are the isotope signatures of evapotranspiration, evaporation and transpiration, respectively (Williams et al., 2004).

Because our experimental system consists of soil-filled boxes either with or without single-stemmed mesquite trees, bare soil evaporation can be further partitioned into bare soil evaporation from under tree canopies ( $E_v$ ), and bare soil evaporation from locations unoccupied by tree canopies ( $E_b$ ). To determine the relative contribution of bare soil evaporation to total  $ET$ , we took advantage of the fact that when the experimental tree

cover is 100% the only contributions to  $ET$  are  $T$  and  $E_v$ , so that  $\frac{T_{100}}{E_{100}} = \frac{T}{E_v} = \eta_v$  (3),

where  $T_{100}$  and  $E_{100}$  refer to estimated transpiration and evaporation determined during the 100% tree cover treatment, and  $\eta_v$  is the ratio of transpiration to evaporation within boxes occupied by trees. Because in every treatment  $ET = E_b + E_v + T$ , we then

combined Equation (2) and (3) to define the ratio of bare soil evaporation in non-

vegetated boxes to transpiration according to  $\frac{E_b}{T} = \frac{1}{F_T} - \frac{1}{\eta_v} - 1$  (4). Finally, we

defined the ratio of bare soil evaporation to transpiration on a per-unit area basis,  $\eta_s$ ,

which is given by  $\eta_s = \frac{1-f}{f} \frac{T}{E_b}$  (5), where  $f$  is the fraction of vegetation cover in each

treatment. Equation (2) makes it clear that resolving the relative rates of evaporation and transpiration requires knowledge of the isotopic composition of both end members ( $\delta_E$  and  $\delta_T$ ) as well as isotopic composition of the total flux itself ( $\delta_{ET}$ ). We determined  $\delta_{ET}$  using the inverse gradient method (or Keeling plot approach), which has been implemented extensively in CO<sub>2</sub> flux applications, but was also recently used to calculate  $\delta_{ET}$  at ecosystem level [*e.g.*, Lee *et al.*, 2007]. The Keeling plot approach is based on the conservation of mass and can be expressed as  $\delta^2H_a = c_b(\delta^2H_b - \delta^2H_s)(1/c_a) + \delta^2H_s$  (6), where  $\delta^2H_a$ ,  $\delta^2H_b$  and  $\delta^2H_s$  are the isotope signatures of ambient (observed) water vapor, background water vapor and evapotranspiration respectively,  $c_a$  is the ambient water vapor concentration, and  $c_b$  is the background water vapor concentrations.

## Results and Discussion

Temporal dynamics of water vapor concentrations and isotopic composition both exhibited diurnal variation that corresponded to plant activity (Figure 1). Water vapor concentrations increased during the early morning and peaked in the early afternoon before gradually decreasing, regardless of sampling heights and vegetation cover (Figure 1a-d). These results indicate that there are measurable diurnal changes in evapotranspiration in our study system and that such patterns are mainly driven by the cycles of solar radiation, as expected (Villegas *et al.*, 2010). Water vapor concentrations always returned to minimum values at night (Figure 1a-d), indicating a complete exchange of air with the outside atmosphere over 8-10 hours. The water vapor  $\delta^2H$  values also showed clear diurnal patterns. Regardless of sampling heights and vegetation cover, the water vapor  $\delta^2H$  values increased from early morning and peaked around noon

then gradually decreased (Figure 1 e-g). The diurnal changes in  $\delta^2\text{H}$  reflect the plant and soil contributions to near surface atmospheric isotopic signatures. Because the total *ET* was dominated by transpiration and transpiration flux has heavier signals compared with background vapor in this case, when plants start transpiring, the atmospheric isotopic signatures will become more enriched. There were often vertical isotope gradients, particularly during the daytime periods, when  $\delta^2\text{H}$  values were higher at 2 m height. Elevated  $\delta^2\text{H}$  signatures generally corresponded to increases of vegetation cover, indicating the increasing contributions of transpiration to total evapotranspiration.

The two methods of characterizing plant transpiration  $\delta^2\text{H}$  signatures differ in their results. The customized chamber method produced a value of -62.1‰, while the LICOR method produced a value of -74.1‰ (Figure 2a-b). Because the irrigation water  $\delta^2\text{H}$  value was  $-63.3 \pm 0.1\text{‰}$ , we only used the chamber method results within our evapotranspiration partition calculations, since this method is more consistent with the expectation that plant transpiration should not result in fractionation. The light LICOR result (~10‰) is most likely caused by contamination of a small amount of ambient water vapor, which had a  $\delta^2\text{H}$  value of around -110‰. There are very few direct measurements of plant transpiration isotopic composition in the literature (e.g., Lai et al., 2005). Given the paucity of direct measurements and the inconsistent results obtained from our different approaches, we expect that future refinement of methods capable of accurately measuring transpiration isotopic composition will have substantial contributions to existing theoretical model predications and explanations of leaf water enrichment during transpiration (Flanagan et al., 1991).

Our calculated evaporation isotopic signature ( $\delta^2\text{H}$ ) was -137‰, which is slightly lower than prior studies in arid environments (e.g., -131‰, (Williams et al., 2004)). As described above, our treatment-level  $\delta_{ET}$  values were calculated using the Keeling plot approach. Notably, our results support the expectation that as woody cover increases,  $\delta_{ET}$  signatures generally increase, due to expected greater contributions of transpiration relative to evaporation (Breshears, 2006). Specifically, the average  $\delta_{ET}$  signatures (10 am-7pm, cf. Methods) are -90.8‰ at 25% woody plant cover, -84.7‰ at 50% cover, -78.4‰ at 75% cover, and -74.7‰ at 100% cover (ANOVA,  $p < 0.001$ , Figure 2c). Because  $\delta_{ET}$ ,  $\delta_E$  and  $\delta_T$  were all measured/calculated independently, the contribution of transpiration to total evapotranspiration ( $F_T$ ) for each level of woody plant cover can be determined (equation 2). Our results showed the expected increase in  $T/ET$  as woody plant cover increases, and  $F_T$  rose from 61% to 83% as vegetation cover increased from 25% to 100% (Figure 2d). The partition values are similar to an independent, concurrent lysimeter and sap flow based measurement that reported  $F_T$  values of 0.36, 0.42, 0.70 and 0.79 for 25%, 50%, 75% and 100% vegetation cover after removing night evaporation (Villegas et al., in preparation). The differences between these two methods range from 4% to 26% with an average of 15.6%. Considering the uncertainties in both sap flow and isotope measurements, the reasonable agreement between these two methods demonstrate the credibility of our new technique. The  $E_b/T$  ratios were 0.43, 0.22 and 0.08 for 25%, 50% and 75% cover, indicating that the relative contribution of bare soil evaporation compared to transpiration rapidly decreases as woody plant cover increases. However, the relative effectiveness of bare soil evaporation per unit area ( $\eta_s$ ) varied only slightly as

cover increased (0.15 at 25% cover, 0.22 at 50%, and 0.23 at 75%), which suggests that in our experiment, the occurrence of sparse and low-LAI canopies have a minimal shading effect on bare soil evaporation. This is consistent with field observations (Villegas et al., 2010).

Our results yield initial insights into how *ET* partitioning can change with woody plant cover, although more general and diverse relationships of *ET* partitioning with woody plant cover remain uncertain and likely vary depending on climate, soils, leaf area and species, among other factors (Huxman et al., 2005; Breshears, 2006). Our experimental design isolated individual containers, precluding belowground connectivity of patches associated with woody plant roots that extend into neighboring patches, as occurs in the field. Such connectivity affects *ET* partitioning at the patch scale between canopy patches of woody plants and the intercanopy patches that separate them (Caylor et al., 2006; Newman et al., 2010), so our reported *ET* partition values at different cover may not be exactly the same as in the field setting.

Our experimental results illustrate the utility of a technique for continuous  $\delta_{ET}$  measurements that enables *ET* partitioning in landscapes. In our experiment, evaporation fluxes only came from bare soil, whereas in natural environments rainfall interception by the vegetation canopy and subsequent evaporation may constitute a significant part of total evaporation. Because evaporation from soil and canopy surfaces are governed by the same principle and has similar signals, this new technique will be able to capture the partitioning of *ET* across many different ecosystems. In areas where soil water evolves much different isotopic composition than rainwater, it may be possible to even further

partition evaporation fluxes between canopy and soil evaporation. Our study also includes development of an approach that directly measures plant transpiration signals, which in the past have been largely estimated by measuring plant source water and modeling water enrichment under non-steady state conditions. Although our technique provides new frameworks and represents important progress, we believe it will be necessary to directly couple high-frequency observations of isotope measurements to eddy covariance systems in order to eliminate the dependence of Keeling plot approaches.

**Acknowledgments.** This project was supported through a National Science Foundation CAREER award to K. Caylor (EAR-847368) and Biosphere 2 Earthscience through Philecology. We are grateful to Dr. Kolby Jardine of University of Arizona for allowing us use of his customized leaf chamber. We greatly appreciate technical assistance received from Maite Guardiola, Dr. Javier Espeleta, Evan Sommer, Ashley Wiede, and Isabel Rivera of University of Arizona and Biosphere 2 support staff.

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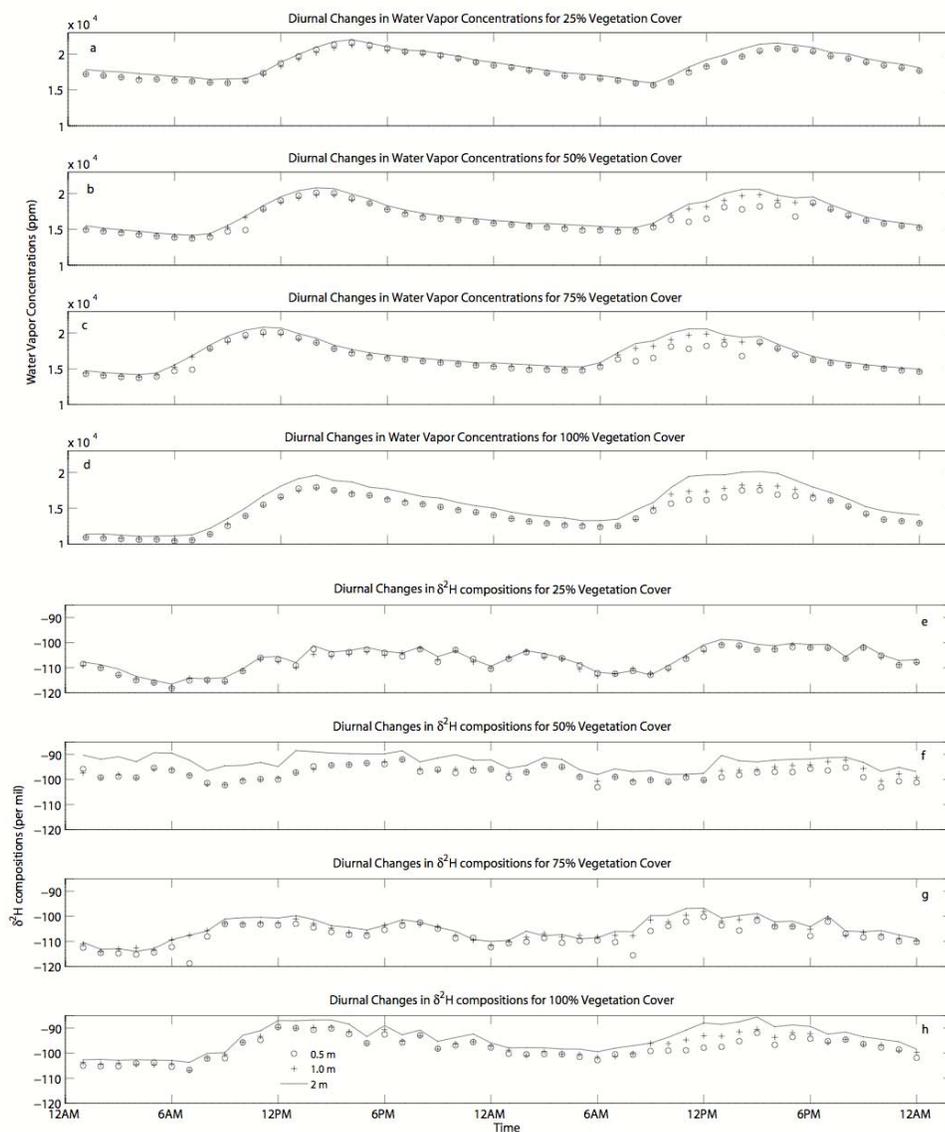
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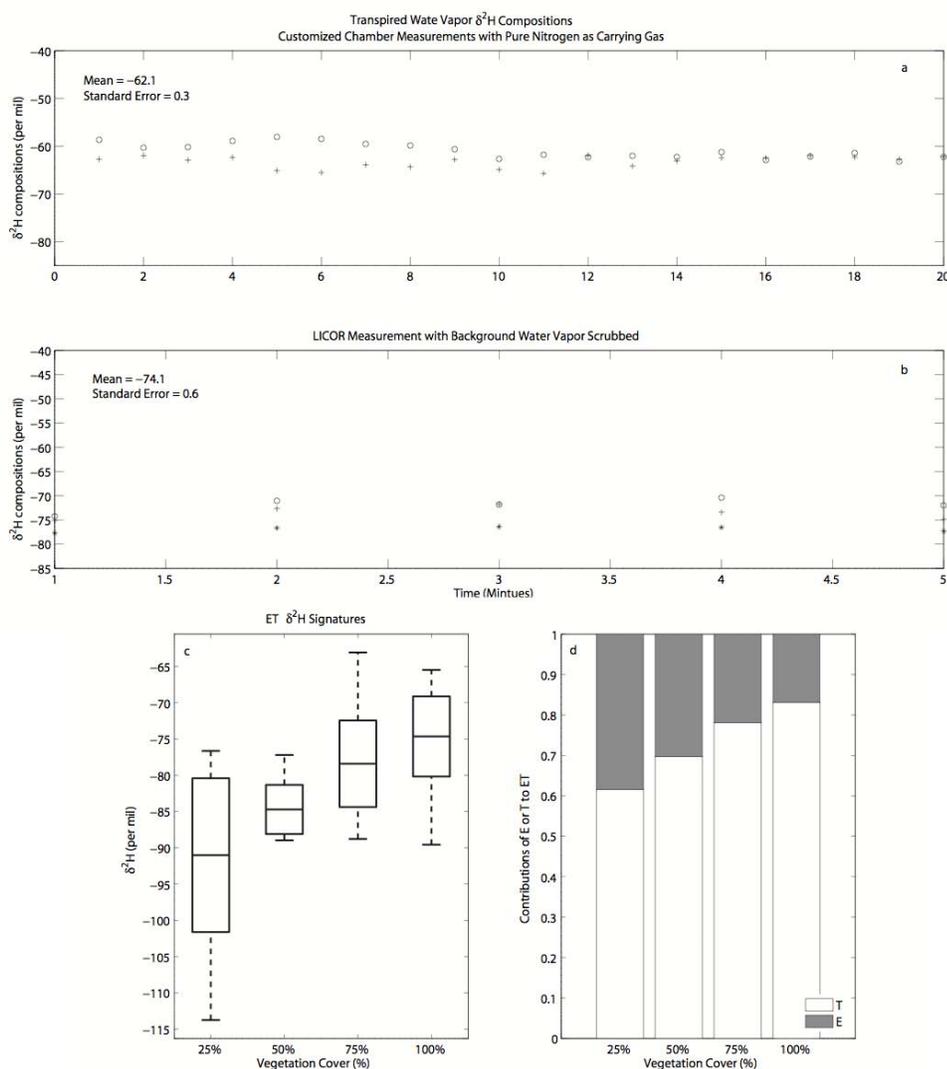
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## Figures



**Figure 1.** Diurnal variations of water vapor concentration (ppm) at different height (0.5 m, 1 m and 2 m) for vegetation cover (a) 25%, (b) 50%, (c) 75% and (d) 100%. Diurnal variations of  $\delta^2\text{H}$  values at different height for vegetation cover (e) 25%, (f) 50%, (g) 75% and (h) 100%.



**Figure 2.** (a) Transpired  $\text{d}^2\text{H}$  signatures measured using a customized chamber with ultra-high purity nitrogen gas as carrying gas and (b) LICOR 6400 leaf chamber with water vapor scrubbing. (c) Calculated evapotranspiration  $\text{d}^2\text{H}$  signatures for different vegetation covers and (d) the contributions of transpiration to evapotranspiration for different vegetation covers.

## APPENDIX E

DEVIATION FROM ASSUMED EVAPOTRANSPIRATION PARTITIONING WITH  
 TREE COVER REALLOCATES LAND-ATMOSPHERE EXCHANGE

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Document type: Manuscript in preparation for submission to Science as of May 1<sup>h</sup> 2010

**Abstract:** Drylands are globally extensive and lose almost all precipitation through evapotranspiration. The partitioning of evapotranspiration between transpiration and evaporation drive key interrelated ecological, hydrological, and atmospheric processes and likely varies with amount of tree cover—a basic land surface variable. However, the lack of controlled measurements has precluded determination of the fundamental nature of this relationship. We experimentally quantified that even in a simplified system, tree cover affects evapotranspiration partitioning non-linearly, contrasting with model assumptions of direct proportionality. When incorporated into a regional surface-atmosphere model, the change in proportionality for this relationship strongly affects

water fluxes. Our results reveal a fundamental ecohydrological relationship that can produce significant deviations in land surface-atmosphere water fluxes relative to those currently predicted, thereby affecting ecological, hydrological, and atmospheric processes.

## **Introduction**

Evapotranspiration is the predominant component of water budgets worldwide and is particularly dominant in globally extensive drylands ecosystems (Zhang et al., 2001; Wilcox et al., 2003; Eamus et al., 2006; Jackson et al., 2009). Because water is limited in drylands, the amount of tree (or shrub) cover is generally partial rather than complete, ranging from grasslands with sparse trees to forests that approach, but lack, complete canopy closure (Belsky and Canham, 1994; Klausmeier, 1999; House et al., 2003; Breshears et al. 2006). The amount of tree cover is a fundamental land surface characteristic that affects key-interrelated ecological, hydrological, and atmospheric processes that drive the exchange of mass and energy with the atmosphere, thereby affecting biogeochemical fluxes of carbon, nutrients and especially water (Bosch and Hewlett, 1982; Sankaran et al., 2005; Scanlon et al., 2005; Breshears 2006; Rotenberg and Yakir, 2010). However, the dynamics of how fluxes of water to the atmosphere, i.e. evapotranspiration, are affected by tree cover remain highly uncertain (McNaughton and Jarvis, 1983; Zhang et al., 2001; Jackson et al., 2009). Not only better estimates of how total evapotranspiration varies with amount of tree cover (or other related metrics such as leaf area index or biomass) are needed, but notably lacking are estimates of how evapotranspiration is partitioned into its two major components (after accounting for

interception losses): soil evaporation and plant transpiration, and how this partitioning is influenced by amount of tree cover—one of the central challenges in ecohydrology (Baldocchi et al., 2004; Huxman et al., 2005; Newman et al., 2006; Moran et al., 2009). Current estimates of evapotranspiration partitioning are often derived from either compilations of site-dependent measurements, or from scaling up transpiration measurements from leaf or individual plant to an ecosystem (Harley and Baldocchi, 1995; Wilson et al., 2001; Williams et al., 2004; Lawrence et al., 2007). Both cases require bridging observations at different scales or applying assumed scaling relationships, that result in considerable uncertainty (Herbst et al. 1996). These limitations preclude a robust determination of the fundamental nature of the relationship between amount of tree cover and evapotranspiration partitioning. In the absence of better information, land-surface atmosphere models often rely for their parameterization on these limited observations or in simplifying assumptions of direct linear proportionality between tree cover and evapotranspiration partitioning (Lawrence et al., 2007). However, previous studies have hypothesized that increasing amount of tree cover should produce a effect on the partitioning of evapotranspiration that deviates this relationship from the direct proportionality and, further, produce a non-linear response associated with the effects of tree cover on both transpiration and direct evaporation: (1) through an increase in transpiration with tree cover, that peaks at intermediate amounts of cover, after where canopies start coalescing and competing for resources, thereby reducing the effective amount of transpiration per unit area; and (2) through a decrease in evaporation that is determined not only by the proportional decrease bare areas, but also

by the effects of woody plants in near-ground radiation availability, wind circulation and surface soil moisture, the drivers of soil evaporation (Huxman et al., 2005; Breshears 2006; Moran et al., 2009; Villegas et al., 2010A; Newman et al., 2010). As a result, the interactions between these mechanisms are expected to produce a non-linear change in the partitioning of evapotranspiration with increasing tree cover, that should notably diverge from a simple 1:1 proportionality expected for non-interactive effects of tree cover on the components of evapotranspiration. Lacking, and largely unfeasible under field conditions, are controlled experiments that assess not only how total evapotranspiration varies with amount of tree cover but, perhaps more importantly, that test the hypothesized trends on the partitioning by simultaneously assessing how soil evaporation and transpiration concurrently vary in response to changes in tree cover.

### **Materials and Methods**

To assess the partitioning of evapotranspiration between soil evaporation and transpiration as a function of amount of tree cover, we designed an experimental study that used the logistical capabilities of the former agricultural/forestry biomes inside the Biosphere 2 glasshouse facility in Oracle, Arizona (USA). Different levels of canopy cover were simulated by establishing regular 10 x 10 grids of containers (each 60 x 60 cm with depth of 80 cm), with either bare soil (consisting of local sandy loam soil) or a planted mesquite (*Prosopis chilensis* – a South American dryland species that is analogous to one of the dominant species in the shrublands of southwestern North America) approximately 2 meters tall. Eight levels of tree cover spanning from 0% to 100% cover were simulated and the partitioning of evapotranspiration was measured for

12 experimental runs spanning these levels of cover between the months of July and October of 2008, with no significant variation in the environmental conditions between runs (Appendix Fig. 2). The spatial configuration of each experimental run, which corresponded to a specific level of tree cover, was defined through randomly-generated positions within the matrix for the containers with trees. Trees assigned to these locations were randomly selected from a pool of 110 available trees. To account for potential edge effects on evapotranspiration, only measurements in the inner 36 containers (a 6 x 6 matrix) were considered in the analysis, leaving 64 containers in the outer 2 rows as a buffer strip. In our experiments, containers with bare soil were sources of evaporation, while containers with trees were sources of evapotranspiration, with transpiration determined by the installation of sap flow sensors in the trees, using the heat pulse technique (Steinberg et al., 1989; Grime and Sinclair, 1999). Sap flow measurements were contrasted with transpiration values estimated as the difference between overall transpiration and overall soil evaporation from the arrangements. Overall evapotranspiration from the arrangement was calculated as the integration of cumulative water loss from individual containers during a dry down period of four days, initiated after all containers were saturated and allowed to drain for 16 hours to reach field capacity. Water loss from each container was measured as the change in gravimetric soil moisture content between the beginning and the end of the drydown. Gravimetric soil moisture was measured using weighing scales (TS-33, Trine's Scale & manufacturing co, inc., Olive Branch, MS, USA) with 0.1 kg resolution (corresponding approximately to 0.06% gravimetric soil water content). Leaf area index values for each level of canopy

cover were estimated as the average leaf area index calculated for each container using hemispherical photography (Rich et al., 1999). Regression analysis was used to define the relationship between the components of evapotranspiration and vegetation cover. All analysis was performed using Matlab R2009b (Mathworks Inc.) and statistical relationships were considered significant at an alpha-level of 0.05. Because the trees were well watered, transpiration was not water limited, and therefore the fact that tree roots are not accessing adjacent intercanopy soil areas (corresponding to the bare soil boxes in our design) as they would under field conditions should not have a substantial effect on estimates of transpiration and the partitioning of evapotranspiration; under drier conditions, this relationship would likely shift, consistent with evapotranspiration partitioning field studies of intercanopy water use by trees (Newman et al. 2010).

To assess the potential ecohydrological consequences of our results, we incorporated our experimentally-derived relationships between vegetation cover and evapotranspiration partitioning into the Advanced Research version (ARW) of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2005). Our decision to use WRF/ARW was based on two considerations: (1) WRF is maintained and supported as a community model to facilitate wide use in the research community; and (2) the code is well documented, modular, and configured to run efficiently in a massively parallel computing environment. Notably, in the original version of the model, total evapotranspiration, which is estimated by constraining potential evapotranspiration with water availability, is partitioned into both direct ground evaporation and transpiration (the variables we directly measured in our experiment) via proportional

linear functions of the shaded fraction (SHDFAC), a variable that represents the percent woody canopy cover for the region. The original and modified version of the equations used to calculate these two variables are presented in Appendix table 2. We ran both the control and modified versions of the regional model for a region in the southwestern U.S., only considering those locations where the model's classification of land cover corresponds to shrublands, dominated by tree species that are analogous to the type of trees that we used in our experiments at Biosphere 2. For our analysis, we used two model-years that corresponded to extremes of precipitation distribution along the North American Monsoon region: 1990 as a typical wetter than average year, with an earlier onset of the monsoon season, and 2000 as a typical dryer than average year in the region (based on high and low values of the Combined Pacific Variability Mode Index, Castro et al., 2007). Climatic and environmental forcing for the model in both years was obtained from NCEP/DOE Reanalysis II data (Kanamitsu et al., 2002). To illustrate the effects of the non-linearity in evapotranspiration partitioning, we computed regional averages of total annual evapotranspiration and direct soil evaporation from the region, as well as the accumulated fluxes during the North American monsoon season, which covers approximately the months of July through September, for both the control and modified versions of the model.

### **Results and discussion**

To assess these hypotheses, we designed an experimental study system for which we could manipulate the amount of tree cover and measure response of evapotranspiration flux and its components within a large controlled glasshouse facility at

Biosphere 2 in Oracle, Arizona USA. More specifically, we evaluated evapotranspiration partitioning in response to different combinations of tree cover ranging from 0 up to 100% tree cover (Appendix methods, Appendix Fig. 1), simulated through spatial arrangements of containers with either bare soil or a mesquite tree (*Prosopis chilensis*). Containers with bare soil were sources of evaporation, while containers with trees were sources of evapotranspiration, for which transpiration was estimated using sap flow sensors in the trees. Sap flow sensors were tested by individual lysimeter measurements and estimations of transpiration for all runs of the experiment were validated by independent calculations in which transpiration was the difference between overall evapotranspiration and soil evaporation (data not shown). We selected trees that were uniform (similar in size and structure), which was reflected in a linear relationship (Fig. 1A) between amount of tree cover and leaf area index (LAI)— a variable used by land surface models to describe vegetation characteristics at surface. Such linear relationship enables a direct linkage between our study and previous modeling efforts that have associated evapotranspiration partitioning to LAI (e.g., Schulze et al., 1994; Lawrence et al., 2007). As expected, total evapotranspiration increased with amount of tree cover (Fig. 1B). This trend was largely reflected in the increase in transpiration with increasing tree cover (Fig. 1C) and associated LAI (Appendix Fig. 2A), but was not present in soil evaporation, which remained relatively constant across all levels of tree cover (Fig. 1D). The increase in overall evapotranspiration with increasing tree cover that we quantify supports previous observations suggesting such an increase in evapotranspiration should occur because, even at the scale of our experiments, trees can use deeper water that is not

available for direct evaporation at the surface (Nepstad et al., 1994; Zhang et al., 2001; Newman et al., 2010). In contrast to the general expectation that soil evaporation should decrease with increasing tree cover (Lin, 2010), as observed in field experiments across a gradient of tree cover with higher values of LAI (Villegas et al., 2010A), the lack of such a relationship may be due to the combination of relatively low values of LAI and the relatively high values of vapor pressure deficit during the experiments (mean  $\pm$  Standard deviation =  $3.10 \pm 1.43$  KPa—Appendix Fig. 1A), consistent with field observations during hot, dry periods (Villegas et al., 2010A). However, when related to total evapotranspiration both the proportion that corresponds to soil evaporation (E/ET in Fig. 2A) and plant transpiration (T/ET in Fig. 2B) exhibit a significant relationship with amount of tree cover (second order polynomial;  $r^2 = 0.87$ ;  $p < 0.0001$ ; Appendix table 1). Although the coefficient in the second order term of the polynomial is not significantly different than zero, the overall quadratic model exhibits a higher  $R^2$  value and lower SSE than a simple linear model, indicating better fitting and explanatory power for the observed variability in the data. Additionally, the physical and biological mechanisms that drive the partitioning of evapotranspiration have been previously hypothesized to generally produce a non-linear effect with increasing amount of tree cover, associated with the magnitude of the non-linear effects of canopy cover on near-ground energy availability and ultimately in soil evaporation (Huxman et al., 2005; Breshears 2006). Notably, independent of the extent of the curvature in the relationship, relative transpiration increased with amount of tree cover, but less than expected if normalized

transpiration increased proportionally—following a 1:1 relationship—with amount of tree cover (and in our case, also with LAI—Appendix fig. 2B).

Our results illustrate a fundamental way in how evapotranspiration is partitioned between soil evaporation and transpiration as a function of amount of tree cover, and is evident in both transpiration and soil evaporation when absolute values of each are considered relative to total evapotranspiration. The slight non-linearity in the partitioning and, notably, the deviation from the 1:1 proportionality do not appear to be due to differences in soil evaporation (Villegas et al., 2010A), but rather from an effect of tree cover on transpiration per unit leaf area. Although overall transpiration increased with tree cover, transpiration per unit leaf area decreased with increasing canopy cover at low to intermediate amounts of cover, and stabilized at intermediate to high levels of tree cover at values smaller than 1.0, which indicates a relative suppression in transpiration with increasing tree cover (Appendix Fig. 2C). A plausible explanation for the relative decrease in transpiration per unit leaf area at these intermediate values of tree cover is density dependent self-shading, as documented in the field (Caylor, et al., 2006; Villegas et al., 2010B). The relative stabilization of transpiration per unit leaf area that occurs at greater values of tree cover (>37%) may reflect a fundamental change in surface roughness of sufficient magnitude to overwhelm the continued effect of self-shading by trees within the matrix (Wolfe and Nickling 1993). In addition, even though a percentage ( $15\% \pm 7\%$ ) of the soil evaporation occurred during nighttime—as also observed in field experiments (Villegas et al, 2010A) and when transpiration is negligible—the

relationship is still slightly non-linear and displaced from the 1:1 proportional in the same direction after accounting for this effect ( $r^2=0.8014$ ;  $p<0.05$ ).

Accounting for the deviation from 1:1 proportionality, and for the modest non-linearity in the relationship between normalized evaporation and transpiration with amount of tree cover that we document has substantial implications for evapotranspiration partitioning at regional scales. To assess these implications, we incorporated the modest non-linearity from our experiments into a widely-used regional surface atmosphere model that originally assumes the partitioning of evapotranspiration to be a linear function of amount of tree cover (Advanced Research version (ARW) of the Weather Research and Forecasting (WRF) Model; Skamarock et al. 2005; Appendix table 2). Using the NCEP/DOE Reanalysis 2 data as lateral boundary forcing, we conducted a simulation for model-years that corresponded to extremes of precipitation availability within the North American Monsoon region, and present the results only for areas where vegetation type was dominated by the “shrubland” land cover class (the appropriate analogue to that used in our experiments given the species studied). The incorporation of the tree-induced variation in the partitioning of evapotranspiration did not represent a statistically significant change in the total annual flux of evapotranspiration from the entire region neither in the wet (Fig. 3A) nor the dry years (Appendix Fig. 3A). However, when considered in a spatially-explicit context, and focusing on the North American monsoon, when the energy and water availability are at their maximum, the effect of changing the parameterization of evapotranspiration partitioning in overall evapotranspiration is more pronounced, inducing reductions in estimated total

evapotranspiration of up to 40% in some areas within the region (Fig 3B; in contrast, such effects were not evident in a dry year suggesting a model sensitivity to annualized ecosystem water availability; Appendix Fig 3B). More important, however, is the effect of replacing the proportional relationship between evapotranspiration partitioning and amount of tree cover by the relationship that we observed, which indicates that the assumption of direct proportionality underestimates annual regional soil evaporation by nearly 200% in both a wet year (Fig. 3C) and a dry one (Appendix Fig. 3C).

Collectively our experimental findings reveal a fundamental ecohydrological relationship that has been previously overlooked and/or omitted due to both technical and theoretical constraints. Our results, which are clearly first approximations to experimentally quantify one of the most important ecohydrological challenges in drylands, illustrate the dynamic and interactive ways in which the amount of tree cover can influence the partitioning of evapotranspiration, the dominant component of the water budget in drylands and many other systems, into direct soil evaporation and plant transpiration. Remarkably, when incorporated into a regional climate model, the relation that we experimentally developed leads to significant changes in the predictions of the proportion of water that is used by plants vs. water that is not, a distinction that has profound ecological, hydrological, atmospheric and biogeochemical implications (Enquist, 2002; Newman, 2006; Scott et al., 2006). Therefore, our results highlight the critical importance of understanding the physical mechanisms that drive fundamental dynamics of land surface-atmosphere interactions. Such fundamental understanding is required to better assess the consequences of current predictions of potential widespread

climate and vegetation change (Zavaleta et al., 2003; Scanlon et al., 2005; IPCC, 2007; Jackson et al., 2009). Most importantly, because current projections of climate change and vegetation change are derived from models, our results provide an important field of improvement for such models and their predictions of the couplings between energy, water and other biogeochemical cycles at scales ranging from the local to, eventually, the global scale.

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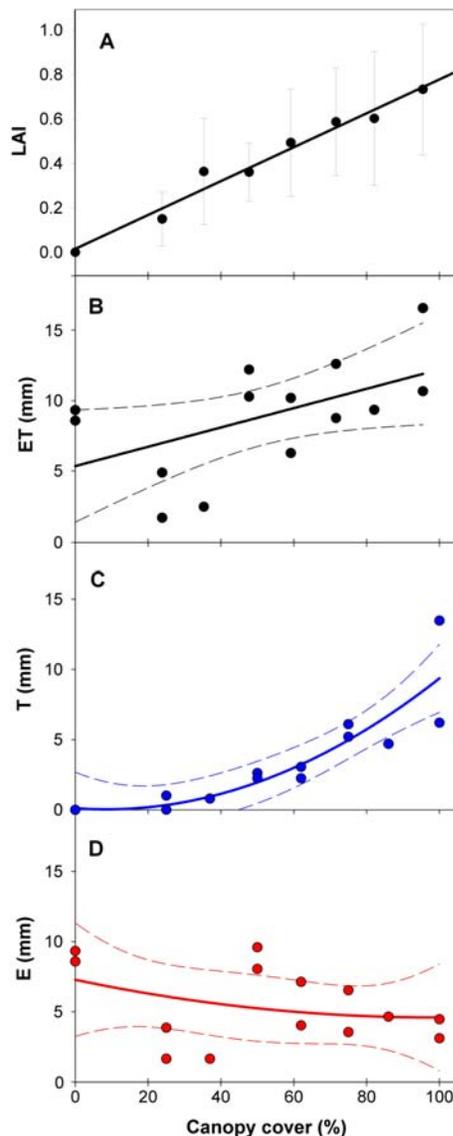
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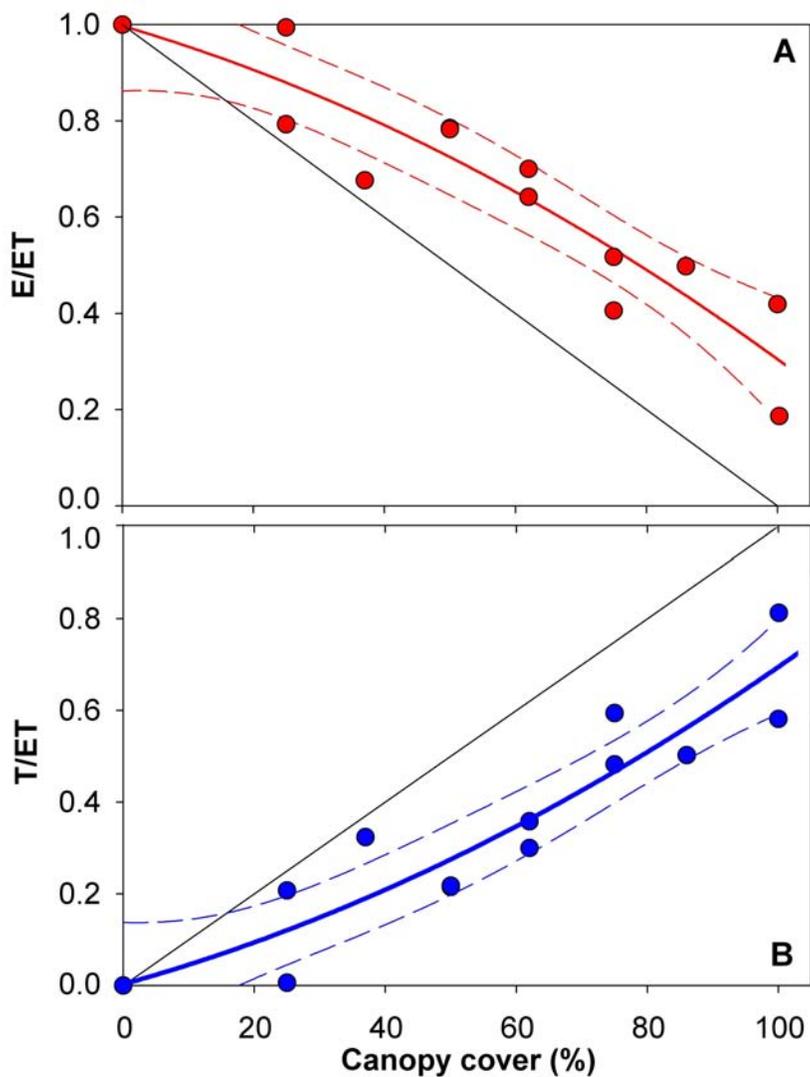
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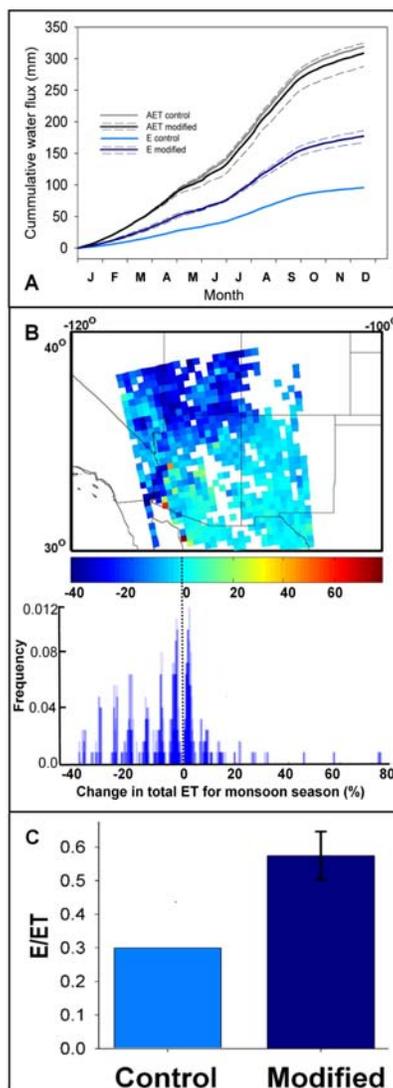
## Figures



**Figure 1.** (A) General relationship between amount of tree cover (represented by the proportion of boxes with trees) and leaf area index (LAI) in our experimental system, error bars are standard deviations for estimated LAI ( $p < 0.0001$ ;  $R^2 = 0.9712$ ). (B) Absolute amount of evapotranspiration as a function of amount of tree cover ( $p = 0.046$ ;  $R^2 = 0.02917$ ). (C) Total tree transpiration as a function of tree cover ( $p = 0.0001$ ;  $R^2 = 0.7997$ ). (D) Total soil evaporation as a function of tree cover ( $p = 0.2587$ ;  $R^2 = 0.1049$ ). Each point corresponds to the average cumulative water loss for a drydown period of four days in an arrangement of 36 containers. Dotted lines indicate 95% confidence intervals around the fitted line.

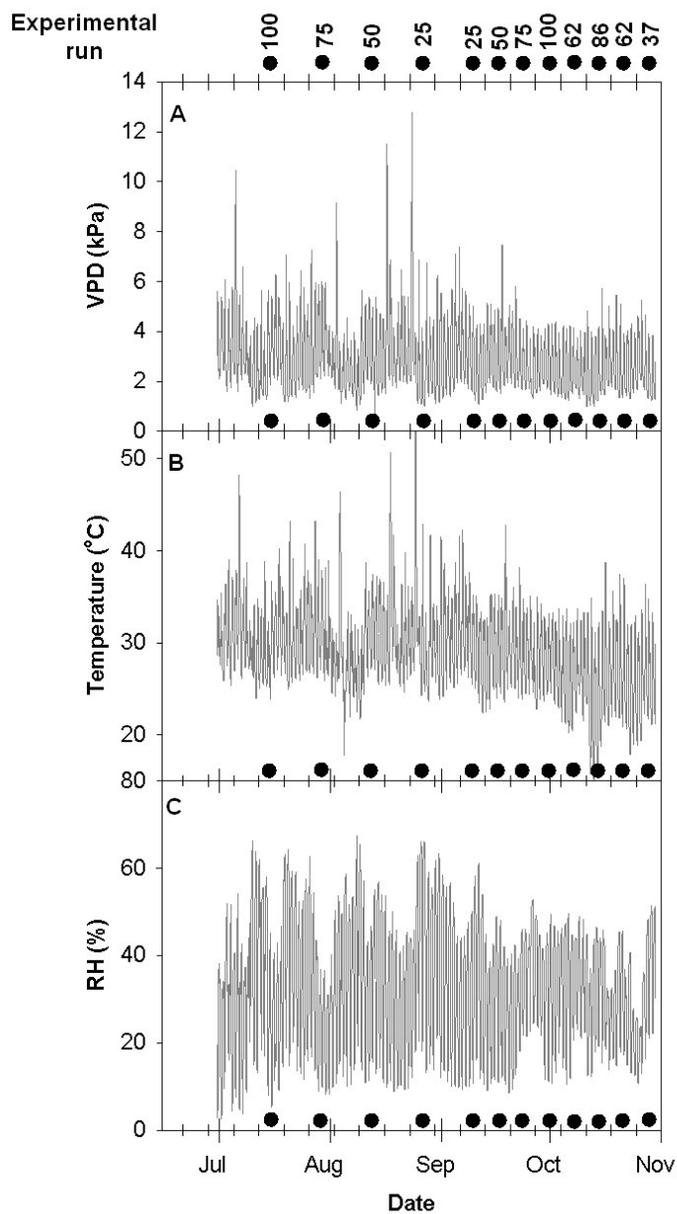


**Figure 2.** Evapotranspiration partitioning as a function of woody canopy cover. (A) Relative soil evaporation ( $p < 0.0001$ ;  $R^2 = 0.8773$ ). (B) Relative transpiration as a function of amount of tree cover. ( $p < 0.0001$ ;  $R^2 = 0.8773$ ). Dotted lines indicate 95% confidence intervals around the fitted trend. Solid black line indicates 1:1 direct proportionality

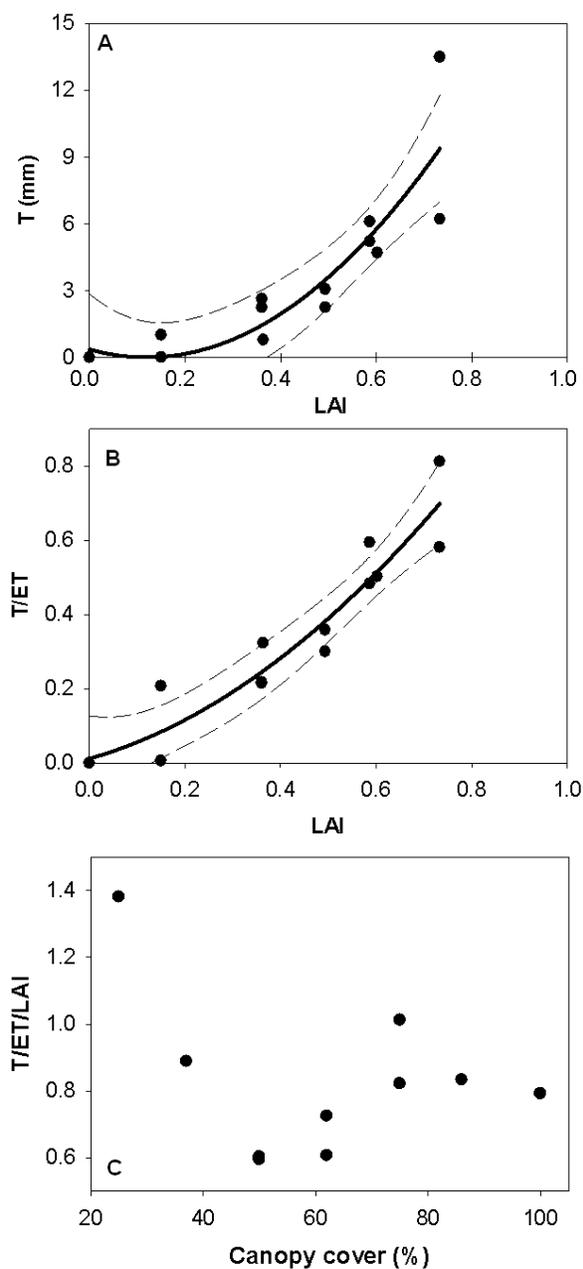


**Figure 3.** Effects of non-linearity of evapotranspiration partitioning in evapotranspiration and its partitioning for a wet year (1990) in shrublands of the North American monsoon region. (A) Accumulated regional average evapotranspiration—AET—and soil evaporation—E—for shrublands in the North American monsoon region for both the current (control) and modified versions of WRF model; dotted lines indicate 95% confidence intervals around the modified version; (B) Spatial distribution of proportional differences in total evapotranspiration between the control and modified versions of WRF for the North American monsoon season (July through September 1990); and (C) Proportion of total evapotranspiration corresponding to soil evaporation in both the original and modified parameterization of the model.

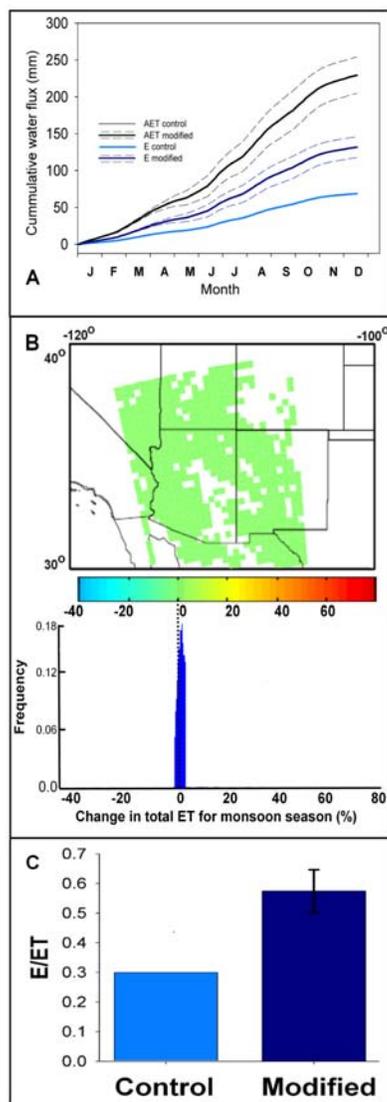
## Appendix Figures



**Appendix Figure 1.** Environmental conditions at Biosphere 2, indicated by (A) Vapor pressure deficit, (B) Temperature and (C) Relative humidity during the time at which runs of the experiment were performed. Black dots indicate weeks in which the experiment was run, with respective values of tree cover for each week indicated on the top.



**Appendix Figure 2.** General relationship between Leaf Area Index—LAI—and (A) absolute amount of transpiration ( $p = 0.0001$ ;  $R^2=0.8023$ ); (B) relative amount of transpiration— $T/ET$ — ( $p<0.0001$ ;  $R^2=0.9067$ ); and (C) change in transpiration per unit leaf area— $T/ET/LAI$ —with amount of tree cover.



**Appendix Figure 3.** Effects of non-linearity of evapotranspiration partitioning in evapotranspiration and its partitioning for a dry year (2000) in shrublands of the North American monsoon region. (A) Accumulated regional average evapotranspiration—AET—and soil evaporation—E—for shrublands in the North American monsoon for both the current (control) and modified versions of WRF model, dotted lines indicate 95% confidence intervals around the modified version; (B) Spatial distribution of proportional differences in total evapotranspiration between the control and modified versions of WRF for the North American monsoon season (July through September 2000); and (C) Proportion of total evapotranspiration corresponding to soil evaporation in both the original and modified parameterization of the model.

## Appendix Tables

**Appendix Table 1.** Parameters of the non-linear relationship of evapotranspiration components with amount of tree cover. Values in parenthesis correspond to 95% confidence intervals around the regression. In the equations E/ET and T/ET correspond to the fraction of evapotranspiration (from 0-1) corresponding to soil evaporation and transpiration, respectively. The variable “cc” refers to proportional amount of tree cover (from 0-1).

ET component	$a*cc^2+b*cc+Y_0$			$R^2$ (p-value)
	a	b	$Y_0$	
T/ET	0.2947 (-0.2951,0.8486)	0.3976 (-0.150,0.650)	0.002795 (-0.1309,0.1356)	0.8773 (p<0.001)
E/ET	-0.2947 (-0.8486, 0.2951)	-0.3976 (-0.650,0.150)	0.99721 (0.8644,0.8691)	0.8773 (p<0.001)

**Appendix Table 2.** Control and modified version of parameterization of the partitioning of evapotranspiration into direct evaporation from the surface and plant transpiration in the WRF model.

Parameter	WRF original parameterization	Modified parameterization (mean values)
Direct evaporation from ground	$EDIR = FX * (1.0 - SHDFAC) * ETP1$	$EDIR = FX * ETP1 * (-0.29470 * SHDFAC^{**2} - 0.39760 * SHDFAC + 0.99721)$
Transpiration	$ETP1A = SHDFAC * PC * ETP1 * (1.0 - (CMC / CMCMAX))^{**} CFACTR$	$ETP1A = (0.29470 * SHDFAC^{**2} + 0.39760 * SHDFAC + 0.00280) * PC * ETP1 * (1.0 - (CMC / CMCMAX))^{**} CFACTR$

\*Where EDIR is direct evaporation from the ground; FX is a parameter function that determines how direct evaporation is related to soil moisture; ETP1 is potential evapotranspiration, calculated from Penman-Monteith; SHDFAC is shaded fraction, corresponding to amount of tree cover (unitless fraction 0-1); PC plant coefficient (unitless fraction, 0-1) dependent of vegetation type; (CMC/CMCMAX)\*\*CFACTR determines the proportion of potential evapotranspiration that goes to direct canopy evaporation. Transpiration from each soil layer is calculated as a weighted function of ETP1A, and integrated into a single variable ETP1.

## APPENDIX F

SPATIAL EXTENT OF THE NORTH AMERICAN MONSOON: INCREASED  
CROSS-REGIONAL LINKAGES VIA ATMOSPHERIC PATHWAYS

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Document Type: Peer-reviewed publication in *Geophysical Research letters*

**Abstract:** The North American monsoon is a key feature affecting summer climate over Southwestern North America. During the monsoon, evapotranspiration from the Southwest promotes transference of water to the atmosphere, which is subsequently distributed across the continent - linking the SW to other regions via atmospheric hydrologic connectivity. However, the degree to which atmospheric connectivity redistributes monsoonal terrestrial moisture throughout the continent and its sensitivity to climate disturbances such as drought is uncertain. We tracked the trajectory of moisture evapotranspired within the semiarid Southwest during the monsoon season using a Lagrangian analytical model. Southwest moisture was advected north-east accounting for ~15% of precipitation in adjacent Great Plains regions. During recent drought (2000–2003), this amount decreased by 45%. Our results illustrate that the spatial extent of the North American monsoon is larger than normally considered when accounting for hydrologic connectivity via soil moisture redistribution through atmospheric pathways.

## **Introduction**

The advent of the North American Monsoon (NAM) during the summer months brings an abrupt precipitation increase to a large region of Southwestern North America. Monsoon rains account for the majority of annual precipitation in the region [Douglas et al., 1993]. While the current consensus encloses the area of influence of the North American Monsoon to the southwest (SW) and nearby regions of northern Mexico, the spatial extent of the monsoon is larger following relocation of terrestrial moisture via atmospheric pathways. In semiarid ecosystems such as the SW, evapotranspiration (ET) is estimated to be more than 90% of incoming precipitation [Wilcox et al., 2003]. SW-ET produced during the monsoon season supports vertically integrated moisture flux divergence from the region [Anderson et al., 2004], making the SW region one of the largest upper-air sources of moisture for the North American continent during the summer [Anderson and Roads, 2001]. This moisture can be relocated via atmospheric pathways and eventually fall as precipitation either in the region (recycling) or elsewhere (export). However, the fate of NAM ET and its contribution to downstream precipitation has been uncertain due to the difficulty in quantifying and tracking atmospheric flows.

Recent advances in our understanding of hydrologic systems, along with the availability of computational resources, enable the delineation of hydrologic connectivity associated with atmospheric pathways that determine source-sink regions of evapotranspired moisture at regional to global scales [Brubaker et al., 2001; Bosilovich et al., 2003; Sudradjat et al., 2003; Stohl and James, 2005; Dominguez et al., 2006]. Consequently, the extent to which the ecohydrological dynamics of one region affect

moisture transport and subsequent precipitation in remote locations can now be assessed. This advance extends the traditional precipitation recycling approach, which focuses only on the contribution of local evapotranspiration (ET) to local precipitation [Budyko, 1974], – by looking at land-atmosphere connectivity at the continental scale.

Our overall goal was to delineate and quantify the spatio-temporal variability of atmospheric pathways that hydrologically link the SW to other regions in North America. Our specific objectives were 1) to evaluate the suitability of a large existing ET data set (North American Regional Reanalysis, or NARR) for addressing our overall goal; 2) to delineate the pathways and quantify the seasonal progression of precipitation that originates as ET from the SW, differentiating the locally recycled and cross-regionally exported components; and 3) to assess how such relationships are altered by severe, protracted drought. We discuss how monsoonal precipitation has a much larger spatial impact than previously thought due to relocation of moisture from the region through atmospheric pathways.

### **Data and Methodology**

The SW drought of the early 2000s was one of the most severe on instrumental record. Therefore, we conducted our analysis for a period from 1996–2006, spanning three types of temporal intervals related to the ecohydrological dynamics of the semi-arid SW: pre-drought (1996–1999), drought (2000–2003) and drought transition (2004–2006). We calculate the amount of precipitation falling over North America originating as ET from the SW using the Dynamic Recycling Model (DRM) [Dominguez et al., 2006]. This model estimates source and sink regions of evapotranspired moisture, and has been used

to study the driving mechanisms of recycling variability in the NAM Region and the Central US Plains [Dominguez et al., 2008; Dominguez and Kumar, 2008]. As with all bulk recycling models, the DRM is derived from the conservation equation for water vapor of recycled origin. The model requires gridded mean and transient values of specific humidity and zonal and meridional winds in the vertical column, and also evapotranspiration and precipitation estimates. The DRM uses a Lagrangian coordinate system that enables us to follow the trajectory of the advected moisture. The model provides an expression for the local recycling ratio  $\rho$  which accounts for the fraction of precipitation falling in one specific cell originating as ET from within the entire region of analysis. The value of  $\rho$  is a function of ET, precipitable water and time, calculated by following the trajectory of the air [see Dominguez et al., 2006]. The DRM can also be used to calculate the contribution of ET originating from certain sub-regions to local and remote precipitation. We used this capability of the model to tag the moisture originating from the SW. Like most analytic recycling models, the DRM assumes that the atmosphere is fully mixed. This assumption is justified by the argument that most of the water vapor in the atmospheric column is contained within the planetary boundary layer (PBL) where the moisture is well mixed as a result of convective processes (see Eltahir and Bras [1996] for reference data and detailed explanation). However, this assumption might not be always valid, as previously discussed from results based on water vapor tracers [Bosilovich, 2003].

We used daily-derived variables from the NARR data set for July through September between 1996 and 2006. The NARR product [Mesinger et al., 2006] improves

upon the earlier global reanalysis, particularly in terms of hydrologic modeling.

Unfortunately land surface observations of variables such as soil moisture and ET are extremely limited, and are currently not assimilated into NARR estimates. Nevertheless, NARR is currently the best long-term, consistent, high-resolution climate data set for North America, providing a much better estimate of land-surface processes than the global reanalysis.

When using assimilated data, the water balance equation must be modified to take into account the residual term  $\alpha$  that arises from closure problems and is not part of the natural physics. The residual term can be as large as the other terms in the equation. Unfortunately, there is no way to systematically account for the residual term in our analyses; however, ET is the only term in the water balance equation that is completely model-derived and has significant uncertainty [see also Nigam and Ruiz-Barradas, 2006]. Because our analysis relies heavily on ET estimates, we compared NARR ET with estimations of ET from six AMERIFLUX sites within the Southwest. The six sites are: Niwot Ridge LTER (40.03°N, 105.56°W), Audubon Research Ranch (31.59°N, 110.51°W), Walnut Gulch-Kendall (31.74°N, 109.94°W), Flagstaff Unmanaged (35.09°N 111.76°W), Flagstaff Wildfire (35.45°N, 111.72°W) and Santa Rita Experimental Range - Mesquite (31.82°N, 110.87°W). We assumed that tower observations for specific locations were comparable to ET estimates for a 32 km NARR pixel.

## Results

### *NARR ET Suitability Assessment*

In our comparisons of NARR-ET to flux tower observations, average NARR-ET was slightly greater than the observed value at each of the six locations (Figure 1); however, the standard deviation from both estimates at a given location was very similar and presents no clear bias. The result was a high correlation between the two daily time series at each location, ( $0.52 \leq \rho \leq 0.84$ ; two-tailed statistical significance  $>0.999$ ), indicating that the temporal variability of ET is accurately captured by the NARR estimates, making them suitable for subsequent analyses.

### *Seasonal Variability of Precipitation Originating as Evapotranspiration From the Southwest*

Our estimates of precipitation recycling within the SW and the associated export of ET to other regions indicates that ET from the semi-arid SW region is subsequently advected throughout North America (Figure 2). Precipitation originating as ET from the SW ( $P_{sw}$ ) contributes to total precipitation throughout the central and eastern US extending to southeastern Canada. Intraseasonal variability of  $P_{sw}$  averaged over 1996–1999 (Figure 2 top) highlights a predominantly north-east trajectory of the moisture in accordance with the dominant seasonal winds, and shows large temporal variability. As SW-ET increases with the monsoon, so does the subsequent moisture export. The exported moisture peaks during early August, and slowly decreases as the monsoon season tapers off. On average 15% of the rainfall in the northeast part of the Four Corners and adjacent areas originates in the SW (Figure 2 bottom). As the moisture

moves east, it contributes less to total precipitation, decaying to only about 2% in the eastern seaboard. In our calculations, the value of  $P_{sw}$  is obtained by multiplying  $\rho_{sw}$  by the total precipitation falling in each pixel; for this reason the distribution of  $P_{sw}$  shows a more heterogeneous pattern than  $\rho_{sw}$ .

*Interannual Variability: The Effect of Drought*

The temporal dynamics of NARR-ET were consistent with the overall precipitation changes over the SW for the three study periods (Figure 3a). Throughout the 11-year analysis average Jul-Sep ET is higher than precipitation, a difference also seen in observations (not shown). This reflects long-term memory in the system as winter or spring surface storage is subsequently evapotranspired in summer. The ratio of local to non-local  $P_{sw}$  highlights that the amount of moisture exported from the region is larger than the recycled precipitation (Figure 3b). Whether falling locally (recycled) or non-locally (exported),  $P_{sw}$  decreased 45% during the years of severe drought (Figure 3b). While pre-drought SW-ET contributed an average 10% of the rainfall in US Great Plains states (Nebraska, South Dakota, Wyoming and Kansas), this value decreased to 6% during the drought (Figure 3c), and has since increased due to increases in SW precipitation and ET. The large regional spatial signature of exported moisture also shrank dramatically during the severe drought, and then expanded in the drought transition periods (Figure 3d). Despite the decrease in  $P_{sw}$ , drought in the SW did not cause significant precipitation anomalies throughout the US Great Plains, and only affected immediately adjacent regions. This is due to the fact that the US Great Plains receives its warm-season moisture primarily from the Mississippi River basin, the Gulf of

Mexico and the Caribbean Sea [Brubaker et al., 2001] and to the out-of-phase relationship between the Southwest and the Great Plains precipitation [Higgins et al., 1997]. Drought in the SW and adjacent regions is characterized by precipitation anomalies between -0.1 and -0.3 mm/day (Figure 3e (middle)), indicating that the changes in export of moisture from the region, which are on the order of 0.1 to 0.2 mm/day, are of the same order of magnitude as precipitation anomalies.

### **Discussion**

Our results delineate the extended region of influence of the NAM following relocation of soil moisture through atmospheric pathways. They highlight how such relocation can be modified by changes in the ecohydrology of the source region. We used the DRM to quantify the contribution of SW ET to precipitable water throughout North America. Because of its assumption of a well-mixed atmosphere, the DRM will likely underestimate the contribution of ET to total recycled and remote precipitation in the Southwest [see Dominguez et al., 2008]. The suitability assessment comparing NARR-ET estimates to field observations from six sites indicates that although NARR slightly overestimates the mean ET value, the temporal variability of NARR-ET estimates is strongly correlated with field observations. This indicates that our estimates of exported ET reflect key aspects of intra- and inter-annual variability of ET production and transport via atmospheric pathways of hydrologic connectivity.

Our work was targeted to assess relationships of recycled and exported moisture when the potential for land surface effects on atmospheric connectivity is greatest (i.e., during the NAM, when the vast majority of precipitation is balanced by

evapotranspiration and subsequent moisture flux divergence from the region). We illustrate that the moisture originating from the SW contributes to precipitation throughout North America. Notably, the amount of recycled precipitation was substantial for some locations within the region (as much as 15%), and perhaps even more importantly, the SW exports more moisture than is recycled back into region. The states of Nebraska, South Dakota, Wyoming and Kansas are the primary beneficiaries of SW ET. Consequently, our results highlight that, due to indirect effects associated with relocation of moisture through atmospheric pathways, the spatial influence of the NAM is more extensive than is normally accounted for. More generally, our approach expands the existing body of work related to hydrologic connectivity in the Southwest which has focused almost exclusively on connectivity associated with surface or subsurface pathways to include key land surface to atmosphere pathways of hydrologic connectivity. This type of hydrologic connectivity may also be relevant to atmospheric science and ecology [Peters et al., 2008].

Temporal changes in atmospheric pathways of hydrological connectivity may also be important. The recent SW drought resulted in a dramatic decrease in regional soil moisture and evapotranspiration. Consequently during the drought, precipitation in other regions originating as SW-ET dropped to less than half that of pre-drought conditions. Further, the spatial signature of exported moisture was muted during the drought years, and has since slowly recovered. Although the drought did not necessarily cause decreased precipitation in other regions, it certainly affected the export of moisture to them from the SW. Other features of the mean-climatological circulation over North America, such as

the out-of-phase relationship between the Southwest and the Great Plains, where wetter monsoons are related to drier great Plains (and vice-versa) [Higgins et al., 1997] might compensate for decreased incoming moisture from the SW and explain the lack of correspondence between the SW drought and precipitation anomalies in adjacent regions. However, our results illustrate that hydrologic connectivity through atmospheric pathways is sensitive to changes in the hydrology of source regions.

The recent drought was severe enough to trigger tree die-off and subsequent changes in vegetation across the SW [Breshears et al., 2005; Rich et al., 2008]. These changes in vegetation are not accounted for in NARR-ET [Gutman and Ignatov, 1998]. However, we expect that these large-scale changes in land surface conditions and associated ET fluxes could potentially amplify the strength of connectivity from land surface to atmosphere, and should be considered in future assessments of hydrologic connectivity.

In conclusion, our results illustrate the importance of a key type of hydrological connectivity in addition to that associated with surface and subsurface pathways: relocation of terrestrial moisture via atmospheric pathways. This hydrologic connectivity produces cross-regional linkages, and shows how a regional phenomenon such as the North American Monsoon extends to a much larger region when relocation of moisture is taken into account.

**Acknowledgments.** The authors thank AmeriFlux Network for the ET flux data. SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) under the STC Program of the National Science Foundation, Agreement EAR-9876800 funds Francina Dominguez.

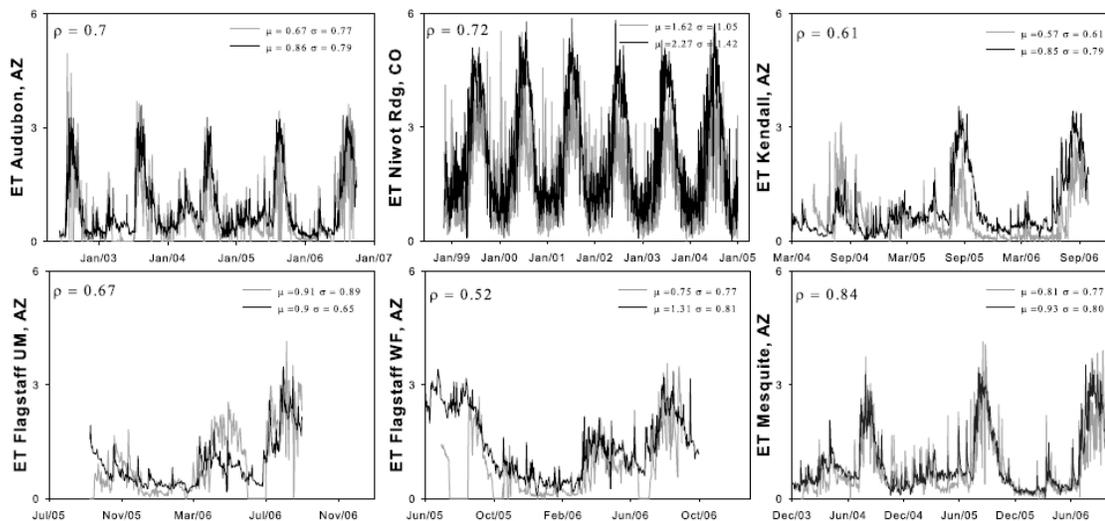
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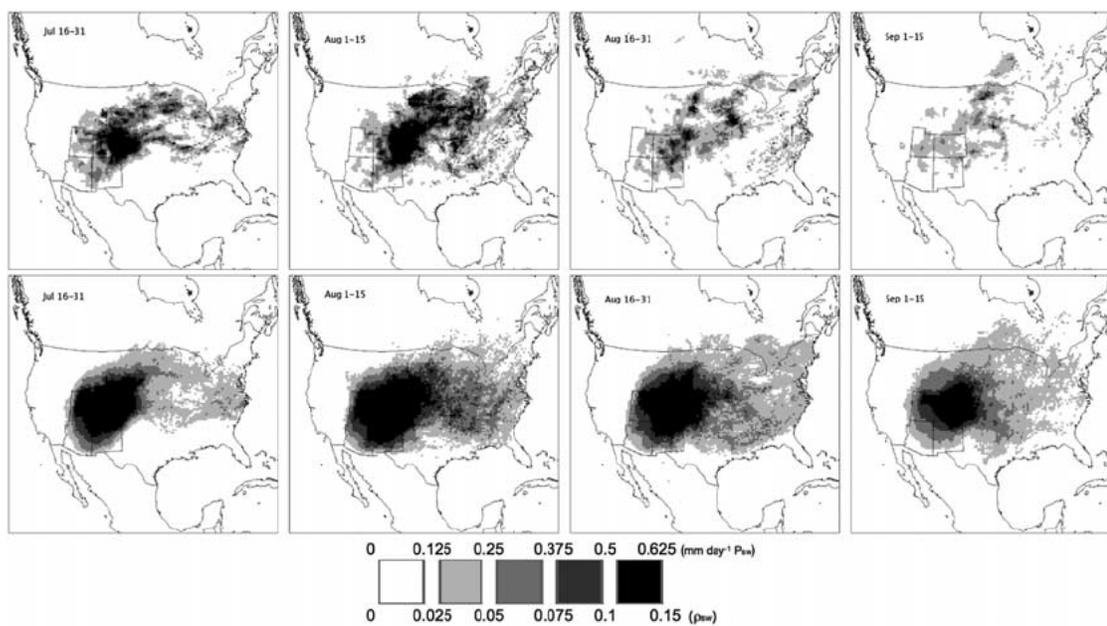
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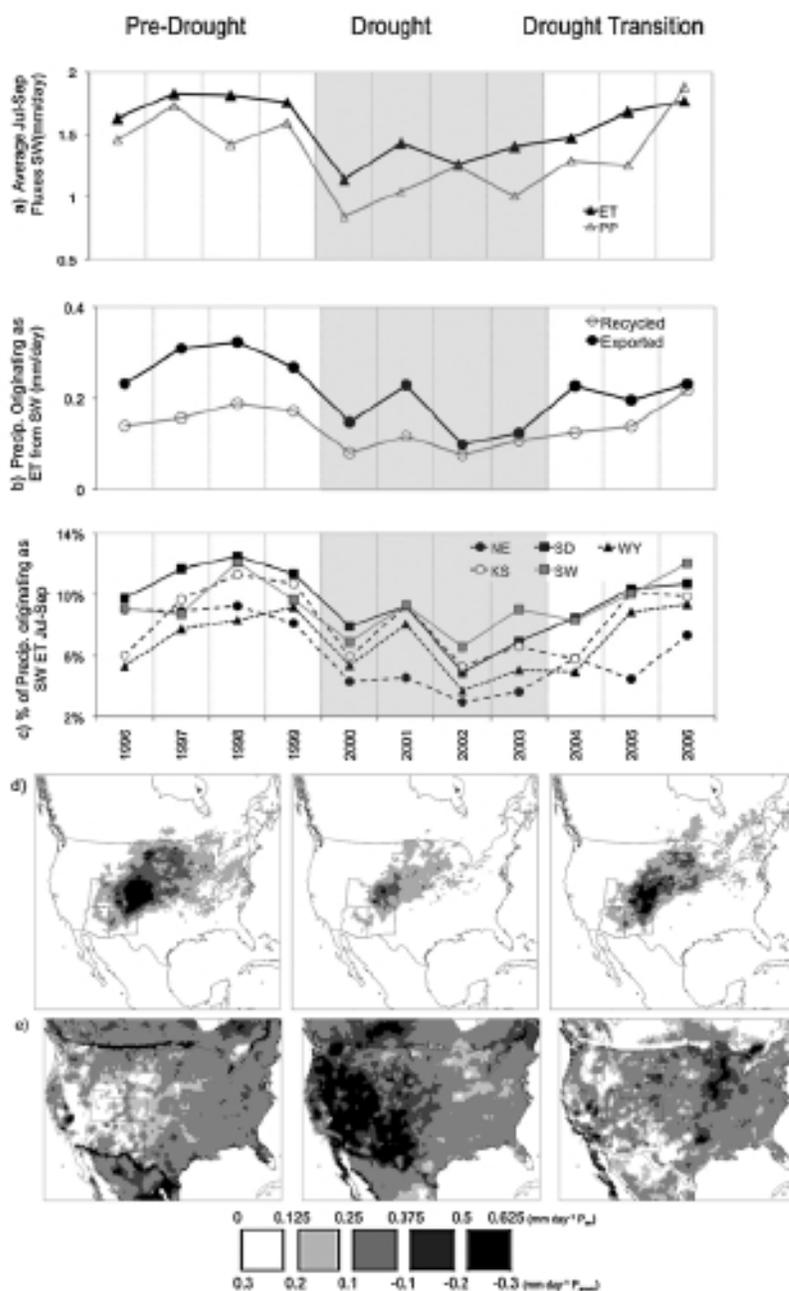
## Figures



**Figure 1.** Daily ET (mm/day) estimates of each of the observation stations and the NARR-ET at the corresponding pixel. The gray lines correspond to observations, while the black line is the NARR estimate. At the top right we present the mean ( $\mu$ ) and standard deviation ( $\sigma$ ) of the NARR and observation data, with the corresponding correlation coefficient between the two ( $r$ ) in the left corner.



**Figure 2.** (top) Average precipitation originating as ET from the SW ( $P_{SW}$ ) for the period 1996–1999. (bottom) Fraction of the total precipitation falling in each pixel that originates as ET from the SW ( $\rho_{SW}$ ) for the period 1996–1999.



**Figure 3.** (a) Summer (JAS) P and ET for the period 1996–2006. (b)  $P_{sw}$  falling within the SW region (Recycled) and outside the SW region (Exported). (c)  $P_{sw}$  as a percentage of total P falling in the states of NE, SD, WY, KS, and within the SW (equal to the recycling ratio) for Jul–Sep. (d) Average Jul–Sep P originating as ET from the SW ( $P_{sw}$ ) during (right) pre-drought (1996–1999), (middle) severe drought (2000–2003) and (left) drought transition (2004–2006) periods. (e) Precipitation anomalies during the same three periods.

## APPENDIX G

THE PARTITIONING OF EVAPOTRANSPIRATION INTO EVAPORATION AND  
TRANSPIRATION: AN EXPERIMENTAL DESIGN ASSESSING THE EFFECTS OF  
CHANGES IN VEGETATION COVER

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Document type: Published in *EcoEd Digital library*

**Abstract.** We present materials and our summary experience of conducting a scientific experiment studying the relationship between changes in vegetation cover and the processes of evaporation and transpiration, conducted in middle, high school and undergraduate science classrooms. Current ecological research highlights the need to address the effects of present and predicted changes in climate and land-use over the dynamics of ecosystems. This experiment provides an exciting opportunity to incorporate these types of questions into the classroom by exploring the coupling between ecological (vegetation changes) and hydrological processes (evapotranspiration). The experiment uses a series of arrangements of potted plants and pots with bare soil to create different

proportions of vegetation cover. Water is added and moisture loss is measured as the weight loss sustained during a 24-hour period after the moisture pulse. Pots with plants are considered sources of transpiration while bare soil pots are considered sources of evaporation. Results from different runs of the experiment can be condensed in a graph showing the relationship between percent vegetation cover to the proportion of evaporation to total evapotranspiration (on a scale of 0 to 1). The resulting curve is expected to be non-linear and the extent of the non-linearity relates to the dependence of evaporation and transpiration processes on vegetation density and environmental conditions. This study is directly relevant to a critical and yet not well-understood process within the water cycle that has important implications for understanding the dynamics of vegetation. The results from this experiment will improve our ability to plan water use and conservation.

### **Learning Objectives**

At the end of this experiment, students will be able to:

- Differentiate between the processes of evaporation and transpiration
- Describe how the processes of evaporation and transpiration are influenced by the amount of vegetation
- Synthesize the real-world importance of studying the water cycle.
- Create and interpret graphs using MS Excel and smart-board technology (where available).
- Gain experience measuring, calculating and interpreting changes in weight over time.

## List of materials

The following list of materials is sufficient for *one* instance of the entire experiment. The experiment includes two groups that run in parallel, each with a 4x5 array of 20 pots, where the pots are filled with either plants or soil. (The particular ratio of plants to soil in each array during the experiment depends on the experiment condition of the current run; this is explained below in the next section, **Procedure and general instructions**). Additional amounts of the materials (e.g., more scales, more cups) may help the experiment run more efficiently in the classroom.

- 40 plant containers – hereafter referred to as *pots* – All should be uniform size, 1 cup to 1 pint (1/4 to 1/2 liter) in size. In past versions of the experiment, we have used pots that are approximately 9 cm x 9cm x 9cm in size.
- Bag of potting soil – the soil we used was a mixture of Sunshine® mix potting soil, vermiculite, and sand (approximately 20 KG). Any standard plant potting soil from a nursery or home garden store is appropriate.
- 25 plants – any green, broad leaf, dense foliage plants that cover the area of the pot surface; the goal is to have the plant's foliage cover the pot surface but not beyond. We have successfully used Peppers and Snapdragons (*Antirrhinum*). Cactuses and succulents are not appropriate.

- A scale that measures to 0.1 gram precision
- Cups, a pitcher or a watering can (with a single, non-shower spout) for pouring water into the pots
- A location to place the pots in a 4x5 array; should be undisturbed overnight; preferably located in a site that receives direct sunlight for part of the day
- A water source (sink, water fountain)

Plants can be grown directly from seed into the pots or purchased and transplanted to them. If plants are grown from seed, planting instructions from the seed package should be followed (conditions for each plant species vary) considering light, humidity and temperature requirements for germination. Germination rates for most species are usually lower than 100%; therefore, an additional 10 plants should be planted to account for non-germinated seeds as well as potential seedling mortality. On the other hand, if plants are purchased in different sized pots and need to be transplanted for the experiment, general considerations for transplant include: trying to minimize disturbance to the root ball; trying to transfer all of the original soil into the newer pot and filling up the remaining volume with potting soil; gently compact the newer soil in the pot (this procedure should also be applied when filling up the pots that contain only soil); water plants right after they are transplanted into the newer pots; allowing some time for plants to adapt to the new pots before starting the experiment, with enough water and sunlight (these requirements are species-specific, and should be provided by the plant seller).

A variety of additional materials may be used for recording the data. Data can be recorded on paper each day with computations being done by hand. A chalkboard or whiteboard could also be used for data entry (but keep in mind that you need to preserve the values, so they will likely have to be copied to paper or computer file). In both paper and chalk/whiteboard approaches, we recommend the instructor first draw a layout of the pot array so that the students are entering the weights in the cells of the layout corresponding to locations of the pots in the pot array. This is important because the goal is to calculate the change in weight from one day to the next, so the weight of a pot on one day needs to be matched to the weight of that same pot the following day.

If a computer with Microsoft Excel<sup>(TM)</sup>, OpenOffice (<http://www.openoffice.org/>) or other spreadsheet program is available, a spreadsheet can be used for data entry. In the accompanying EcoEd Digital Library materials associated with this project, we have included two example Excel workbooks in the format we used in our runs of the experiment. The advantage of this approach is that the spatial layout of the data is immediately available and the spreadsheet cells can also be set up to immediately compute the desired values and even update a plot the data.

Additionally, if a smart board or other display technology (overhead projector or computer display projection) is available, then this can be used to display the spreadsheet and any graphs as the data are entered. See the Section **Student Data**, below, for more information on our experience with data entry.

**Procedure and general instructions (for instructor)**

The experiment is developed in a set of five runs, each run taking a day. The term “run” refers to a specific spatial arrangement and ratio of pots containing plants and soil. Each arrangement consists of a total of 20 pots, organized in a 5x4 matrix. The proportion of pots with plants vs. pots with only soil will vary day by day. Depending on the number of students in the classroom, each student is given one or more positions within the arrangement, making him or her responsible for getting the data for that specific position at every run, as well as making sure that for every run the position has the correspondent type of pot (soil or plant). Runs take one day to be complete, starting with the addition of water and weighing of plant and soil pots and finishing with re-weighing the following day (ideally 24-hours after water was added and the initial weight recorded). Ideally, two parallel experimental set-ups are installed in the classroom. Students are divided into two groups, each group running one of the set-ups. This allows some level of replication in the experiment, and could lead to student discussions around the similarities and differences of their results. However, although ideal, such replication is not necessary, and the experiment can be completed without it.

The general day-by-day procedure involves simple activities of watering and weighing plant and soil pots combined with data entry and review.

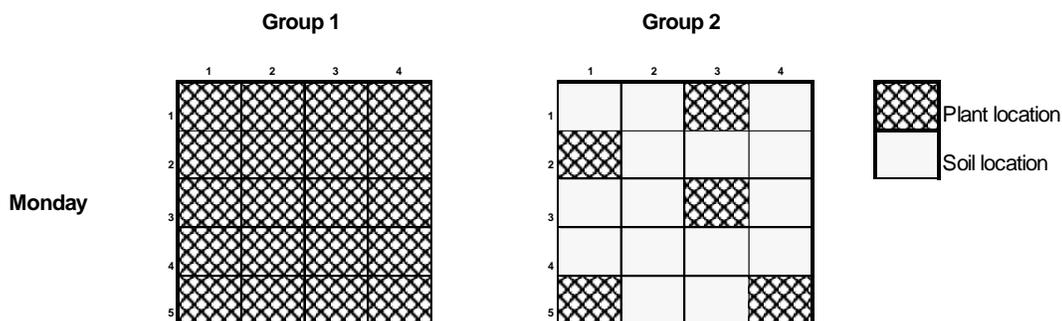
**Day 1**

This day marks the start of the experiment. Group 1 starts with a run that contains 20 plants (no soil-only pots), representing a total cover of 100%. Group 2 starts with an

arrangement of 5 plants and 15 soil pots, representing a cover level of 25%. Both groups will have a mini arrangement of 4 soil pots (2x2) that will be running every day and will be useful to understand how much water is being evaporated from only soils, as well as a representation of a 0% cover run, which corresponds to the effect of not having any plants at all.

Procedure:

1. The first task is to add water to each pot until saturation. This amount is variable, depending on the type of soil and the size of the pots. The point of saturation is reached when pots start draining from the bottom
2. Then, 1 by 1, the students weigh the pots on the scale and record the weight on the table provided. The weights should be taken in grams, which is the international unit of weight used by scientists.
3. After each weight is recorded, the students will place the plants and soil pots in the order illustrated in the following figure.



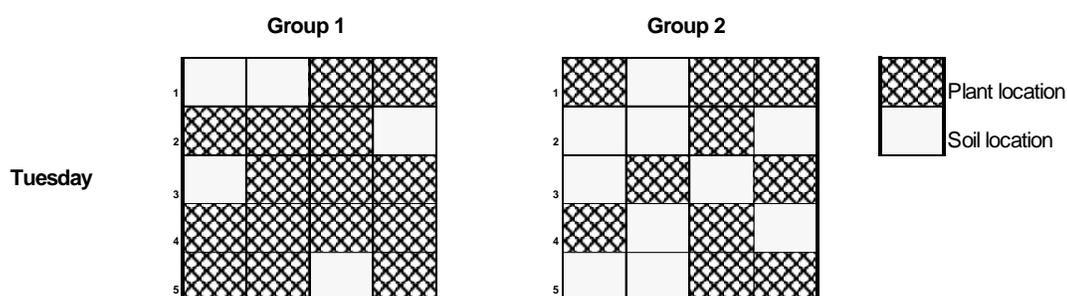
## Day 2

On this day, the first run of the experiment is finished and the second run started. As mentioned before, measurements need to be carried out at approximately the same time every day, so that all runs have the same length of time between initial watering and weighing and later re-weighing so that measurements of evapotranspiration can be comparable between runs. The first task on day 2 will be to complete the run from day 1, by measuring how much water has been lost in that 24 hour period. After this, the students start the second run; in this run, group 1 will have 75% plant cover and group 2 will have 50% cover. Group 1 will have a total of 15 plant and 5 soil pots while group 2 will have a total of 10 plant and 10 soil pots.

### Procedure:

1. The students first re-weigh all of their pots on the arrangements from day 1 to estimate how much water was lost during the 24-hour period, carefully recording the new weight on the format provided. Then the total weight lost during the day for each pot is calculated. This is done by subtracting the new weight (Day 2) from the original weight (Recorded on day 1).
2. Redistribute the pots, so that each group ends with the appropriate proportion of soil and plant pots for the second run.
3. Once groups have all the pots for this day's run, add water to each pot, again trying to reach water saturation of the soil. Quantity should be similar to the average water loss from the first run.

4. Then, 1 by 1, weigh the pots on the scale and record the weight on the table provided.
5. After each weight is recorded, place the plants and soil pots in the order illustrated in the following figure.



### Day 3

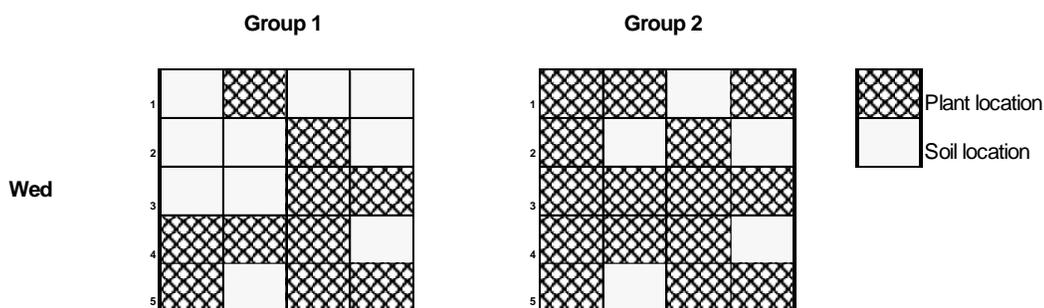
On this day, the second run of the experiment is finished and the third run started. The first task on day 3 will be to complete the run started on day 2, by measuring how much water has been lost during the day from the arrangement. After this, we are going to start the third run, which corresponds to 50% cover for group 1 and 75% cover for group 2. Group 1 will have a total of 10 plant and 10 soil pots while group 2 will have a total of 15 plant and 15 soil pots.

### Procedure:

1. Re-weigh all of the pots on the arrangements from day 2 to estimate how much water was lost during the 24-hour period, carefully recording the new weight on the format provided and calculating the total weight lost during the day for each

pot. This is done by subtracting the new weight (Day 3) from the original weight (Recorded on day 2).

2. Redistribute the pots, so that each group ends with the appropriate proportion of soil and plant pots for the third run.
3. Once groups have all the pots for this day's run, add water to each pot, again trying to saturate the soil of each pot with water. Quantity should be similar to the average water loss from the previous run.
4. Then, 1 by 1, weigh the pots on the scale and record the weight on the table provided.
5. After each weight is recorded, place the plants and soil pots in the order illustrated in the following figure.



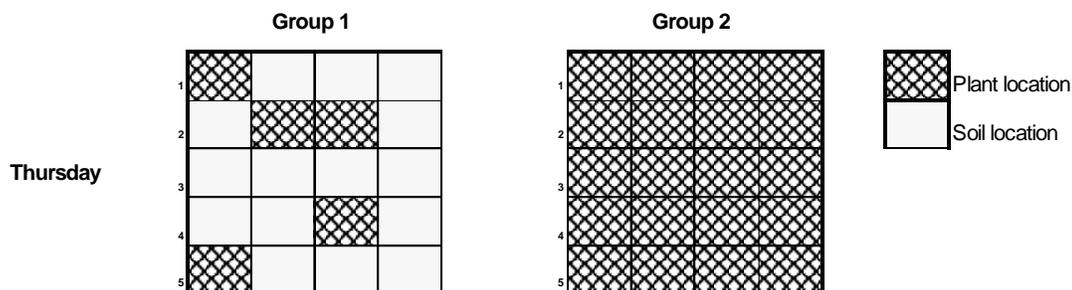
#### Day 4

On this day, the third run of the experiment is finished and the fourth and last run started. The first task on day 4 will be to complete the run from day 3 by measuring how much water has been lost during the previous day from the arrangement. After this, we are going to start the fourth run, which corresponds to 25% cover for group 1 and 100%

cover for group 2. Group 1 will have a total of 5 plant and 15 soil pots while group 2 will have a total of 20 plant and no soil pots.

Procedure:

1. Re-weigh all of the pots on the arrangements from day 3 to estimate how much water was lost during the 24-hour period, carefully recording the new weight on the format provided and calculating the total weight lost during the day for each pot (including the little 2x2 control with soils). This is done by subtracting the new weight (Day 4) from the original weight (Recorded on day 3).
2. Redistribute the pots, so that each group ends with the appropriate proportion of soil and plant pots for the fourth run.
3. Once groups have all the pots for this day's run, add water to each pot, again trying to saturate the soil of each pot with water. Quantity should be similar to the average water loss from the previous run.
4. Then, 1 by 1, weigh the pots on the scale and record the weight on the table provided.
5. After each weight is recorded, place the plants and soil pots in the order illustrated in the following figure.



### Day 5

This is last day of the experiment. By the end of this day's activity, the fourth (and last) run will be finished and the students will now have enough data to evaluate how much water was lost due to evapotranspiration on each run of the experiment, and more importantly, to assess the extent to which changing the proportion of plant to soil pots influences the proportion of water lost via direct evaporation from the soil versus water lost from water transpiration through the plants. For this day, students should be able to complete

#### Procedure:

1. 1 by 1, weigh the pots on the scale and record the weight on the table provided.  
The weights should be taken in grams, which is the international unit of weight normally used by scientists.
2. Calculate water lost during the day
3. Plot the final weight values that relate the partitioning of evapotranspiration to change in vegetation cover (described in the student data section). At this point, you can discuss the potential causes and consequences of the shape of this curve and how it might vary under different environmental conditions

#### **Student data**

During the runs of the experiment, we used a Microsoft Excel<sup>(TM)</sup> workbook for data entry (included with EcoEd DL materials). The spreadsheet was set up to automatically compute differences in plant weights once data was entered, and the results were

displayed in a graph. The classrooms in which we conducted the experiments were equipped with smart boards. In each class, we displayed the Excel workbook on the smart board. As students finished weighing their pots, they entered the weight into the appropriate cell of the workbook at the smart board. The workbook cell computations immediately updated the totals and differences between previous and new pot weights, and this in turn updated the graph displaying the ratio of evaporation to combined evapotranspiration. The combination of the worksheet and its display and data entry through the smart board was very successful. We made the following observations:

- The spatial layout of the spreadsheet for data entry enhanced student understanding of the relationships between the data values.
- Use of the smart board really engaged students: we found the students “took ownership” of their measurements; having the values displayed publicly in an easy to read fashion led to discussion as well as error correction.
- The students were engaged by the immediate feedback the spreadsheet calculations provided; the students liked seeing the graph of the data update immediately as values were entered.

In the materials kit provided in the EcoEd Digital Library entry for this project we have included two example Excel workbooks. The first is empty and ready for use. The second includes data to show how values entered in the cells for the initial and next-day weights of each run contribute to the summary data and the plot. NOTE: the data in the

second workbook are made up because the original data are the subject of an ongoing study that will be published in a scientific journal.

Each workbook is split into 6 worksheets: 1 sheet for each run (a total of 4), 1 sheet that summarizes the total differences for each run (“Data for Graph”) and 1 sheet that displays a graph of the results.

Each run worksheet contains three 4x5 cell-arrays. The array cells correspond to the positions of the pots in the experiment, and array cells are colored by whether the pot contained a plant or soil only. The top array represents the initial weights of the pots after adding water. The middle array represents the weights of the pots after one day (no water added in between). The bottom array represents the differences in weights between the top and middle arrays, representing the total water lost over the 24 hour period.

To the right are total values for each of the three arrays:

**E** represents the total water due to soil-only (Evaporation);

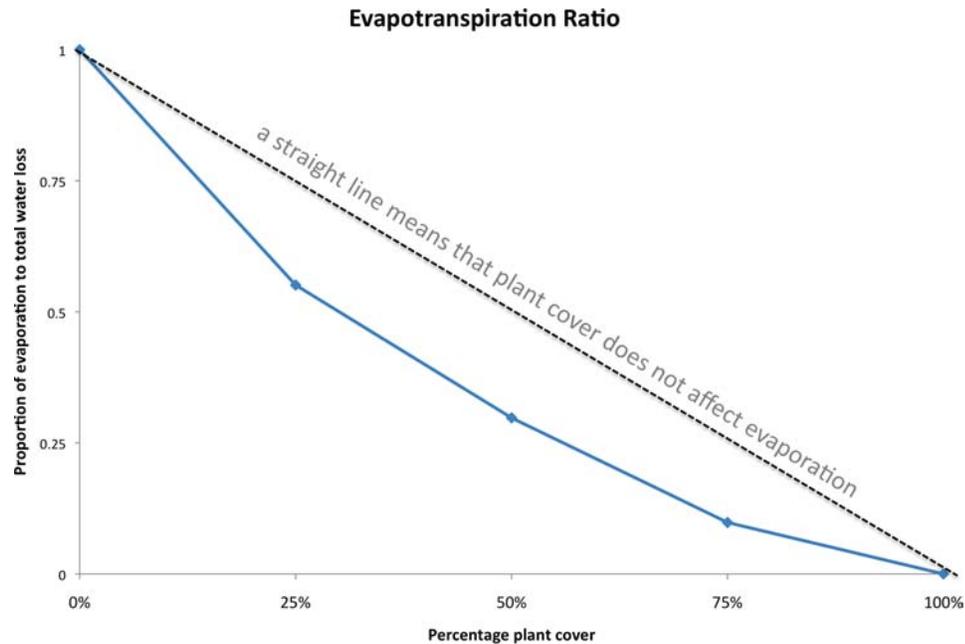
**T** represents the total water in each array due to plants (Transpiration); and

**C** represents the total water from the control arrays.

On the sheet labeled “Data for Graph”, the final (*bottom*) E and T values (representing the weight *differences*) on each of the Run sheets are combined using the following equation:  $\text{Cell value} = E/(E+T)$ . This computes the ratio of the amount of water loss due to evaporation (soil-only pots) over the combined total water loss (due to evaporation (soil only) *and* transpiration (plants)). Note that the top value in the table, for 0 plant

cover, has an assumed value of 1 because no plants would be present – only pots with soil are present so no contribution from transpiration. Similarly for run 1: it will always be evaluated to 0 because only pots with plants are included, no soil (and thus, no contribution of evaporation).

Finally, the sheet labeled “Graph” displays the graph of the results, using the summary values on the “Data for Graph” page. Below is the graph from the example worksheet with made-up data. The y-axis represents the proportion of total water loss due to evaporation, that is, the values that result from the computation of  $E/(E+T)$ . The x-axis represent the percentage of plant cover, one value for each of the run conditions. We have also included a dashed straight line along the diagonal that represents the line we would expect to see if there was no effect of plant cover on the amount of water loss. With this made up data, we see that there is in fact an affect, with plant cover tending to increase water loss, and the degree to which it increases water loss is non-linear with the amount of plant cover.



### Suggestions and materials for assessing student learning

We have developed a question bank that can be used to assess the effectiveness of the activity in accomplishing the learning objectives. The questions vary in their level of difficulty and can be used discretionally, according to the teacher's criteria and the student's science background.

#### (1) Fill in the Blanks:

Evapotranspiration is \_\_\_\_\_ from the sum of \_\_\_\_\_ plus \_\_\_\_\_

If all the trees in a forest are removed, you would expect a \_\_\_\_\_ (increase/decrease) in evaporation and a \_\_\_\_\_ (increase/decrease) in transpiration

**(2) True or False:**

Temperature affects evapotranspiration. (True) (False).

Humidity affects evapotranspiration. (True) (False).

Evapotranspiration is the same as condensation. (True) (False).

Plants have nothing to do with evapotranspiration. (True) (False).

**(3) Multiple choice:**

Evapotranspiration is an essential component of:

- a) The Water Cycle
- b) the Vegetable Cycle
- c) the Economic Cycle
- d) None of the Above.
- e) All of the Above.

Evapotranspiration occurs in:

- a) Outer Space
- b) The Rainforest
- c) The Desert
- d) Answers (b) and (c)
- e) All of the Above

To study evapotranspiration I will need:

- a) Soil
- b) Sun
- c) Water
- d) Answers (a) and (c)
- e) All of the Above

Evaporation is most likely to occur in a:

- a) hot and humid place
- b) cold and humid place
- c) hot and dry place
- d) cold and dry place

Water moves through plants as part of:

- a) the magnetic attraction of the sun
- b) the magnetic attraction of hydrogen
- c) photosynthesis involving exchange of gases with the atmosphere
- d) photosynthesis involving exchange of gases with the soil

Transpiration is the process where:

- a) water vapor leaves plants
- b) water droplets fall from the sky to the ground
- c) water evaporates from the soil
- d) water takes on a crystalline state as it freezes

Which of the following does NOT affect evaporation?

- a) wind speed
- b) relative humidity
- c) plant cover
- d) Sun's microwave radiation

Which of the following statements is correct?

- a) plants absorb water through their roots and release it through their leaves
- b) plants absorb water through their leaves and release it through their roots
- c) plants use their leaves to block the intake of water from the atmosphere
- d) plants use their roots to block the intake of water from the soil

Evapotranspiration refers to

- a) the process in which contaminated water is cleaned and made safe to drink
- b) the loss of water from soil evaporation and transpiration from plants
- c) the loss of water vapor from plants but not evaporation from soil
- d) the process in which water molecules bond with other elements in soil

Evapotranspiration is part of:

- a) the water cycle
- b) the fluid dynamics cycle
- c) the effluvia cycle
- d) the nonlinear interaction of fluid processes

Evapotranspiration can be observed:

- a) in outer space, that is, above the atmosphere of the Earth

- b) only in arid lands and desert regions
- c) only in the rainforests
- d) in all regions of the globe

John is a football player who wants to find out how much he weighs. Which of the following scales is the best to use?

- a) a scale that measures 0 to 1600 grams
- b) a scale that measures 0 to 250 ounces
- c) a scale that measures 0 to 250 kilograms
- d) a scale that measures 0 to 250 units of newton

One ounce is

- a) about the same weight as one gram
- b) much lighter than one gram
- c) heavier than one gram
- d) another term for one dram (not gram)

You have a nice big apple for lunch. It probably weighs about

- a) 300 grams
- b) 30 grams
- c) 3 grams
- d) 0.3 grams

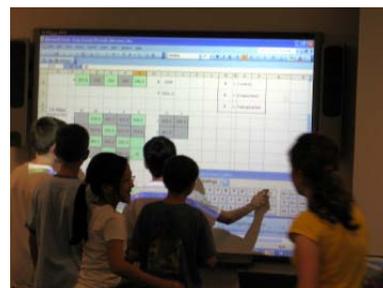
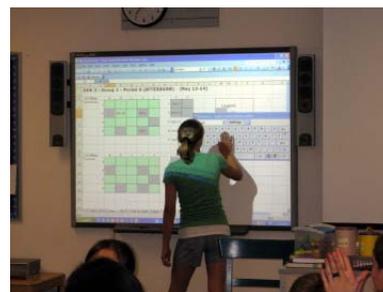
John is a teenager. He wants to find out how much he weighs. Three scales are available: (a) measures from 0 to 1600 grams, (b) measure 0 to 250 ounces, and (c) measures 0 to 250 kilograms. Which scale is the best one to use? (Circle one.)

- a) Scale a
- b) Scale b
- c) Scale c
- d) None of the above

**(4) Open-ended questions:**

- At noon, just before lunch, John weighed himself and found he was 78 pounds. After lunch, his friend Jane asked him how much the food he ate weighed. How can John and Jane figure out how much the food he ate weighed? (Only a short answer is needed.)
- There are about 28.35 grams in 1 ounce. There are 16 ounces in 1 pound. How many grams are in one pound?
- The city where you live in is currently designing a new park and is committed to decrease the amount of water that is lost from evaporation, but they don't want to cover the entire park area with plants. You are invited to a session where decisions about how to do with this situation need to be taken. Based on what you have just seen in this experiment (where evaporation and transpiration are sensitive to changes in vegetation cover), explain what you would do to satisfy the need of the city.
- Describe how based on this experience you would include the role that plants play in the water cycle (draw a diagram if you consider it necessary).

### Appendix: Experiment Photographs



## APPENDIX H

## IMPACT OF AN ECOHYDROLOGY CLASSROOM ACTIVITY ON MIDDLE SCHOOL STUDENTS' UNDERSTANDING OF EVAPOTRANSPIRATION

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Document type: In review as of December 3<sup>rd</sup> 2009

**Abstract.** Current trends in ecological research emphasize interdisciplinary approaches for assessing the environmental effects of predicted and observed changes in climate, land-use and vegetation cover. One such emerging interdisciplinary field is the discipline of ecohydrology, which studies the feedbacks and interactions between ecological and hydrological processes. However this interdisciplinary approach has not yet been translated into the science curriculum of K-12 education. We adapted an ecohydrological research project carried out at the University of Arizona Biosphere 2 research facility to middle school classrooms. The resulting experiment focused on the effects of changes in landscape vegetation cover on evapotranspiration, the major component of the water budget. In particular, the experiment explored how the partitioning of evapotranspiration into plant transpiration and soil evaporation responded to changes in vegetation cover.

The one-week long experiment was conducted by Grade 6 students (N=82) in classrooms of Oro Valley, Arizona. Students completed pre- and post- experiment tests designed to assess their general understanding of the components of evapotranspiration. Our results show significant improvement between the pre- and post- experiment evaluations on the understanding of the water cycle concepts, particularly those associated with evapotranspiration. Further, our results illustrate how the incorporation of experimental knowledge can constitute a key instrument in successful delivery and understanding of scientific information in the classroom. We discuss how current scientific research can be effectively incorporated into the science curriculum, which in turn can be used as an instrumental tool to produce scientifically-relevant data.

### **Introduction**

Incorporating current scientific research into K-12 education curricula constitutes a fundamental challenge for both scientists and educators. Of particular urgency is the call to increase scientific literacy among students and the general public to encourage a society that makes informed policy decisions about current and predicted changes in the environment (Hurd, 1997; National Research Council [NRC], 2006). In particular, ecology is one field of science recognized for its importance in K-12 education for promoting better understanding of human interactions with the natural world (Jordan et al., 2009). In particular, the importance of incorporating experimentation when teaching ecology has been recognized and increasingly used in educational settings (Finn et al., 2002). Science educators have recognized the importance of transitioning from declarative to procedural knowledge with an emphasis on teaching scientific inquiry for

delivering scientific content more effectively in the classroom (Orr, 1992; Torp and Sage, 2002; Jordan et al., 2009). Inquiry-based approaches to teaching the scientific method and research processes have been implemented and embraced in middle school curriculum (Steel et al., 2004). Specifically, the process of providing children the opportunity to carry out their own project in a relatively short period of time can be a particularly successful strategy to deliver ecological content (Colley, 2006). By actively engaging in hands-on activities and inquiry-based experiments, students acquire a feeling of ownership and investment in the scientific process that enhances their overall experience and desire to continue knowledge acquisition and sharing. In addition, the communication of actual research results and interacting with scientists has been recognized as a successful way to interest children in science, and particularly in ecology (Kats et al., 2008). When students develop personal connections to scientists and their research, they are more likely to see science as a viable career (Hill et al., 1990) and the science as more relevant to their lives (Fusco, 2001). These interactions not only enhance the student's perception of science, but also provide an opportunity to incorporate up to date scientific questions into the classroom.

Current environmental changes not only affect individual components of ecosystems, but also operate within interactions and feedbacks between ecosystem processes (Pickett et al., 2001; Peters et al., 2004). This has increased the necessity of developing interdisciplinary research fields such as ecohydrology, plant ecophysiology, and biogeochemistry, among others. The complex nature of ecological processes constitutes a major challenge to teaching ecology in basic education cycles. Properly

communicating causal mechanisms (Grotzer and Bell, 2003) and feedback cycles (Carlsson, 2002) are key to engaging students in the study of ecology and ecosystems. Finding ways to introduce students to these processes and mechanisms in hands-on activities is key to enhancing their familiarity with the subject. In this context, water, could represent an important topic that constitutes a building block for children to understanding ecosystem feedbacks (Covitt et al., 2009). Notably, the water cycle provides a fundamental tool to teach students not only about the role of water in the ecosystem, but also the interactions between humans and their ecosystem. Based on such interactions, educators can develop curricula that draw connections between students, science, and their environment (Varelas et al., 2001). In particular, the interactions between water cycle and ecological processes provide an important opportunity to incorporate interdisciplinary science into the science curriculum.

The interdisciplinary field of ecohydrology seeks to understand the feedbacks and interaction between ecosystems and the water cycle (Rodriguez-Iturbe, 2000; Van Dijk, 2004; Breshears, 2005). One of the fundamental challenges in ecohydrology is to understand the dynamics of evapotranspiration, the dominant component of the water budget (Wilcox et al., 2003; Kurc and Small, 2004; Huxman et al., 2005). We currently lack studies describing how evapotranspiration is partitioned into its major components – soil evaporation and plant transpiration – in response to changes in vegetation cover. This relationship can have important implications for understanding the biological feedbacks in the water cycle (Williams et. al. 2004; Huxman et. al. 2005). To address this knowledge gap, a large-scale experiment was carried out at the Biosphere 2 glasshouse

facility (Villegas et al., unpublished data; Wang et al., unpublished data). Different levels of canopy cover were simulated by establishing regular 10 x 10 arrangements of containers with either bare soil or a mesquite tree (*Prosopis chilensis*) approximately 2.5m tall. Total evapotranspiration from the arrangement was calculated as the integration of water loss from individual containers. Containers with bare soil were sources of evaporation, while containers with trees were sources of evapotranspiration, discriminated by the installation of sap flow sensors in the trees. The results from this study (Villegas et al., unpublished data) illustrate how the partitioning of evapotranspiration at the landscape scale responds in a non-linear way to changes in vegetation cover. This experiment, which used the unique logistical capabilities of the Biosphere 2 glasshouse facility, highlights the systematic and interactive effects of vegetation cover in hydrological variables that influence ecosystem processes and properties.

While running the study with this apparatus and at this scale is critical to directly test hypotheses about the dynamics of the partitioning of evapotranspiration in response to overall vegetation cover, there are still other processes that require further experimentation. In particular, there is a great need for exploratory data collection to help formulate further hypotheses about the sensitivity of evapotranspiration partitioning to variations on the characteristics of vegetation type and climatic variables (Lawrence et al., 2007). We identified a key-opportunity to develop such exploratory data collection while simultaneously providing a unique educational experience. With this purpose, we developed an adaptation of the large-scale experiment that explored some of these effects

associated with vegetation type while also making the study amenable to a hands-on educational activity in 6<sup>th</sup> grade classrooms in Oro Valley, Arizona.

This project is particularly relevant for the 6<sup>th</sup> grade classroom for several reasons. The space and time required and the plant species used can all be modified to the convenience and limitations of the classroom (Villegas et al., 2009a). The experiment also provides the possibility for participation in data collection by every student in a classroom; in addition, the project incorporates concepts of mathematics, graphing, and technology in the processes of generating and explaining the data. Finally, the project is well aligned with specific portions of the 6<sup>th</sup> grade education standards including scientific inquiry, Earth system processes, and science and technology (Kuhn, 2002; Michaels et al., 2007; NRC, 2006). Further, the project provides extended opportunities for follow-on scientific questioning, hypothesis generation, data exploration, and experimentation.

In the following sections we present the adaptation of the on-going interdisciplinary research project from Biosphere 2 into a local middle school curriculum. We examined whether the students' understanding of the water cycle and the role of vegetation on it was changed by the activity. The main objectives of this project were: (a) to provide students with a hands-on approach to study the water cycle, with specific emphasis on the process of evapotranspiration, and (b) to evaluate the effect that the experiment and direct contact with scientists had on understanding of the water cycle and its relation to other environmental processes. We discuss how the incorporation of experimental knowledge can constitute a key instrument in successful delivery and

understanding of scientific information in the classroom and how the information generated in the classroom can help improve the scientist's capability to further improve their understanding around their specific field of study.

## **Materials and Methods**

### *Classroom Activity*

This classroom experimental activity is designed to explore the partitioning of evapotranspiration into its two major components — evaporation from the soil and plant transpiration — as a function of vegetation cover. The experiment uses a series of arrangements of potted plants and pots with bare soil to create different proportions of vegetation cover, each arrangement consisting of a total of 20 pots, organized in a 5x4 matrix. Pots with plants are considered sources of transpiration whereas bare soil pots are considered sources of evaporation. The experiment is developed in a series of four runs, corresponding to four levels of vegetation cover, each run taking 24 hours to complete. The term “run” refers to a specific arrangement of pots that determines both the proportion and spatial arrangement of plants and soil pots. Each run starts with the addition of water, followed by weighing the plant and soil pots, and finishes with re-weighing the following day (ideally 24-hours after water was added and the initial weight recorded). Water loss from each pot (which accounts for evaporation in soil pots and transpiration in pots with plants) is calculated as the difference between the final and initial weights. This procedure assumes that there is no drainage from the bottom of the pots, and the only possible mechanism for water loss is via evaporation or transpiration. The experiment also assumes that evaporation from the soil in pots with plants is

negligible. This assumption is reasonable when the experiment is conducted with plants that offer a complete cover of the soil surface in the pots. The complete details of the procedure and materials for this experiment have been described elsewhere and are freely available on-line (Villegas et al., 2009a).

During the experiment, we used a Microsoft Excel<sup>(TM)</sup> workbook for data entry. The spreadsheet was designed so that the spatial arrangement of the cells for data entry corresponded to the spatial arrangement of the pots in each run. The spreadsheet cells were set up to automatically compute differences in plant weights once data was entered, and the results were displayed in a graph. Examples of the workbook are available in Villegas et al. (2009a). The classrooms in which we conducted the experiments were equipped with interactive whiteboards that were used to display the spreadsheet on the projection screen, and students entered their data using the interactive whiteboard interface. As students finished weighing their pots, they entered the weight into the appropriate cell of the workbook and the workbook cell computations immediately updated the totals and differences between previous and new pot weights; this in turn updated the graph displaying the ratio of evaporation to combined evapotranspiration.

#### *Student learning assessment*

##### *Participants*

Two 6<sup>th</sup> grade classrooms in an Arizona middle school were chosen to participate as a pilot in this outreach effort due to the natural alignment of 6<sup>th</sup> grade science standards (Arizona Department of Education, 2005; Kraicik et al., 1998; NRC, 2006; Roth and Lee, 2004) to the principles explored in the experiment. There were 82 students

who completed both the pre-test and the post-test. Ten additional students were present for only the pre- or post-test; their data were not included in the analyses. The final sample included 42 boys, 37 girls, and 3 students whose gender was not identified.

### *Procedure*

Students completed the pre-test during their science class period, the school-day before the experimental activity started, under the supervision of their science teacher. After the pre-test, students listened to a 45 minute overview presentation by the first author of this paper about principles and procedures of the activity that would be conducted the following school-week. On the first day of the school-week, two trays of pots were delivered to each classroom. The data collection portion of the experiment ran for four days. On the last day of the study, students completed the post-test under the supervision of their teachers who collected the tests and returned them to the researchers for scoring and analysis.

### *Pre- and post-tests*

Students' learning was assessed by their responses to a study-specific test that was applied before and after the experiment was carried out. The test addressed concepts of evaporation and transpiration, understanding of weight and place value, and problem solving strategies. The 11 question test included one definition item, four true-false items, three multiple-choice items, and three items that focused on concepts of weight (one open-ended problem, one involving conversion between units of weight, and one involving concepts of place value). The test items are presented in the appendix.

### *Statistical analysis*

Students' responses to the questions in the pre- and post-tests were scored and then summed to yield a total score for each test. Possible scores ranged from 0 to a maximum of 15 points. Results from pre- and post-test were compared using matched-pairs t-tests. Results are considered significant at an alpha-level of 0.05.

### **Results**

Mean scores for the pre- and post-tests are presented in Figure 1. Overall, students showed improvement on the test as a result of the activity. A matched-pairs t test indicated that the improvement was significant ( $t(81) = 9.530, p < 0.001$  Figure 1A). Individual question analyses indicate that overall, student performance in the test was improved by the activity. However, in some cases, the performance did not improve as a result of the activity (Figure 1B).

Definition. The first test question required students to define "evapotranspiration" by listing the three key components: "water", "evaporation" and "transpiration". Students received one point for each correct term listed, yielding a score from 0 to 3. Fill-in-the-blank questions tend to be challenging for students, and performance on this item was generally poor. However, students did show significant improvement on the post-test ( $t(81) = 6.138, p < 0.001$  – Figure 1B).

True-false questions. Correct responses on these four items were summed for each student to yield a true-false score ranging from 0 to 4. Results indicate that students showed significant improvement on the post-test ( $t(81) = 7.419, p < 0.001$  – Figure 1B). In this case, average improvement was on the order of one additional true-false item correct on the post-test.

Multiple-choice questions. Correct answers were summed for these items, yielding a score of 0 to 3 for each student. Our results indicate that improvement from pre- to post-test was significant ( $t(81) = 5.854, p < 0.001$  – Figure 1B).

Open-ended weight problem. Students wrote out their solution strategy in the answer space below this question. These answers were coded as follows: Students received a score of 0 if they left the question blank; 1 point if they attempted to answer but the answer was incorrect, incomplete or irrelevant (e.g., “use a scale” “get more food” “drink some water”); 2 points for a clear and accurate explanation (“weigh the person after lunch and subtract his initial weight to find the difference”). Our results indicate that students significantly improved from pre- to post-test ( $t(81) = 2.387, p < 0.05$  – Figure 1B).

Math problem. Students were asked to calculate the number of grams in one pound, given the information that there are 16 ounces in one pound and each ounce is equivalent to 28.35 grams. Students received a score of 0 for a blank or incorrect answer, and a score of 1 for a correct solution. Mean scores for this question on the pre- and post-tests were not significantly different ( $t(81) = 0.727, N.S.$  – Figure 1B).

Scale problem. On this multiple-choice item, students had to choose the best scale for obtaining one’s weight. Students received a score of 0 for an incorrect choice and a score of 1 for choosing the correct option. There was significant improvement from pre- to post-test on this item ( $t(81) = 3.965, p < 0.001$  – Figure 1B).

## Discussion

In this study, 6<sup>th</sup> grade students conducted an experiment adapted from a current scientific project being carried out at the University of Arizona Biosphere 2 glasshouse facility. Over the course of one week, students examined the effect of increasing vegetation cover on the partitioning of evapotranspiration into its major components (evaporation from the soil and transpiration from plants). The students obtained data by calculating the differential weight loss in pots with either bare soil (sources of soil evaporation) or a plant (sources of transpiration) for a 24 hour period. They repeated the procedure, varying the ratio of plants to soil, and entered their data into a spreadsheet that allowed real-time display of data and results as the activity progressed. By participating in this experiment, the students became active scientists in-training with their results contributing directly to the larger evapotranspiration study performed by University of Arizona researchers.

We conducted pre- and post- assessment tests to evaluate the effect of this activity on the students' understanding of the water cycle and its relation to other environmental processes. The results indicate that students performed significantly better on the post-test for questions about evaporation, transpiration, and concepts of measurement (Figure 1). Students were more likely to provide accurate definitions for key terms, to recognize the factors and conditions that influenced evapotranspiration, and to suggest reasonable strategies for calculating weight (figure 1B). Because the same test was used for both the pre- and post- test, it is possible for students to have learned from the first exposure to the test, and thus perform better on a second attempt simply because they have seen the

questions before (Schaughnessy et al., 2009). However, in this study students did not show uniform improvement across the items in the test and, in fact, did not improve at all on the mathematical problem that required them to convert from pounds to grams (Figure 1B). They were also not more likely to attempt items on the post-test which would have been likely to occur if familiarity with the test was a factor explaining the overall improvement. Thus, the improvement in their performance does not seem to be solely due to simply retaking the test.

Our results illustrate how incorporating active hands-on derived knowledge into the classroom produced a significant improvement of students' knowledge of the focal subject (Orr, 1992; Songer et al., 2002; McComas, 2004; Jordan et al., 2009). However, when conducting the experiment, it was less clear whether young adolescents would be able to collect scientific data that would be of real value to researchers. In particular, the process of weighing plants required considerable attention to relatively fine-grained measurements and the use of the metric scale – topics that are known to be challenging for middle school students in the United States (Slavin and Lake, 2008). In addition, the activity was sensitive to the successful completion of multiple sequential steps: students had to weigh the plants, record the values in decimal format to the second decimal place, and then enter the data into the workbook on the smart board. Processes that involve multiple steps are often prone to error, especially with relatively young participants (Michaels et al., 2007; Hassard and Diaz, 2008). Nonetheless, during the week long experiment there was surprisingly little off-task or disruptive behavior. Although students' reactions to the activity were not formally evaluated, their focused behaviors

and spontaneous comments suggested that they found the research experience to be highly engaging. Through informal classroom conversations with the students and their teachers, we were given feedback that the spatial layout of the spreadsheet designed for data entry enhanced student understanding of the relationships between the data values. The use of the smart board technology was also noted as a contributor to student engagement in the activity. We observed that students “took ownership” of their measurements; having the values displayed publicly in an easy to read fashion led to interesting classroom discussion. This promoted an informal peer review-like process in which the students corrected errors immediately during the data collection and analysis phases of the project. Finally, the students were engaged by the immediate feedback the spreadsheet calculations provided, expressing their interest in analyzing the immediate graphic update as values were entered. It is likely that the presence of the university researchers in the classroom helped to support the success of the experiment. In addition, the two participating science teachers were experienced middle school instructors who were skilled in classroom management. Further research is required to evaluate the degree to which the activity can be implemented without the physical presence of the researchers or with less experienced teachers.

The data generated by the four sub-groups in this experiment, which was consistent among groups and physically-consistent, has been directly used to broaden the breadth experimental results of the larger scale Biosphere 2 study and has led to the proposition of new conceptual frameworks about the effects of vegetation type and structure on the partitioning of evapotranspiration (Villegas et al., 2009b). Notably, our

results illustrate how educational experiences can be used as a mechanism to develop the concept of “citizen science” (Evans et al., 2001; Cohn, 2008; Silvertown, 2009), where non-scientists can collect data and contribute to relevant ecological research while gaining an enhanced relationship with their community and with nature. This “closes the loop” between students, teachers and scientists, with current scientific research being translated and incorporated into existing science curriculum, providing students with hands-on experience through active participation in an experiment, and generating useful data that flows back to scientists while also informing them as to how to better communicate what they are doing (Roth and Lee, 2004; Trumbull et al., 2000; Baumgartner, 2006) (Figure 2). While this model may not work for all kinds of scientific enquiry – it requires that the subject of the scientific investigation can be successfully translated into classroom activities – we contend that there are many such opportunities to “close the loop” between science and education.

In summary, our results illustrate that the incorporation of experimental knowledge supported by data management tools can constitute a key instrument in successful delivery and understanding of scientific information in the classroom. Our classroom activity demonstrates how current scientific research can be effectively incorporated into the science curriculum, which in turn can be used as an instrumental tool to produce scientifically-relevant data that can benefit both educational processes as well as the advance of natural sciences.

**Acknowledgments.** Partial funding for this project comes from the University of Arizona B2 EarthScience at Biosphere 2 through the Philecology Foundation. The authors would like to thank classroom teachers Nicole Tilicki and Cheryl Cook for their enthusiastic support of the research, along with the principal and administrative staff of the Wilson K-8 School in Oro Valley, Arizona. We would also like to thank Ashley Wiede, Adriana Quirós-Arauz and Daniel Espeleta for their important contributions to the project. Finally, thanks are due to Paul Cohen for his support of and inspiration for the project.

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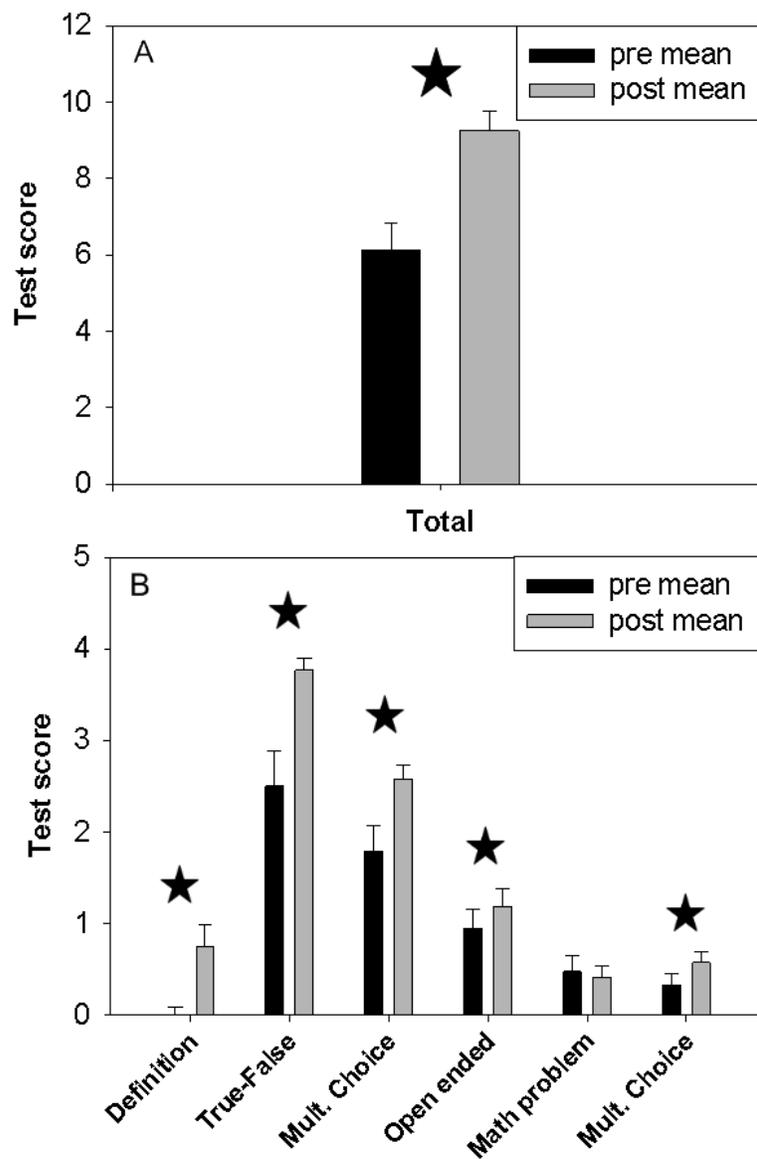
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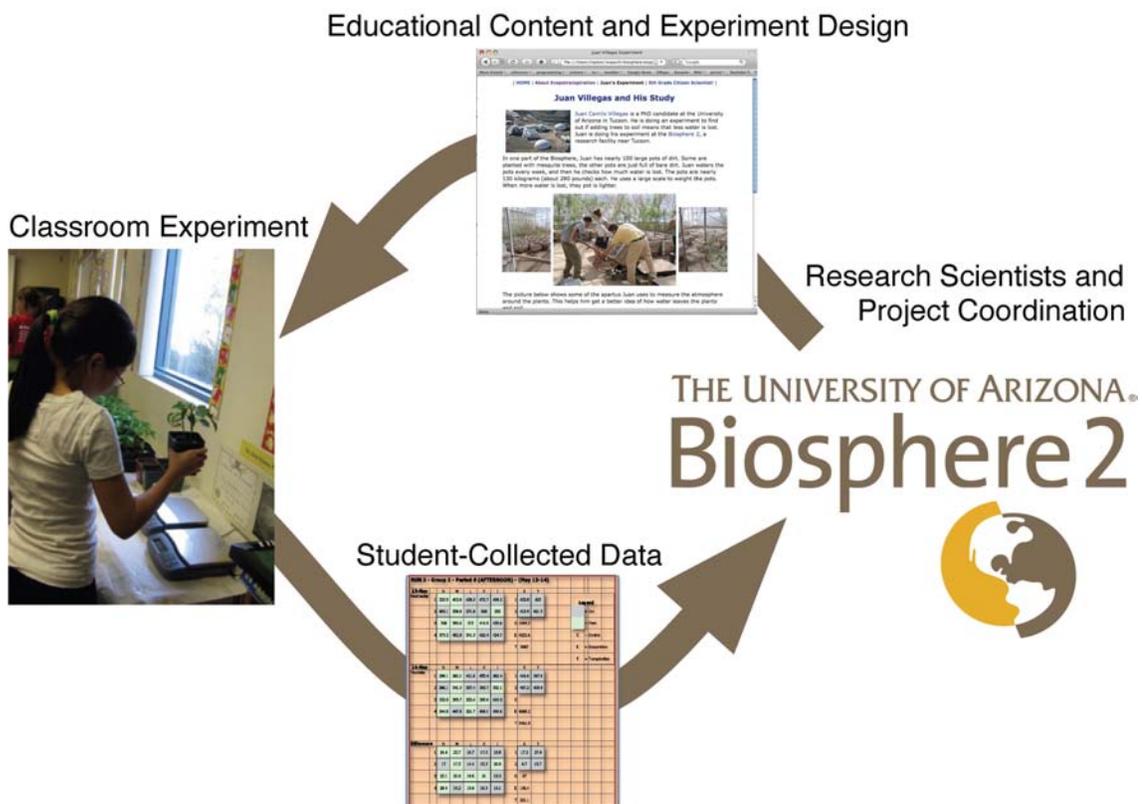
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## Figures



**Figure 1.** (A) Overall mean results from the pre- and post-assessment tests applied to the students before and after the completion of the experiment, and (B) mean results from each question type from pre- and post-assessment tests. Error bars indicate 95% confidence intervals around the mean values. Stars indicate significant differences between pre- and post-test results at an alpha level of 0.05.



**Figure 2.** Conceptual diagram illustrating the feedback cycle highlighted in this research-educational experience, starting from a current interdisciplinary scientific research project being developed at the University of Arizona’s Biosphere 2 glasshouse facility which has been adapted to be incorporated into the middle school science curriculum. This project incorporates important educational and experimental elements that improve the students’ understanding of both conceptual and practical elements in the topic, while gathering experimental data that informs the original scientific experiment.

**Appendix: Pre- and Post assessment instrument**  
**Evapotranspiration Project**

**Name:** \_\_\_\_\_ **Date:** \_\_\_\_\_ **Time:**

**Teacher:** \_\_\_\_\_

**NOTE: if you don't know the answer, just leave it blank.**

**(1) Fill in the Blanks:**

*Evapotranspiration* is \_\_\_\_\_ from the sum of \_\_\_\_\_ plus \_\_\_\_\_.

**(2) True or False (circle your answer):**

Temperature affects evapotranspiration. (True) (False).

Humidity affects evapotranspiration. (True) (False).

Evapotranspiration is the same as condensation. (True) (False).

Plants have nothing to do with evapotranspiration. (True) (False).

**(3) Choose the correct answer:**

**Evapotranspiration is an essential component of:**

(a) The Water Cycle (b) the Vegetable Cycle

(c) the Economic Cycle (d) All of the Above

(e) None of the Above

**Evapotranspiration is found in:**

(a) Outer Space (b) The Rainforest

(c) The Desert (d) Answers (b) and (c)

(e) All of the Above

**To study evapotranspiration I will need:**

(a) Soil (b) Sun

(c) Water (d) All of the Above

(e) Answers (a) and (c)

**(4) At noon, just before lunch, John weighed himself and found he was 78 pounds. After lunch, his friend Jane asked him how much the food he ate weighed. How can John and Jane figure out how much the food he ate weighed? (Only a short answer is needed.)**

**(5) There are about 28.35 grams in 1 ounce. There are 16 ounces in 1 pound. How many grams are in one pound?**

**(6) John is a teenager. He wants to find out how much he weighs. Three scales are available: (a) measures from 0 to 1600 grams, (b) measure 0 to 250 ounces, and (c) measures 0 to 250 kilograms. Which scale is the best one to use? (Circle one.)**

(a) Scale a

(b) Scale b

(c) Scale c

(d) None of the above