

THE INFLUENCE OF SNOW COVER DURATION
ON EVAPORATION AND SOIL RESPIRATION
IN MIXED-CONIFER ECOSYSTEMS

By

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Figure 1. Site figures of Santa Catalina Mountain research site: a) location within Arizona; b) percentage of annual precipitation that falls during the winter months, with eddy covariance flux tower location and vicinity to Tucson.

ABSTRACT

This thesis reports the results of a study that observed how the duration of snow season could influence evaporation and respiration fluxes from montane soils. The study occurred in the Santa Catalina Mountains north of Tucson, AZ from July, 2010 through September, 2011. It consisted of routinely measuring fluxes at locations determined to see earlier or later snow melt times, which were used as proxies to represent shorter and longer snow seasons, respectively.

The results of this study showed a strong correlation between evaporation fluxes and soil moisture, and soil respiration and soil temperature. Additionally, short snow season sites often saw higher fluxes of both evaporation and soil respiration than long snow season sites on any given day that measurements were taken. This suggests that if climate change results in shorter snow seasons, there will be increased carbon and water fluxes from the soil in these montane ecosystems.

1. INTRODUCTION

1.1 Climate Change and Subalpine Mixed-Conifer Ecosystems

Global temperatures are predicted to rise as much as 5°C within the next century (USGCRP 2009). This may result in changes to precipitation patterns of both rain and snow (Molotch et al. 2009) as well as the timing of snowmelt (Mote et al. 2005, Knowles et al. 2006). These changes may have profound effects on ecosystems at higher elevations, where snowmelt plays a large role in ecosystem processes (Bales et al. 2006). Thus, it is important to understand the climate changes that may occur, as well as what effects they may have on ecosystems, in order to better prepare for changing resource availability in the future.

As timing of snowfall and melt changes, it affects the water balance that is vital to the survival of montane forests (Barnett et al. 2005). In mixed-conifer ecosystems in the southwestern United States, snowmelt is fundamental to start the spring growing season and to sustain the plants through the summer until the monsoon rains arrive (Bales et al. 2006, Hamlet et al. 2007). Without adequate snowfall, there is less snowmelt to sustain the ecosystem. Montane forest zones, especially those found in the semi-arid southwestern United States, are also important water sources for watersheds downstream, and many ecosystems in the Southwest depend on precipitation from these 'sky islands' to sustain desert ecosystems (Viviroli and Weingartner 2004, Bales et al. 2006). The mountains create orographic uplift that causes air to cool and the water vapor to

condense, producing precipitation (Wu et al. 2009). This precipitation is important to downstream ecosystems that may not see much rain directly, but utilize the streams and groundwater supplies that are replenished from higher elevations (MEA 2005).

Snowpack is expected to decrease in semi-arid mixed-conifer ecosystems due to climate change (Mote et al. 2005, Knowles et al. 2006). A decreased snowpack results in less snowmelt to provide water to the montane regions and their water-dependent watersheds, thus there is less water for agricultural and ecological needs (MEA 2005). Additionally, if temperatures in the future increase, then snowmelt will occur earlier in the spring (Groisman et al. 2004), resulting in a longer growing season, in which more water is needed to sustain the vegetation. Under these decreased precipitation conditions, there will be less plant available moisture throughout the spring and summer (Leung et al. 2004, Hamlet et al. 2007), increasing the likelihood of drought conditions and stress on the vegetation. Over prolonged periods of drought, the vegetation of these montane ecosystems become more prone to insect infestations (Anderson et al. 2010, Kane and Kolb 2010) and less resistant to fire (Bessie and Johnson 1995, Sibold and Veblen 2006, Blarquez and Carcaillet 2010), potentially resulting in massive losses of these ecosystems.

1.2 Climate Change Implications for Soil Evaporation and Soil Respiration in Subalpine Mixed-Conifer Ecosystems

Aside from changing precipitation patterns, evaporation also plays a large role in the amount of moisture that remains within a catchment. About half of precipitation can

be intercepted by vegetation as it falls, much of which evaporates before it can reach the ground (Musselman et al. 2008). Of the precipitation that does reach the ground, a significant portion of it evaporates before it can infiltrate into the soil or be used by plants. In the Southwest, large percentages of precipitation can easily be lost to evaporation, especially in low-elevation ecosystems (Kurc and Small 2004). In order to better predict water availability in the future, it is essential to understand how evaporative fluxes may change.

Research has tended to focus on evaporative fluxes related to vegetation (evapotranspiration) when working on ecosystem-level scales in mixed-conifer ecosystems because it tends to be easier to measure than evaporation alone (Hamlet et al. 2007, LaMalfa and Ryle 2008). Some ecosystem-scale studies have worked to break apart evapotranspiration into its components, evaporation and transpiration, but these are often based on equations and/or remote sensing data rather than in situ measurements (Seguin et al. 1994, Carlson et al. 1995). Research has also explored how vegetation may impact evaporation due to radiative forcing and distribution of snow accumulation, with open inter-canopy areas resulting in earlier snowmelt and greater snow ablation and usually resulting in more evaporation (Thomas and Rowntree 1992, Molotch et al. 2009). Other studies have explored how climatic changes will affect the water balance, specifically in the form of snow sublimation or evaporation during snowmelt, showing that years with warmer spring temperatures and earlier snowmelt result in more water lost to evaporation (Schmidt et al. 1998, Moore et al. 2008). However, most of these studies focus on winter months, when snow is present, and largely miss what happens to the evaporation fluxes from the soil throughout the summer. Thus, this study works to link

the snow season duration to the soil evaporation fluxes seen throughout the year, in order to better understand how a changing snow season will affect annual evaporation trends.

In addition to changes in evaporation, climate change may also alter terrestrial carbon fluxes. Soils contain large stores of carbon, and increasing temperatures may release greater amounts of carbon from the soils to the atmosphere (DeForest et al. 2006, Bond-Lamberty and Thomson 2010). This release of carbon in the form of carbon dioxide, i.e. soil respiration (R), is mainly composed of components from microbe and plant root processes (Bond-Lamberty and Thomson 2010). Since such a contribution of greenhouse gases to the atmosphere could further propagate climate change, and since R can be such a large percentage of total ecosystem respiration (Barron-Gafford et al. 2011), it is important to study how soil respiration might change in the future.

In recent years, studies have begun to explore how carbon fluxes to the atmosphere may change in coming decades by observing ecosystem-scale respiration utilizing eddy-covariance towers to study responses to climatic factors (i.e. precipitation, temperature changes; e.g. Brown-Mitic et al. 2007, Anderson-Teixeira et al. 2011, Riveros-Iregui et al. 2011). Fewer have tried to partition between sources of carbon within the ecosystem (e.g. DeForest et al. 2006, Bond-Lamberty and Thomson 2010, Hasselquist et al. 2010, Khomik et al. 2010). While many of the ecosystem-scale studies have been conducted in subalpine mixed-conifer ecosystems, most of these ecosystems are in snow-dominated regions that lack significant reliance on summer rains. Additionally, the partitioning studies have spanned a range of ecosystems (i.e. boreal to deciduous), often resulting in conflicting ideas of whether R will increase or decrease with changing soil moisture and temperatures, making these findings difficult to apply to

ecosystems that rely heavily on snowmelt. The partitioning studies have also largely overlooked how the duration of snow cover may alter R fluxes, and many only conduct measurements over one portion of the year (Hirano 2005, Concilio et al. 2009, Peichl et al. 2010). Thus, to more fully understand how changes within the mixed-conifer ecosystems of the North American Southwest may influence R fluxes, this study looks to how changing duration of snow seasons will alter carbon fluxes throughout the year.

1.3 Research Objectives

While predicting changes due to potential future climate conditions can be difficult, it is clear that more studies need to be conducted to better understand how evaporation and soil respiration might be affected by climate variations, such as snowmelt. Of particular importance is how these factors might change in semi-arid mixed-conifer ecosystems like those found in the southwestern United States so that we can better understand water availability and changes to the carbon balance.

This study was designed to fill this knowledge gap. Here we observed different areas classified to have earlier and later snowmelt times and tracked water and carbon fluxes for over a year. We identified three different study locations within an existing study site on Mt. Bigelow in the Santa Catalina Mountains north of Tucson, AZ (Figure 1). We installed soil collars (PVC pipe) into the soil in sites we had identified to have later or earlier snowmelt, referred to as ‘short snow season’ and ‘long snow season’ sites, respectively (three collars in each site type, across all three study locations, for a total of

18 collars). We expected to see higher levels of evaporation and soil respiration from the late snow melt sites. This was due to the prediction that these sites would have more water entering the soil later in the spring, resulting in a greater soil water content during higher temperature days to drive respiration and evaporation compared to the short snow season sites. We also expected peak fluxes to occur later in the spring for the long snow season sites than the short snow season sites, since spring peaks would be influenced by the different timing of snowmelt. Finally, we expected summer peaks to occur at the same time for both site types since summer peaks would be driven by monsoon rains, which occur at the same time for both the long and short snow season sites.

1.4 Site Description

The study area is located in the Santa Catalina Mountains in southern Arizona, about 10 km north of Tucson (Figure 1). The climate of the site is semi-arid, with precipitation falling primarily in a bimodal pattern (Brown-Mitic et al. 2007), as snow during the winter (December through March) and rain during the North American monsoon (July and August; Gochis et al. 2006). Average annual precipitation is 750 mm, and average temperatures range from -5 to 32°C (Brown-Mitic et al. 2007). The dominant species in the study area are primarily Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*), and soils are a sandy loam. An eddy covariance tower is located in the middle of the study area and stands 30 m tall at an elevation of 2570 m a.s.l.. This tower measures ecosystem-scale water vapor and carbon fluxes,

incoming and outgoing radiation, wind speed and direction, precipitation, and sensible heat (for more information, see Brown-Mitic et al. 2007). Additionally, placed within the footprint of this tower are three time-lapse digital cameras used to observe and study snowfall patterns and under-canopy growth.

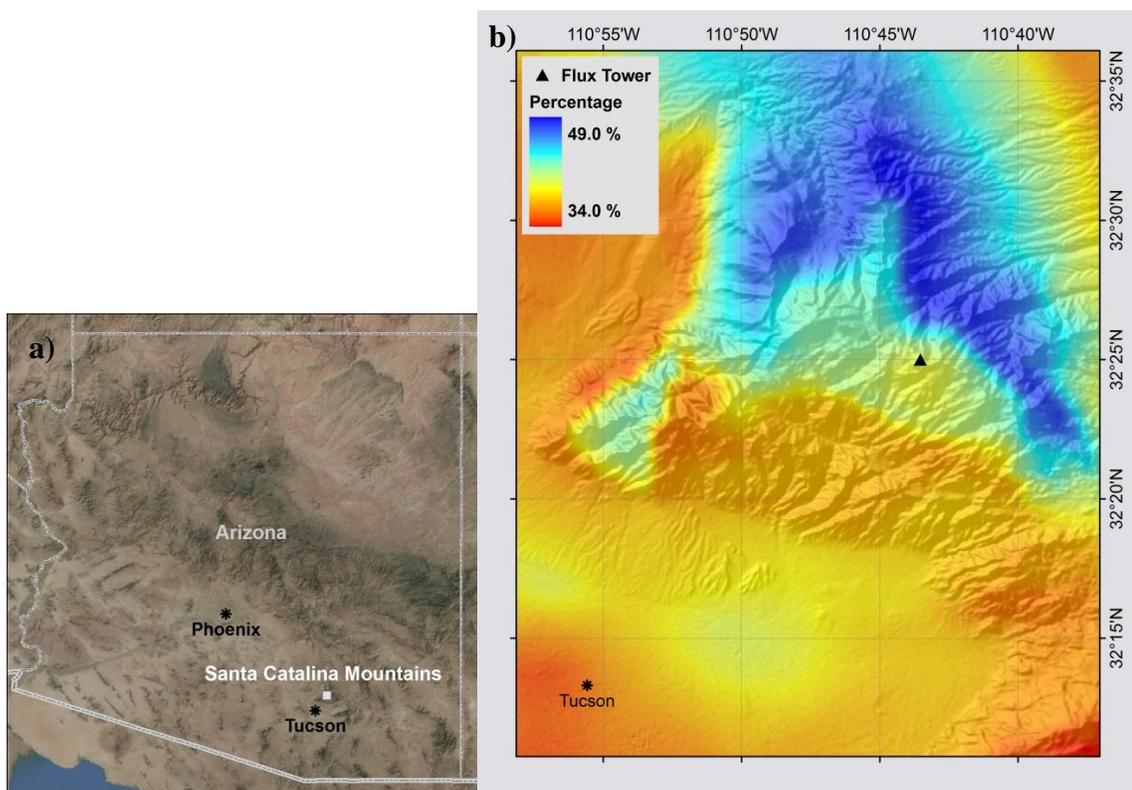


Figure 1: a) Location of study site in Arizona. b) Study site (black triangle) in relation to Tucson, showing distribution of percentage of precipitation that falls during winter months. This figure was produced using monthly precipitation averages from 1971-2000.

1.5 Structure of Subsequent Chapters

The body of this study is in manuscript form, included in its entirety in Appendix A. The appendix includes the detailed methods, results, and discussion. The manuscript is planned for submission to a peer reviewed publication in early 2012.

The following section, Present Study, includes the abstract summarizing Appendix A.

2. PRESENT STUDY

The methods, results, and discussion of this study are provided in the appendix of this thesis. Supplied here is an abstract of Appendix A, which describes the study in detail in the form of a paper to be submitted for publication.

2.1 Abstract of Appendix A: Influence of snow season duration on evaporation and soil respiration effluxes in mixed-conifer ecosystems

Subalpine mixed-conifer ecosystems are dependent on snowfall, which is expected to decrease under projected climate change. Changes in snowpack are likely to have important consequences for water and carbon cycling in these ecosystems and those downstream in the watersheds. Particularly within semiarid environments, snowpack changes will directly influence localized water and carbon dynamics and indirectly influence regional-scale levels of water availability and carbon sequestration. In this study we monitor soil evaporation (E) and soil respiration (R) and evaluate how snow cover affects these effluxes within a mixed-conifer ecosystem within the Santa Catalina Mountains about 10 km north of Tucson, Arizona. Using time-lapsed digital photos we identified areas of consistent short and long snow duration and we monitored E and R in these areas every two weeks for fifteen months. Our primary findings include: (1) E does not vary much between long and short snow season sites, (2) E for both short and long

snow seasons has a strong relationship with soil moisture and a poor relationship with soil temperature, (3) R varies noticeably between long and short snow season sites throughout the year, with short snow season fluxes typically higher than those of long snow season sites, and (4) R for short and long snow seasons has a strong relationship with soil temperature and a poor relationship with soil moisture. Our findings suggest that soil respiration may be influenced enough by these environmental changes such that we might expect greater carbon losses to the atmosphere given current climate change scenarios.

3. REFERENCES

- Anderson, R. S., S. J. Smith, A. M. Lynch, and B. W. Geils. 2010. The pollen record of a 20th century spruce beetle (*Dendroctonus rufipennis*) outbreak in a Colorado subalpine forest, USA. *Forest Ecology and Management* **260**:448-455.
- Anderson-Teixeira, K. J., J. P. Delong, A. M. Fox, D. A. Brese, and M. E. Litvak. 2011. Differential responses of production and respiration to temperature and moisture drive the carbon balance across a climatic gradient in New Mexico. *Global Change Biology* **17**:410-424.
- Bales, R. C., N. P. Molotch, T. H. Painter, M. D. Dettinger, R. Rice, and J. Dozier. 2006. Mountain hydrology of the western United States. *Water Resources Research* **42**.
- Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**:303-309.
- Barron-Gafford, G. A., R. L. Scott, G. D. Jenerette, and T. E. Huxman. 2011. The relative controls of temperature, soil moisture, and plant functional group on soil CO₂ efflux at diel, seasonal, and annual scales. *Journal of Geophysical Research-Biogeosciences* **116**:16.
- Bessie, W. C. and E. A. Johnson. 1995. THE RELATIVE IMPORTANCE OF FUELS AND WEATHER ON FIRE BEHAVIOR IN SUB-ALPINE FORESTS. *Ecology* **76**:747-762.
- Blarquez, O. and C. Carcaillet. 2010. Fire, Fuel Composition and Resilience Threshold in Subalpine Ecosystem. *Plos One* **5**:8.
- Bond-Lamberty, B. and A. Thomson. 2010. Temperature-associated increases in the global soil respiration record. *Nature* **464**:579-U132.
- Brown-Mitic, C., W. J. Shuttleworth, R. C. Harlow, J. Petti, E. Burke, and R. Bales. 2007. Seasonal water dynamics of a sky island subalpine forest in semi-arid southwestern United States. *Journal of Arid Environments* **69**:237-258.
- Carlson, T. N., W. J. Capehart, and R. R. Gillies. 1995. A NEW LOOK AT THE SIMPLIFIED METHOD FOR REMOTE-SENSING OF DAILY EVAPOTRANSPIRATION. *Remote Sensing of Environment* **54**:161-167.
- Concilio, A., J. Q. Chen, S. Ma, and M. North. 2009. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest. *Climatic Change* **92**:109-122.

- DeForest, J. L., A. Noormets, S. G. McNulty, G. Sun, G. Tenney, and J. Q. Chen. 2006. Phenophases alter the soil respiration-temperature relationship in an oak-dominated forest. *International Journal of Biometeorology* **51**:135-144.
- Gochis, D. J., L. Brito-Castillo, and W. J. Shuttleworth. 2006. Hydroclimatology of the North American Monsoon region in northwest Mexico. *Journal of Hydrology* **316**:53-70.
- Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. M. Sun, and J. H. Lawrimore. 2004. Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* **5**:64-85.
- Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2007. Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. *Journal of Climate* **20**:1468-1486.
- Hasselquist, N. J., R. Vargas, and M. F. Allen. 2010. Using soil sensing technology to examine interactions and controls between ectomycorrhizal growth and environmental factors on soil CO₂ dynamics. *Plant and Soil* **331**:17-29.
- Hirano, T. 2005. Seasonal and diurnal variations in topsoil and subsoil respiration under snowpack in a temperate deciduous forest. *Global Biogeochemical Cycles* **19**.
- Kane, J. M. and T. E. Kolb. 2010. Importance of resin ducts in reducing ponderosa pine mortality from bark beetle attack. *Oecologia* **164**:601-609.
- Khomik, M., M. A. Arain, J. J. Brodeur, M. Peichl, N. Restrepo-Coupe, and J. D. McLaren. 2010. Relative contributions of soil, foliar, and woody tissue respiration to total ecosystem respiration in four pine forests of different ages. *Journal of Geophysical Research-Biogeosciences* **115**:17.
- Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the Western United States. *Journal of Climate* **19**:4545-4559.
- Kurc, S. A. and E. E. Small. 2004. Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico. *Water Resources Research* **40**.
- LaMalfa, E. M. and R. Ryle. 2008. Differential snowpack accumulation and water dynamics in aspen and conifer communities: Implications for water yield and ecosystem function. *Ecosystems* **11**:569-581.
- Leung, L. R., Y. Qian, X. D. Bian, W. M. Washington, J. G. Han, and J. O. Roads. 2004. Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change* **62**:75-113.

- MEA. 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Desertification Synthesis. World Resources Institute, Washington, DC.
- Molotch, N. P., P. D. Brooks, S. P. Burns, M. Litvak, R. K. Monson, J. R. McConnell, and K. Musselman. 2009. Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. *Ecohydrology* **2**:129-142.
- Moore, D. J. P., J. Hu, W. J. Sacks, D. S. Schimel, and R. K. Monson. 2008. Estimating transpiration and the sensitivity of carbon uptake to water availability in a subalpine forest using a simple ecosystem process model informed by measured net CO₂ and H₂O fluxes. *Agricultural and Forest Meteorology* **148**:1467-1477.
- Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in western north America. *Bulletin of the American Meteorological Society* **86**:39-+.
- Musselman, K. N., N. P. Molotch, and P. D. Brooks. 2008. Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrological Processes* **22**:2767-2776.
- Peichl, M., M. A. Arain, S. Ullah, and T. R. Moore. 2010. Carbon dioxide, methane, and nitrous oxide exchanges in an age-sequence of temperate pine forests. *Global Change Biology* **16**:2198-2212.
- Riveros-Iregui, D. A., J. Hu, S. P. Burns, D. R. Bowling, and R. K. Monson. 2011. An interannual assessment of the relationship between the stable carbon isotopic composition of ecosystem respiration and climate in a high-elevation subalpine forest. *Journal of Geophysical Research-Biogeosciences* **116**:15.
- Schmidt, R. A., C. A. Troendle, and J. R. Meiman. 1998. Sublimation of snowpacks in subalpine conifer forests. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* **28**:501-513.
- Seguin, B., D. Courault, and M. Guerif. 1994. SURFACE-TEMPERATURE AND EVAPOTRANSPIRATION - APPLICATION OF LOCAL SCALE METHODS TO REGIONAL SCALES USING SATELLITE DATA. *Remote Sensing of Environment* **49**:287-295.
- Sibold, J. S. and T. T. Veblen. 2006. Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. *Journal of Biogeography* **33**:833-842.
- Thomas, G. and P. R. Rowntree. 1992. THE BOREAL FORESTS AND CLIMATE. *Quarterly Journal of the Royal Meteorological Society* **118**:469-497.
- USGCRP. 2009. Global Climate Change Impacts in the United States. United States Global Change Research Program.

- Viviroli, D. and R. Weingartner. 2004. The hydrological significance of mountains: from regional to global scale. *Hydrology and Earth System Sciences* **8**:1016-1029.
- Wu, G. X., Y. Liu, X. Zhu, W. Li, R. Ren, A. Duan, and X. Liang. 2009. Multi-scale forcing and the formation of subtropical desert and monsoon. *Annales Geophysicae* **27**:3631-3644.

APPENDIX A: INFLUENCE OF SNOW COVER DURATION ON SOIL
EVAPORATION AND RESPIRATION EFFLUX IN MIXED-CONIFER
ECOSYSTEMS

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1. Introduction

Evidence suggests that the global climate is changing [IPCC, 2007], and that these changes are affecting ecosystems worldwide both directly [Breshears *et al.*, 2005; Feeley *et al.*, 2007; Jump *et al.*, 2006; van Mantgem and Stephenson, 2007] and indirectly [e.g. Bentz *et al.*, 2010; Kulakowski *et al.*, 2011; Littell *et al.*, 2009]. Forested ecosystems at subalpine elevations may be particularly vulnerable to climatic changes [Crimmins *et al.*, 2011; Parmesan, 2006; Sang and Bai, 2009], which will have important consequences for areas downstream of them [e.g. Brown *et al.*, 2008; Lopez and Justribo, 2011; Viviroli and Weingartner, 2004]. Unquestionably, understanding how changes in climate may affect subalpine forested ecosystems is of critical importance in forest and watershed management [e.g. Allen *et al.*, 2010; Viviroli *et al.*, 2003].

Within the semiarid southwestern United States (US), a transition to a drier climate began in the late 20th century and is expected to be sustained well into the future [Seager *et al.*, 2007; Woodhouse *et al.*, 2010]. In the higher elevation areas, this translates to less precipitation that occurs as snow [Barnett *et al.*, 2008; Knowles *et al.*, 2006; Miller *et al.*, 2003; Mote *et al.*, 2005] and an earlier onset of snowmelt [Hidalgo *et al.*, 2009; Stewart *et al.*, 2005]. As a consequence of less snowpack and earlier melt, less soil moisture will be available in the spring at the onset of the growing season [Gimenez-Benavides *et al.*, 2007; Hamlet *et al.*, 2007; Kueppers and Harte, 2005] and throughout the summer [Leung *et al.*, 2004; Peterson and Peterson, 1994; Quiring and Kluver, 2009] in these subalpine ecosystems. Furthermore, while summer rainfall events are expected to increase in intensity in the southwestern US, the frequency of these events is likely to

decrease [Seager *et al.*, 2007]. This new rainfall regime should further limit the amount of soil moisture available for ecohydrological processes in these ecosystems [Hamlet *et al.*, 2007; Wetherald and Manabe, 2002].

Despite their influence on fluxes of water and carbon lower in the watershed, few field studies have looked at ecohydrological processes in subalpine forested ecosystems [Bales *et al.*, 2006; Matyssek *et al.*, 2009], especially within semiarid regions.

Ecohydrological processes within these forested ecosystems generally depend on two main soil moisture seasons; the first associated with spring snow melt and the second with summer rains [e.g. Brown-Mitic *et al.*, 2007; LaMalfa and Ryle, 2008]. Soil moisture in these two seasons tends to penetrate the soil column to depths in the rooting zone beyond the influence of evaporative demand [Boulet *et al.*, 1997], enabling an increase in plant-driven ecohydrological processes such as water loss through transpiration [Matyssek *et al.*, 2009; Small and McConnell, 2008] and carbon sequestration through photosynthesis [Kueppers and Harte, 2005; Monson *et al.*, 2002]. Moisture provided from snow melt has also been shown to persist throughout the summer, the presence of which tends to elevate summer soil respiration in these subalpine mixed-conifer ecosystems within semiarid regions [Concilio *et al.*, 2009; Hogberg *et al.*, 2001].

Few field-based research studies have evaluated how ecohydrological processes will be impacted by climate change, especially with respect to changes in winter precipitation dynamics. Previous research in a deciduous forest demonstrated that annual carbon dynamics were strongly dependent on growing season length and amount of snow cover, such that years with longer growing seasons were associated with more

carbon sequestration and years with deeper insulating snowpack were associated with more carbon release [Goulden *et al.*, 1996]. However, a recent long-term study in a subalpine forested ecosystem illustrated that an increase in the length of the growing season was actually associated with a decrease in carbon uptake [Hu *et al.*, 2010; Monson *et al.*, 2002]. This unexpected finding is a consequence of years with longer growing seasons tending to have less snow cover, a critical resource for this mixed-conifer ecosystem that depends on snowmelt water for about 70 % of its gross primary productivity [Hu *et al.*, 2010]. Noticeably absent is a study from a subalpine forested ecosystem which also receives significant summer rains in addition to winter snow. Given the expected changes in the length of snow cover [e.g. Brown and Mote, 2009; Mote *et al.*, 2005] and in the length of the growing season [e.g. Menzel and Fabian, 1999; Schwartz *et al.*, 2006], a more complete understanding of the role of winter precipitation dynamics in ecohydrological processes is critical for predicting how water and carbon cycles will be altered under the pressures of climate change.

Trends in snowpack appear to provide a critical coupling between climate and water and carbon cycles that is not well understood. To help address this knowledge gap, we looked at the influence of snow cover duration on ecohydrological processes in a subalpine mixed-conifer forest ecosystem of the southwestern US. By evaluating multiple years of time-lapse digital photos, we identified persistent sites of long and short snow duration within our ecosystem. At these sites, we evaluated the seasonal dynamics of soil evaporation (E) and soil respiration (R) for over a year across the two main soil moisture seasons (winter snow, summer rain) to address the following hypotheses. We hypothesized that (i) the time series of E and R would be bimodal, responding first to

spring snow melt and then to summer rain; (ii) sites of long snow duration would have a lagged but larger springtime peak in E than sites of short snow duration; and (iii) the springtime respiration response to snowmelt would be larger than the summer respiration response to rain and that this springtime response would be greater in the sites of long snow duration. These hypotheses were based on the assumptions that (i) greater water availability would result in higher E and R rates, (ii) water would become available for evaporation later at the long snow season sites due to later snowmelt, and (iii) snowmelt would result in more water entering the soil in a shorter amount of time than would the summer rains, leading to higher spring respiration rates.

2. Methods

2.1 Study Area

The study was conducted in the Santa Catalina Mountains in southern Arizona, about 10 km north of Tucson (Figure 1). The climate is semiarid and precipitation falls primarily in a bimodal pattern [*Brown-Mitic et al.*, 2007], as snow during the winter (December through March) and rain during the North American monsoon (July and August) [*Gochis et al.*, 2006]. Average annual precipitation is about 750 mm, and average temperatures range from -5 to 32°C [*Brown-Mitic et al.*, 2007]. The dominant plant species in the study area are primarily Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) and the soil is predominantly sandy loam. An eddy covariance (EC) tower is centrally located in the study area and stands 30 m tall at an elevation of 2570 m. The instrumentation at this EC tower provides ecosystem-scale

estimates of water vapor and carbon fluxes, incoming and outgoing radiation, wind speed and direction, precipitation, and sensible heat flux (for more information, see Brown-Mitic et al. [2007]). Additionally, within the footprint of this EC tower are three time-lapse digital cameras used to observe and study snowfall patterns and under-canopy growth.

2.2 Soil Evaporation and Soil Respiration Measurements

2.2.1 Soil Collar Sites

Three Game Spy I-60 digital cameras (Moultrie Feeders, Alabaster, AL) were installed at 1 m above the ground within the eddy covariance tower footprint in the winter of 2009-2010. The cameras are set to take hourly red-green-blue spectrum (RGB) images, which are downloaded every two weeks. These images are used to observe snow melt patterns, as persistent bare and snow-covered patches became apparent in the images throughout the spring. Sites for Long Snow Season (LSS) and Short Snow Season (SSS) sites were selected based on the duration of snow cover in the image frame. Within each camera frame, three LSS collar sites and three SSS collar sites were selected for a total of 18 collar sites across the three camera sites (Figure 2). For our study period, which began in July 2010, the average difference in snow cover seasons between LSS and SSS sites was 12 days, but ranged in length from 38 to 56 days long for SSS sites and 45 to 64 days for LSS sites. This 12-day difference falls within the projected change in snow season length of one to four weeks [Stewart et al., 2005]. For this study, we use the average difference in snow cover season (i.e. the number of days collars were covered in snow) as a proxy for differences in snow cover duration between the sites. We note that this

approach may be less than ideal as vegetation and microclimatic forcings may shape snow cover at this scale. However, the collars are within several meters of each other and previous research has shown that soil moisture differences at this scale are not statistically distinct [Bales *et al.*, 2011]. Therefore, we feel this novel approach offers the best means at non-invasively examining how snow cover duration may influence evaporation and respiration while holding larger scale climate forcings constant.

2.2.2 Sampling Design

We installed polyvinyl chloride (PVC) soil collars (10.2 cm diameter) 5 cm into the soil within the field of view of each time-lapse camera at LSS and SSS sites. In the summer of 2010, soil respiration measurements were conducted before, during, and after several rainfall events (DOY 174, 188, 195, 208, 217). Beginning in September of 2010, measurements were taken biweekly until the onset of the snow season. Measurements were always taken between 0900-1200 local time. To avoid disturbing the melting patterns during the snow season, measurements were not taken when snow on the ground prevented access to the collars. Measurements were also not taken if snow was present in the collar.

2.2.3 Data Collection and Analysis

Measurements were taken at each collar using an infrared gas analyzer system (LI-840, LI-COR Biosciences, Lincoln, NE). A custom PVC chamber (3 L volume) connected to the gas analyzer was fitted tightly onto the collar and concentrations of CO₂ and water vapor (H₂O) were measured at 1 Hz for two minutes (similar to methods

described in Barron-Gafford et al. [2011]). A small fan within the chamber ensured the gases remained well-mixed. Thermocouples within the chamber were used to measure air temperature and surface soil temperature. Additional measurements taken within 15 cm of the outside edge of the chamber included volumetric soil moisture in the upper 6 cm (W.E.T. sensor, Delta-T Devices, Cambridge, UK) and soil temperature in the top 10 cm (15-077-8B digital thermometer, Fischer Scientific, Pittsburgh, PA). Depth from the top edge of the collar to the soil surface within the collar was also measured using a ruler at four points along the circumference. The average of these depths was used to determine the additional volume of the collar for the flux calculations.

2.2.4 Calculating Soil Evaporation and Soil Respiration Fluxes

To calculate the soil respiration (R) within each chamber, CO₂ concentration measurements taken during the two-minute interval were graphed as a function of time. The slope was then calculated and used in the following equation to convert the measured change in concentration of CO₂ within the chamber into a flux value:

$$R = n \times \frac{P}{\mathfrak{R}T} \times \frac{V}{A} \quad (1)$$

where R is soil respiration ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), n is the slope from the time-CO₂ relationship (ppm s^{-1}), P is the pressure inside the chamber (atm), \mathfrak{R} is the universal gas constant ($\text{L atm mol}^{-1} \text{ K}^{-1}$), T is the temperature of the air within the chamber (K), V is the

combined volume of the chamber and the collar (L), and A is the cross sectional area of the collar (cm^2).

Likewise, evaporation (E) was calculated within each chamber based on measurements taken during this same two-minute interval. The slope of H_2O concentration as a function of time was then calculated and used in the following equation to convert the measured change in concentration within the chamber into a flux value:

$$E = n \times \frac{P}{RT} \times \frac{V}{A} \quad (2)$$

where E is soil evaporation ($\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), n is the slope from the time- H_2O relationship (ppt s^{-1}), and the other variables are the same as in Equation (1). For the analysis throughout this study, units of $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ were converted to mm d^{-1} .

3. Results

3.1 Temperature, Precipitation, and Soil Moisture Dynamics

Throughout the study period, integrated soil temperature (T , i.e. average temperature from the soil surface to a depth of 10 cm) followed a typical annual cycle beginning high in the summer, decreasing into the winter, and increasing again through the spring (Figure 3a). Little variation was observed between years. Precipitation, measured at the eddy covariance tower, showed a bimodal pattern typical of semi-arid ecosystems in the southwestern US (Figure 3b). Large rainstorms occurred frequently

throughout the 2010 summer (194.1 mm), while summer of 2011 experienced much less precipitation (78.99 mm).

Soil moisture (θ) varied throughout the course of the year and was largely linked to precipitation events (Figure 3c). In both years, θ increased at the onset of the summer precipitation season (early July). In 2010, this summer increase in θ persisted until mid-September, when θ peaked, then decreased as rainfall became less frequent. In 2011, the summer increase in θ persisted for only a couple of weeks, peaking in July, before it began to decrease again. Throughout the winter, θ remained elevated in response to winter precipitation events, declining in February in the absence of precipitation events, but increased again in early March with the onset of snowmelt.

In 2010, snow fall began in December, but snow cover was only observed for two days at the LSS sites and did not remain at the SSS sites for nearly the entire month (Figure 3d). By the end of December 2010 and into 2011, a consistent snow cover was established at both the LSS and SSS sites. This snow cover remained through mid-February for LSS sites, while SSS sites were already becoming exposed in late January and finished melting earlier in February than the LSS sites. The last observable snow cover in spring 2011 was due to one small snowfall event at the end of February and resulted in two days of snow cover in both LSS and SSS sites. The average difference in snow cover between LSS and SSS sites was 12 days.

3.2 Evaporation and Soil Respiration Dynamics

As was seen for soil moisture, E dynamics generally followed precipitation dynamics (Figure 4a). Evaporation was high in the summer with the onset of summer

precipitation in both 2010 and 2011. However, in summer 2011, E was much lower than 2010, which is consistent with lower summer precipitation inputs in 2011 than 2010. Evaporation rates began to decline as soil temperatures declined (Figure 4a; Figure 2b), reaching minimum rates in December. A spring spike in E (Figure 4a), appeared to be linked to a combination of snowmelt (Figure 3d), a small precipitation event in late February (Figure 3b), and an increase in soil temperature (Figure 3a). Overall, SSS sites tended to experience slightly higher E rates than LSS sites, especially when E rates were at their maximums (Figure 4a). However, the opposite was occasionally true (e.g. in 2010, DOY 188, 195, 253; in 2011, DOY 39, 130, 147, 193, 224).

Soil respiration dynamics were similar to evaporation dynamics throughout the study period (Figure 4b), though we observed interesting advanced differences between the two fluxes. Soil respiration was highest in the summer in both years, associated with the onset of summer precipitation and increased soil moisture. As opposed to E , however, the magnitude of R was not much lower in 2011 than in 2010 despite the difference in summer precipitation inputs between the years. Similar to the response seen for E , the summer increases in R happened quickly (over 1 month) but R decreased to the minimum values more slowly (over 3 months). Respiration also exhibited a small, quick peak in May 2011 shortly after snowmelt, but otherwise R remained low for the remainder of the spring and into the early summer. Throughout the study period, respiration rates at SSS sites were predominantly higher than at LSS sites, with only a few exceptions.

In order to better understand the differences in E and R fluxes between the SSS and LSS sites, we computed cumulative values for the 2010-2011 water year (October 1,

2010 – October 1, 2011). We began by interpolating the data using a simple linear interpolation between the collected data points in order to obtain daily values for both E and R using a method similar to that described in Riveros-Iregui et al. [2008]. These daily values were then summed over the course of the water year to obtain cumulative values for each day (Figure 5). At the end of the water year, E had almost identical values between SSS and LSS sites (48.4 and 47.7 mm, respectively; Figure 5a), which accounted for approximately 20% of the total precipitation for that time. The figure also illustrates how E between SSS and LSS sites tended to be almost identical except during the spring, when SSS sites had higher E rates for about 3 months. At the end of this time, however, LSS fluxes increased while SSS fluxes leveled off, resulting in almost matching values once again. Contrary to the E results, the cumulative R graph (Figure 5b) shows a notable difference between SSS and LSS sites throughout the course of the year. The difference between the SSS and LSS fluxes increased slightly through the spring and summer, then decreased slightly in the spring, but SSS sites saw consistently higher values. By the end of the water year, SSS sites had released 3782 g/m² of CO₂, while LSS sites had only released 3440 g/m² of CO₂.

3.3 Soil Temperature and Soil Moisture Controls on E and R

Soil temperature exerted minimal control on E regardless of snow season length ($R^2 = 0.07$ and $R^2 = 0.06$ respectively; Figure 6a, Table 1). While still not strong, soil moisture control on E was greater than that for T ($R^2 = 0.23$ and $R^2 = 0.20$ respectively; Figure 6b, Table 1). Overall, SSS sites appeared to be slightly more sensitive to both θ and T (slightly steeper slopes; Figure 6, Table 1).

For both SSS and LSS sites, T appeared to strongly control R ($R^2 = 0.58$ and $R^2 = 0.56$ respectively Figure 7a, Table 1). Soil moisture control was minimal on R in both SSS and LSS sites ($R^2 = 0.07$ and $R^2 = 0.01$ respectively Figure 7b, Table 1). While both SSS and LSS sites were similarly sensitive to soil temperature (similarly steep slopes; Figure 7a, Table 1), SSS sites appeared to be more sensitive to soil moisture than LSS sites (steeper slope; Figure 7b, Table 1).

3.4 Soil “Water Use Efficiency”

In plant physiological ecology, water use efficiency (WUE) is traditionally defined as “the ratio between above-ground gain in biomass and loss of water during the production of biomass” [Lambers *et al.*, 2008, p. 56]. Here, we consider a more generic meaning of the term – the ratio between a particular process and the amount of water used for that process – to define soil water use efficiency (WUE_{soil}) as the ratio between carbon loss from the soil and the amount of water lost during that loss of carbon, i.e. R/E . This suggests that more carbon is lost through respiration in a site with high WUE_{soil} than is lost in a site with low WUE_{soil} for the same amount of water lost through evaporation.

The relationship between R and E was strong for both SSS and LSS sites ($R^2 = 0.61$ and 0.59 , respectively; Figure 8a, 8b, and Table 2). However, LSS sites had a higher WUE_{soil} than SSS sites, i.e. the slope of regression between R and E was significantly greater for LSS sites than for SSS sites (Figure 8a, 8b, and Table 2). Interestingly, SSS sites had higher WUE_{soil} when soil moisture was low than LSS sites (Figure 8c, 8d, and Table 2), suggesting that SSS sites became more efficient at carbon loss (i.e. used less water for their carbon release) as the soil dried than LSS sites. While

not as strong as for soil moisture, the case was similar for soil temperature: SSS sites had slightly higher WUE_{soil} than LSS sites when soil temperature was high (Figure 8e, 8f, and Table 2). This suggests that SSS sites became slightly more efficient at carbon loss as the soil warmed than LSS sites.

4. Discussion

4.1 Dynamics of E and R in a Subalpine Mixed-conifer Ecosystem

As we hypothesized, in this subalpine mixed-conifer ecosystem the time series of E and R were bimodal, responding first to spring snow melt and then to summer rain (Figure 4). The response to summer rain for both E and R during the drier year (2011) was smaller than the response during the wetter year (2010). For both E and R , the response to spring snow melt (Figure 4, March – April) was much smaller and shorter in duration compared to the response to summer rains (Figure 4, July – October). This was contrary to our hypothesis that the response of R to spring snow melt would be greater than that to summer rain, which was founded on the prediction that there would be more water available in the spring to increase the production of R . However, our original hypothesis did not consider the role of winter microbial activity, which can be large under snowpack [e.g. *Brooks et al.*, 1996; *Mast et al.*, 1998; *Monson et al.*, 2006], potentially leading to a reduction in substrate availability once temperatures increase during spring snow melt [*Brooks et al.*, 2005]. Mixed-conifer ecosystems experience litter fall throughout the year with two main peaks, one in the fall and one in the spring

[e.g. *Lin et al.*, 2006; *Owen*, 1954], with the spring peak potentially providing a replenishment of substrate for summer microbial activity.

Soil moisture was greatest in the spring after snow melt (Figure 3), which suggests that *E* and *R* were mostly temperature limited in the spring, but moisture limited in the summer. This is consistent with other studies that have demonstrated that soil temperature exerts a seasonal control on *R*, while soil moisture provides more of an interannual control on *R* in these types of forested ecosystems [e.g. *Saiz et al.*, 2006; *Scott-Denton et al.*, 2003]. Our data also showed that while soil temperature influenced both *R* (Figure 7a) and *E* (Figure 6a), the temperature influence was much stronger for *R* than for *E*. Alternatively, while soil moisture also influenced both *R* (Figure 7b) and *E* (Figure 6b), the soil moisture influence was much stronger for *E* than for *R*. This is also consistent with other studies that have demonstrated that evaporation from the forest floor is strongly linked to the presence of moisture in the soil surface and litter layer [e.g. *Raz-Yaseef et al.*, 2010; *Wilson et al.*, 2000].

By observing the cumulative values of *E* and *R* for SSS and LSS sites, we were able to identify a few differences (Figure 5). Cumulative values of *E* remained very similar between SSS and LSS sites throughout most of the year (Figure 5a). Notably different values only occurred in the spring and early summer, where *E* for the SSS sites increased first and maintained higher values until late summer. This may have been due to increased subsurface microbial or plant respiration in these areas, perhaps related to water becoming available earlier at these sites. In June, the LSS sites increased in *E* faster than the SSS sites so that the values merged and remained nearly identical through the fall months. In contrast, cumulative values of *R* varied notably between SSS and LSS

sites (Figure 5b), with SSS sites experiencing higher rates of R throughout the course of the year. By the end of the water year, SSS sites released 342 g/m^2 , or about 10%, more CO_2 than the LSS sites. While this value is comparable to what has been seen between different ecosystems (e.g. the difference in R between semiarid riparian and upland ecosystems is about 60 g/m^2 , or ~8%, over the course of a summer using similar methods [Riveros-Iregui *et al.*, 2008]), a 10% change in R due to a change in snow season length of less than two weeks is an important consequence of climate change.

Looking into the relationship between R and E , where $R/E = WUE_{soil}$ represents the ratio between carbon loss from the soil and the amount of water lost during that loss of carbon, offers some insight on the confounding differences between the controls on R and E . In our mixed-conifer ecosystem, E and R were strongly correlated ($R^2 > 0.55$; Figure 8 and Table 2), suggesting that increased water loss through E resulted in increased carbon loss through R . This was a much stronger relationship than had been found between E and R in a nearby semiarid shrubland ($R^2 = 0.12$), where R was modeled based on night time eddy covariance values [Scott *et al.*, 2006]. Scott *et al.* [2006] suggest that the lack of correlation between R and E at this shrubland could be a result of frequent drying–rewetting events. Frequent drying–rewetting events have been shown to significantly reduce the amount of carbon dioxide released following a rewetting event [Fierer and Schimel, 2002], while water loss would remain the same. Our subalpine mixed-conifer ecosystem experiences drying–rewetting cycles, but these are not as frequent as in a semiarid dryland ecosystem, and photosynthetic uptake by the vegetation is not as pulse-driven, so a stronger correlation between R and E in our study areas is consistent with this line of reasoning. We further show that the forest floor of our mixed-

conifer ecosystem tends to become “more efficient” at respiring carbon as the soil dries out (Figure 8c, d), but “less efficient” at respiring carbon as the soil warms up (Figure 8e, f). Consistent with these findings, a recent continental scale evaluation of ecosystems points to a decrease in the efficiency of microbial decomposition of carbon as temperatures are decreased [Fierer *et al.*, 2006], which further points towards sensitivity of R to dynamics in soil moisture and temperature. Climate change will only exacerbate drying-wetting cycles and cooling-warming cycles in subalpine and other ecosystems; therefore detangling these complex relationships becomes increasingly important for understanding shifts in carbon dynamics [e.g. Barron-Gafford *et al.*, 2011; Chatterjee and Jenerette, 2011; Craine and Gelderman, 2011; Koch *et al.*, 2008]. This is especially true given the scarcity of data on E and R within this ecotype that characterizes so much of the southwestern US.

4.2 Influence of Snow Cover Duration on E and R

Contrary to our second hypothesis, our results showed that the timing of peak E associated with spring moisture was similar for LSS and SSS sites (Figure 4a). During this transition season, it is possible that our measurement frequency may not have been high enough to capture differences in peak water fluxes between LSS and SSS sites; dynamics of dry down in these systems may be on the order of days [e.g. Hunt *et al.*, 2002; Kurc and Small, 2004]. Alternatively, given the close proximity of the sampling sites, redistribution of soil moisture under these spring snow melt conditions may have smoothed any differences in timing of the moisture available for E between the LSS and SSS sites [McNamara *et al.*, 2005]. Further contradicting our second hypothesis, we

found that the spring peak in E was larger at SSS sites than at LSS sites (Figure 4a). Similarly, the spring peak in R was also larger in SSS sites than in LSS sites, which was contrary to our third hypothesis. If this was due to differences in soil moisture between sites, then this suggests a contradiction to Bales *et al.* [2011] and could be a result of the complex terrain found at the study site. However, if a smoothing of soil moisture conditions between the LSS and SSS sites did occur in this wet spring season, micro-scale radiation differences due to vegetation cover could explain the higher E and R in these SSS sites [e.g. Royer *et al.*, 2010; Villegas *et al.*, 2010].

Evaporation from SSS sites was more sensitive to soil moisture than LSS sites (Figure 6b, Table 1), meaning that more water was lost through evaporation at higher soil moisture in SSS sites than in LSS sites. This suggests that evaporative losses may be increased with a shortened snow season. Alternatively, micro-scale radiation differences may provide conditions for increased E in these SSS sites [e.g. Royer *et al.*, 2010; Villegas *et al.*, 2010]; however, this explanation is complicated by the result that sensitivity of E to soil temperature in SSS and LSS was not significantly different (Figure 6a, Table 1). On the other hand, R in both SSS and LSS sites was very sensitive to temperature, but there was not a significant difference in this sensitivity between the SSS and LSS sites (Figure 7a, Table 1). As opposed to E , the sensitivity of R to soil moisture in the SSS sites was larger than for LSS sites, but in both SSS and LSS sites the influence of soil moisture on respiration was small (Figure 7b, Table 1).

Again, because of the confounding differences between the controls on R and E , we explored the differences in LSS and SSS sites in light of the organizing tendency of the WUE_{soil} framework. At both LSS and SSS sites, E and R were strongly correlated

(Figure 8, Table 2). While both LSS and SSS sites became “more efficient” at respiring carbon as the soil dried out (Figure 8c, d), but “less efficient” at respiring carbon as the soil warmed up (Figure 8e, f), this relationship was stronger at the SSS sites than at the LSS sites. This difference could be linked to potential differences in substrate availability after the snow pack season [Brooks *et al.*, 2005] coupled with the temperature dependence of the efficiency of microbial decomposition of carbon [Fierer *et al.*, 2006; Larionova *et al.*, 2007].

5. Conclusions

The functioning of subalpine mixed-conifer ecosystems is largely dependent on winter precipitation that comes as snowfall [Brown-Mitic *et al.*, 2007; Monson *et al.*, 2005], which is expected to decrease under projected climate change [e.g. Knowles *et al.*, 2006; Mote *et al.*, 2005]. Snowpack is critical for sustaining one of the two main soil moisture seasons in these ecosystems; the first associated with spring snow melt and the second with summer rains. Our research shows that changes in snowpack are likely to have important consequences for water and carbon cycling in these ecosystems. We show that loss of water by E is independent of snow cover duration, and that regardless of the length of snow cover duration, E was strongly correlated with soil moisture but weakly correlated with soil temperature. We also show that snow duration does have an influence on R , with short snow season fluxes typically higher than those of long snow season sites throughout the year. This suggests that these environmental changes may influence R in such a way that we might expect greater carbon losses to the atmosphere

with decreasing snowpack in these ecosystems. Regardless of the length of snow cover duration, R was strongly correlated with soil temperature but weakly correlated with soil moisture. Finally, our research showed that even a small difference between length of snow season (12 days) can produce noticeable differences in water and carbon cycling within the soils of this ecosystem, suggesting that future changes due to climate change may have profound effects on subalpine ecosystems.

Because of the confounding differences between the controls on R and E , we also explored a new way of thinking about the ratio of R and E ($R/E = WUE_{soil}$), the ratio between carbon loss from the soil and the amount of water lost during that loss of carbon. Regardless of snow duration, the soil became “more efficient” at respiring carbon as the soil dried out, but “less efficient” at respiring carbon as the soil warmed up. This relationship was stronger for sites that experienced a shorter snow cover season. Substrate availability may change after microbial activity throughout the snow pack season [Brooks *et al.*, 2005] and therefore differences in the length of the snow season could also influence substrate availability. Differences in substrate availability coupled with a temperature dependence on the efficiency of microbial decomposition of carbon [Fierer *et al.*, 2006; Larionova *et al.*, 2007] could explain these differences in soil water use efficiency based on snow cover duration. Because climate change will only exacerbate both drying-wetting cycles and cooling-warming cycles, detangling these complex relationships becomes increasingly important for understanding shifts in carbon dynamics in these subalpine mixed-conifer ecosystems.

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References

- Allen, C. D., et al. (2010), A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, *For. Ecol. Manage.*, 259(4), 660-684.
- Bales, R. C., et al. (2006), Mountain hydrology of the western United States, *Water Resour. Res.*, 42(8), 13.
- Bales, R. C., et al. (2011), Soil Moisture Response to Snowmelt and Rainfall in a Sierra Nevada Mixed-Conifer Forest, *Vadose Zone J.*, 10(3), 786-799.
- Barnett, T. P., et al. (2008), Human-induced changes in the hydrology of the western United States, *Science*, 319(5866), 1080-1083.
- Barron-Gafford, G. A., et al. (2011), The relative controls of temperature, soil moisture, and plant functional group on soil CO₂ efflux at diel, seasonal, and annual scales, *J. Geophys. Res.-Biogeosci.*, 116, 16.
- Bentz, B. J., et al. (2010), Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects, *Bioscience*, 60(8), 602-613.
- Boulet, G., et al. (1997), Study of the mechanisms of evaporation under arid conditions using a detailed model of the soil-atmosphere continuum. Application to the EFEDA I experiment, *J. Hydrol.*, 193(1-4), 114-141.
- Breshears, D. D., et al. (2005), Regional vegetation die-off in response to global-change-type drought, *Proc. Natl. Acad. Sci. U. S. A.*, 102(42), 15144-15148.
- Brooks, P. D., et al. (1996), Microbial activity under alpine snowpacks, Niwot Ridge, Colorado, *Biogeochemistry*, 32(2), 93-113.
- Brooks, P. D., et al. (2005), Carbon limitation of soil respiration under winter snowpacks: potential feedbacks between growing season and winter carbon fluxes, *Glob. Change Biol.*, 11(2), 231-238.
- Brown-Mitic, C., et al. (2007), Seasonal water dynamics of a sky island subalpine forest in semi-arid southwestern United States, *J. Arid. Environ.*, 69(2), 237-258.
- Brown, P. D., et al. (2008), Lakes and forests as determinants of downstream nutrient concentrations in small mountain watersheds, *Arct. Antarct. Alp. Res.*, 40(3), 462-469.
- Brown, R. D., and P. W. Mote (2009), The Response of Northern Hemisphere Snow Cover to a Changing Climate, *J. Clim.*, 22(8), 2124-2145.

- Chatterjee, A., and G. D. Jenerette (2011), Changes in soil respiration $Q(10)$ during drying-rewetting along a semi-arid elevation gradient, *Geoderma*, 163(3-4), 171-177.
- Concilio, A., et al. (2009), Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest, *Clim. Change*, 92(1-2), 109-122.
- Craine, J. M., and T. M. Gelderman (2011), Soil moisture controls on temperature sensitivity of soil organic carbon decomposition for a mesic grassland, *Soil Biol. Biochem.*, 43(2), 455-457.
- Crimmins, T. M., et al. (2011), Onset of summer flowering in a 'Sky Island' is driven by monsoon moisture, *New Phytol.*, 191(2), 468-479.
- Feeley, K. J., et al. (2007), Decelerating growth in tropical forest trees, *Ecol. Lett.*, 10(6), 461-469.
- Fierer, N., and J. P. Schimel (2002), Effects of drying-rewetting frequency on soil carbon and nitrogen transformations, *Soil Biol. Biochem.*, 34(6), 777-787.
- Fierer, N., et al. (2006), Predicting the temperature dependence of microbial respiration in soil: A continental-scale analysis, *Glob. Biogeochem. Cycle*, 20(3), 10.
- Gimenez-Benavides, L., et al. (2007), Reproductive limits of a late-flowering high-mountain Mediterranean plant along an elevational climate gradient, *New Phytol.*, 173(2), 367-382.
- Gochis, D. J., et al. (2006), Hydroclimatology of the North American Monsoon region in northwest Mexico, *J. Hydrol.*, 316(1-4), 53-70.
- Goulden, M. L., et al. (1996), Exchange of carbon dioxide by a deciduous forest: Response to interannual climate variability, *Science*, 271(5255), 1576-1578.
- Hamlet, A. F., et al. (2007), Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States, *J. Clim.*, 20(8), 1468-1486.
- Hidalgo, H. G., et al. (2009), Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States, *J. Clim.*, 22(13), 3838-3855.
- Hogberg, P., et al. (2001), Large-scale forest girdling shows that current photosynthesis drives soil respiration, *Nature*, 411(6839), 789-792.
- Hu, J., et al. (2010), Longer growing seasons lead to less carbon sequestration by a subalpine forest, *Glob. Change Biol.*, 16(2), 771-783.

- Hunt, J. E., et al. (2002), Evaporation and carbon dioxide exchange between the atmosphere and a tussock grassland during a summer drought, *Agric. For. Meteorol.*, *111*(1), 65-82.
- IPCC (2007), 2007. Climate Change 2007: The Physical Science Basis. Summary for Policymakers., edited by I. P. o. C. Change, New York: Cambridge University Press.
- Jump, A. S., et al. (2006), Rapid climate change-related growth decline at the southern range edge of *Fagus sylvatica*, *Glob. Change Biol.*, *12*(11), 2163-2174.
- Knowles, N., et al. (2006), Trends in snowfall versus rainfall in the Western United States, *J. Clim.*, *19*(18), 4545-4559.
- Koch, O., et al. (2008), Interannual ecosystem CO₂ dynamics in the alpine zone of the Eastern Alps, Austria, *Arct. Antarct. Alp. Res.*, *40*(3), 487-496.
- Kueppers, L. M., and J. Harte (2005), Subalpine forest carbon cycling: Short- and long-term influence of climate and species, *Ecol. Appl.*, *15*(6), 1984-1999.
- Kulakowski, D., et al. (2011), The interacting effects of land use change, climate change and suppression of natural disturbances on landscape forest structure in the Swiss Alps, *Oikos*, *120*(2), 216-225.
- Kurc, S. A., and E. E. Small (2004), Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico, *Water Resour. Res.*, *40*(9), 15.
- LaMalfa, E. M., and R. Ryle (2008), Differential snowpack accumulation and water dynamics in aspen and conifer communities: Implications for water yield and ecosystem function, *Ecosystems*, *11*(4), 569-581.
- Lambers, H., et al. (2008), *Plant Physiological Ecology*, Springer, New York.
- Larionova, A. A., et al. (2007), Temperature response of soil respiration is dependent on concentration of readily decomposable C, *Biogeosciences*, *4*(6), 1073-1081.
- Leung, L. R., et al. (2004), Mid-century ensemble regional climate change scenarios for the western United States, *Clim. Change*, *62*(1-3), 75-113.
- Lin, B., et al. (2006), Nutrient and litter patterns in three subalpine coniferous forests of western Sichuan, China, *Pedosphere*, *16*(3), 380-389.
- Littell, J. S., et al. (2009), Climate and wildfire area burned in western U. S. ecoprovinces, 1916-2003, *Ecol. Appl.*, *19*(4), 1003-1021.

- Lopez, R., and C. Justribo (2011), The hydrological significance of mountains: a regional case study, the Ebro River basin, northeast Iberian Peninsula, *Hydrol. Sci. J.-J. Sci. Hydrol.*, 55(2), 223-233.
- Mast, M. A., et al. (1998), Winter fluxes of CO₂ and CH₄ from subalpine soils in Rocky Mountain National Park, Colorado, *Glob. Biogeochem. Cycle*, 12(4), 607-620.
- Matyssek, R., et al. (2009), Transpiration of forest trees and stands at different altitude: consistencies rather than contrasts?, *Eur. J. For. Res.*, 128(6), 579-596.
- McNamara, J. P., et al. (2005), Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment, *Hydrol. Process.*, 19(20), 4023-4038.
- Menzel, A., and P. Fabian (1999), Growing season extended in Europe, *Nature*, 397(6721), 659-659.
- Miller, N. L., et al. (2003), Potential impacts of climate change on California hydrology, *J. Am. Water Resour. Assoc.*, 39(4), 771-784.
- Monson, R. K., et al. (2002), Carbon sequestration in a high-elevation, subalpine forest, *Glob. Change Biol.*, 8(5), 459-478.
- Monson, R. K., et al. (2005), Climatic influences on net ecosystem CO₂ exchange during the transition from wintertime carbon source to springtime carbon sink in a high-elevation, subalpine forest, *Oecologia*, 146(1), 130-147.
- Monson, R. K., et al. (2006), The contribution of beneath-snow soil respiration to total ecosystem respiration in a high-elevation, subalpine forest, *Glob. Biogeochem. Cycle*, 20(3), 13.
- Mote, P. W., et al. (2005), Declining mountain snowpack in western north America, *Bull. Amer. Meteorol. Soc.*, 86(1), 39-+.
- Owen, T. H. (1954), Observations of the monthly litter-fall and nutrient content of sitka spruce litter, *Forestry*, 27(1), 7-15.
- Parmesan, C. (2006), Ecological and evolutionary responses to recent climate change, *Annu. Rev. Ecol. Evol. Syst.*, 37, 637-669.
- Peterson, D. W., and D. L. Peterson (1994), Effects of climate on radial growth of sub-alpine conifers in the North Cascade Mountains, *Can. J. For. Res.-Rev. Can. Rech. For.*, 24(9), 1921-1932.

- Quiring, S. M., and D. B. Kluver (2009), Relationship between Winter/Spring Snowfall and Summer Precipitation in the Northern Great Plains of North America, *J. Hydrometeorol.*, 10(5), 1203-1217.
- Raz-Yaseef, N., et al. (2010), Effects of spatial variations in soil evaporation caused by tree shading on water flux partitioning in a semi-arid pine forest, *Agric. For. Meteorol.*, 150(3), 454-462.
- Riveros-Iregui, D. A., et al. (2008), Interpretation and evaluation of combined measurement techniques for soil CO₂ efflux: Discrete surface chambers and continuous soil CO₂ concentration probes, *J. Geophys. Res.-Biogeosci.*, 113(11).
- Royer, P. D., et al. (2010), Ecohydrological energy inputs in semiarid coniferous gradients: Responses to management- and drought-induced tree reductions, *For. Ecol. Manage.*, 260(10), 1646-1655.
- Saiz, G., et al. (2006), Seasonal and spatial variability of soil respiration in four Sitka spruce stands, *Plant Soil*, 287(1-2), 161-176.
- Sang, W. G., and F. Bai (2009), Vascular diversity patterns of forest ecosystem before and after a 43-year interval under changing climate conditions in the Changbaishan Nature Reserve, northeastern China, *Plant Ecology*, 201(1), 115-130.
- Schwartz, M. D., et al. (2006), Onset of spring starting earlier across the Northern Hemisphere, *Glob. Change Biol.*, 12(2), 343-351.
- Scott-Denton, L. E., et al. (2003), Spatial and temporal controls of soil respiration rate in a high-elevation, subalpine forest, *Soil Biol. Biochem.*, 35(4), 525-534.
- Scott, R. L., et al. (2006), Partitioning of evapotranspiration and its relation to carbon dioxide exchange in a Chihuahuan Desert shrubland, *Hydrol. Process.*, 20(15), 3227-3243.
- Seager, R., et al. (2007), Model projections of an imminent transition to a more arid climate in southwestern North America, *Science*, 316(5828), 1181-1184.
- Small, E. E., and J. R. McConnell (2008), Comparison of soil moisture and meteorological controls on pine and spruce transpiration, *Ecohydrology*, 1(3), 205-214.
- Stewart, I. T., et al. (2005), Changes toward earlier streamflow timing across western North America, *J. Clim.*, 18(8), 1136-1155.
- van Mantgem, P. J., and N. L. Stephenson (2007), Apparent climatically induced increase of tree mortality rates in a temperate forest, *Ecol. Lett.*, 10(10), 909-916.

- Villegas, J. C., et al. (2010), Seasonally Pulsed Heterogeneity in Microclimate: Phenology and Cover Effects along Deciduous Grassland-Forest Continuum, *Vadose Zone J.*, 9(3), 537-547.
- Viviroli, D., et al. (2003), Assessing the hydrological significance of the world's mountains, *Mt. Res. Dev.*, 23(1), 32-40.
- Viviroli, D., and R. Weingartner (2004), The hydrological significance of mountains: from regional to global scale, *Hydrol. Earth Syst. Sci.*, 8(6), 1016-1029.
- Wetherald, R. T., and S. Manabe (2002), Simulation of hydrologic changes associated with global warming, *J. Geophys. Res.-Atmos.*, 107(D19), 15.
- Wilson, K. B., et al. (2000), Factors controlling evaporation and energy partitioning beneath a deciduous forest over an annual cycle, *Agricultural and Forest Meteorology*, 102(2-3), 83-103.
- Woodhouse, C. A., et al. (2010), A 1,200-year perspective of 21st century drought in southwestern North America, *Proc. Natl. Acad. Sci. U. S. A.*, 107(50), 21283-21288.

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Table 1: Slope and statistical significance values corresponding to Figure 6 (soil evaporation) and Figure 7 (soil respiration).

	E			R		
	Slope	R ²	Pval	Slope	R ²	Pval
Temp, SSS	0.006	0.07	0.2	0.347	0.56	0
Temp, LSS	0.004	0.06	0.22	0.327	0.58	0
VWC, SSS	0.011	0.23	0.01	0.121	0.07	0.19
VWC, LSS	0.007	0.2	0.02	0.04	0.01	0.63

Table 2: Slope and statistical significance values corresponding to Figure 8 (soil water use efficiency).

	R vs. E			WUE vs. VWC			WUE vs. T_{soil}		
	Slope	R^2	Pval	Slope	R^2	Pval	Slope	R^2	Pval
SSS	12.157	0.61	0.00	-3.336	0.51	0.00	2.031	0.17	0.10
LSS	13.868	0.59	0.00	-2.038	0.37	0.01	1.484	0.14	0.13

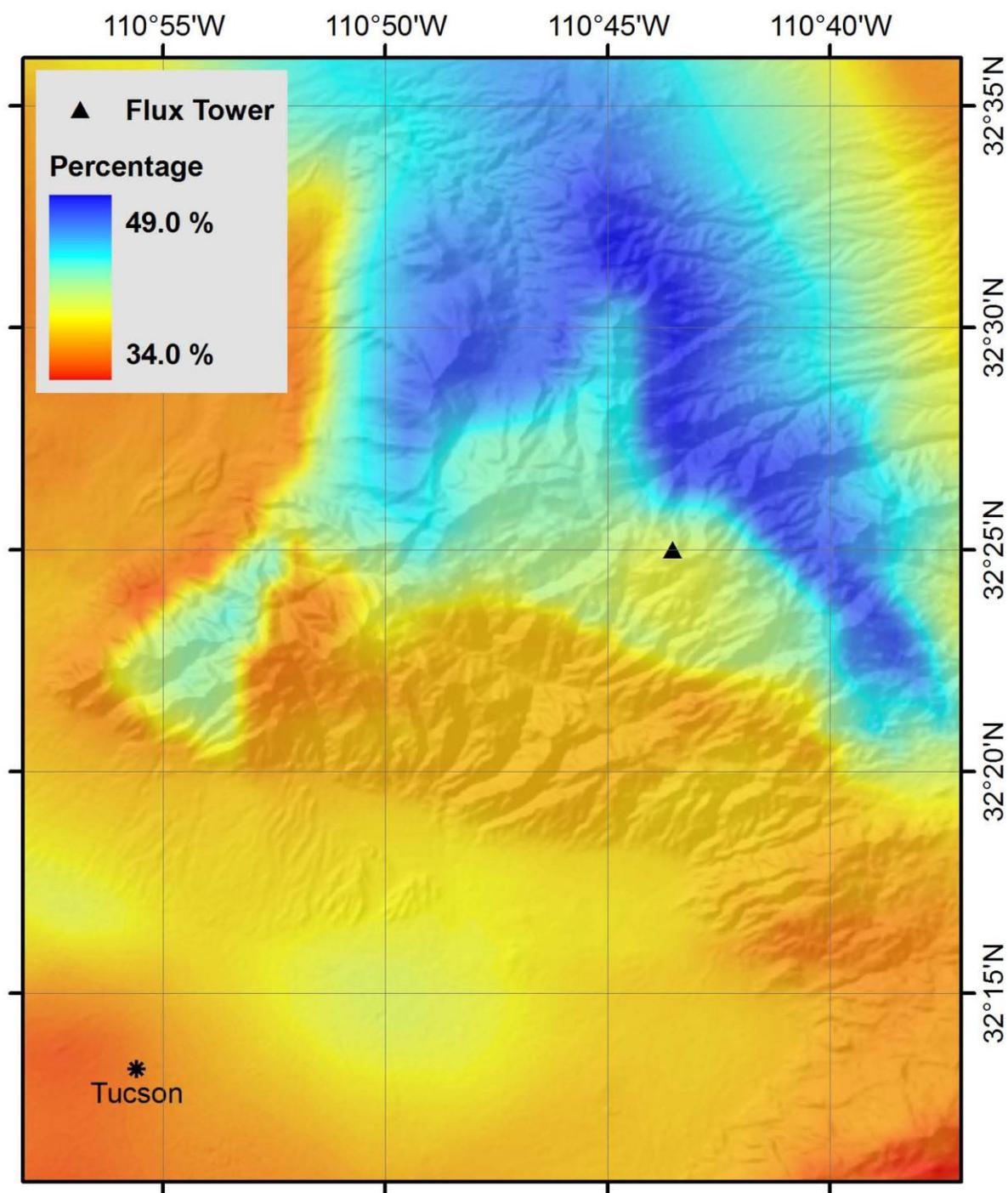
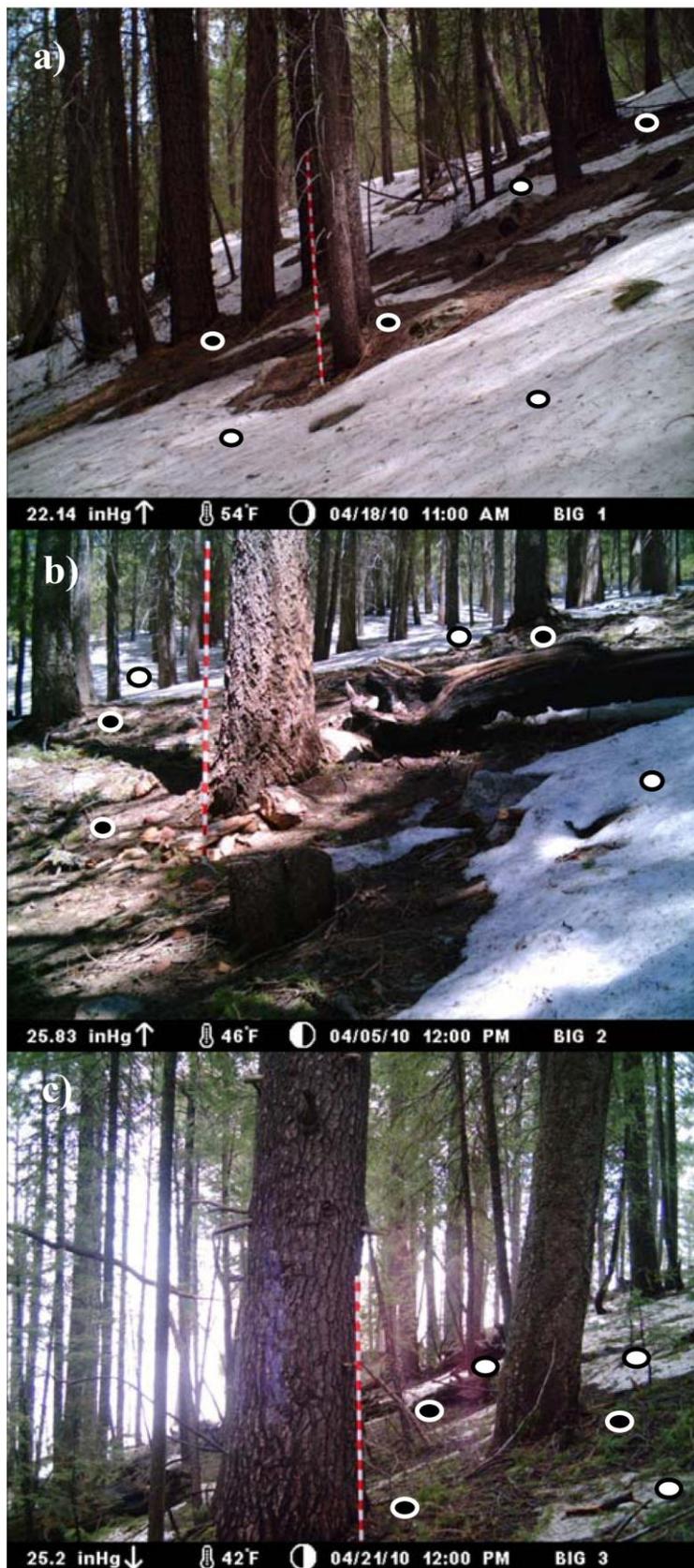


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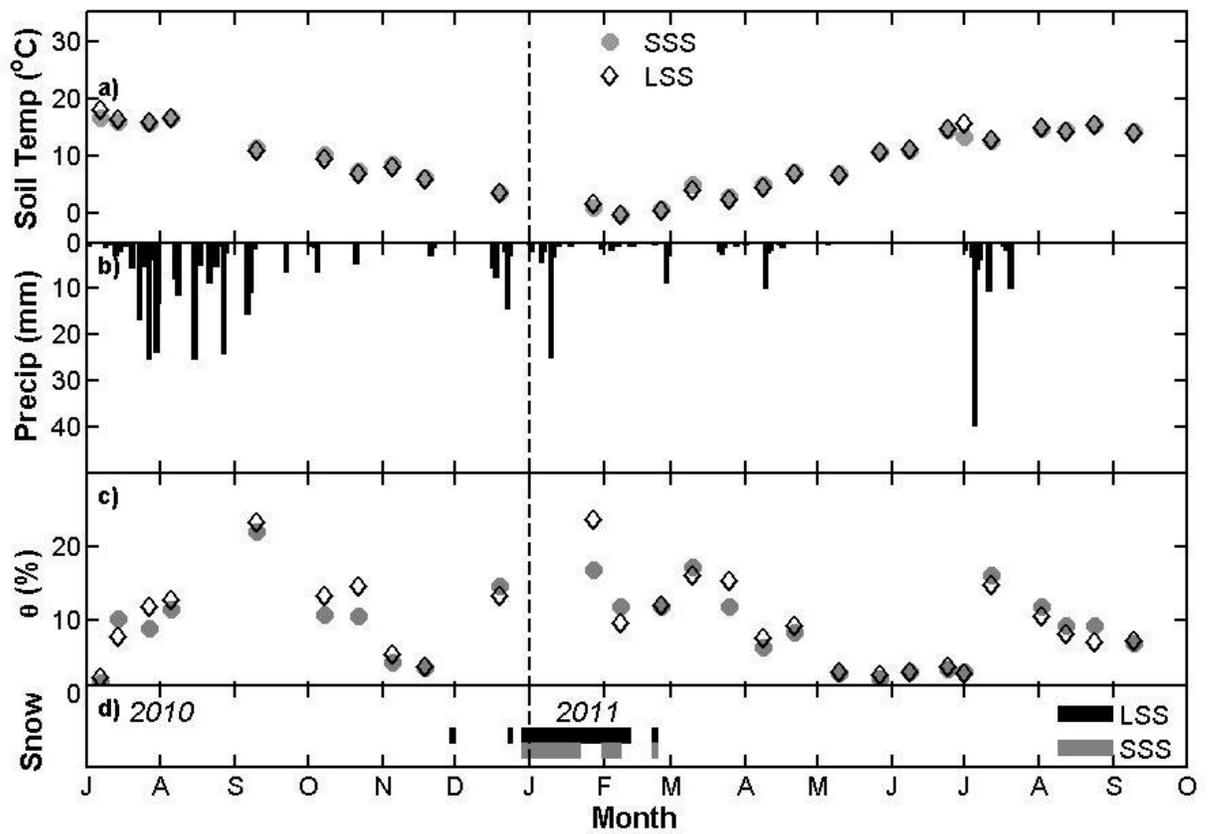


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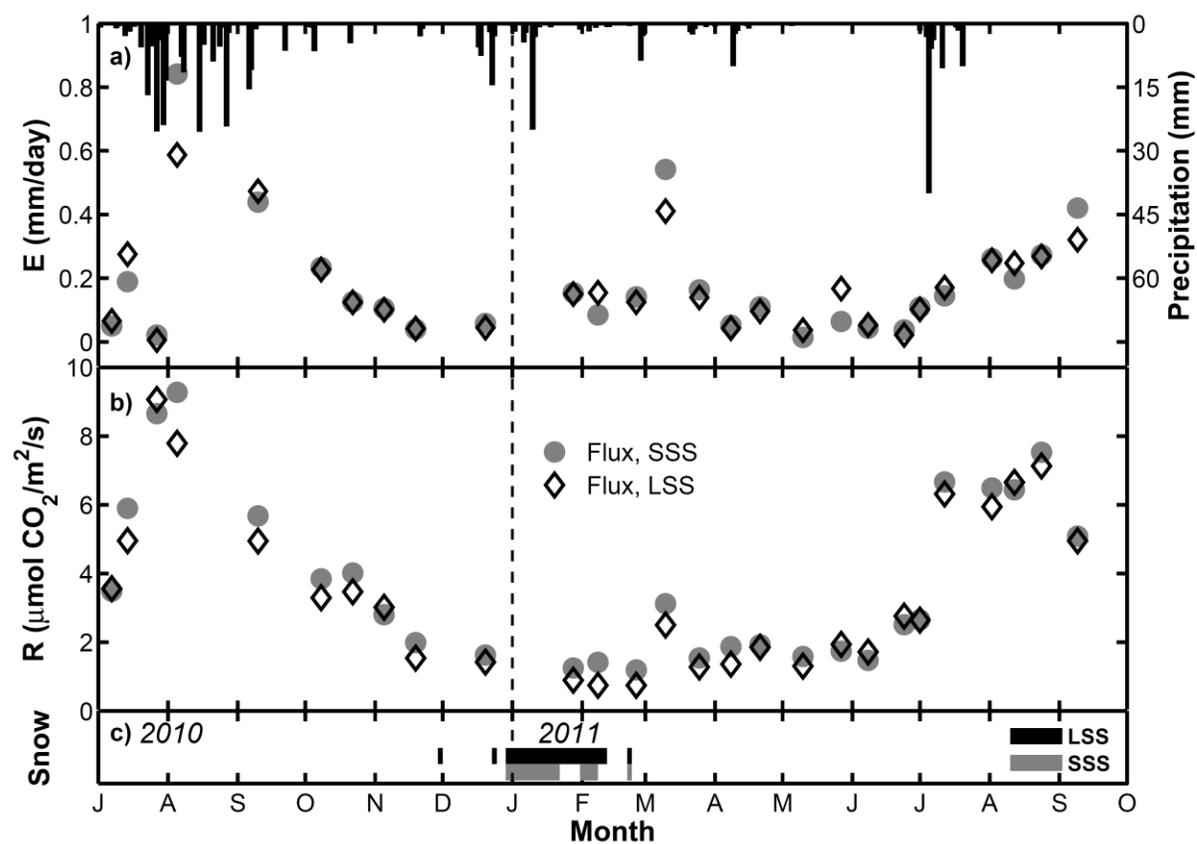


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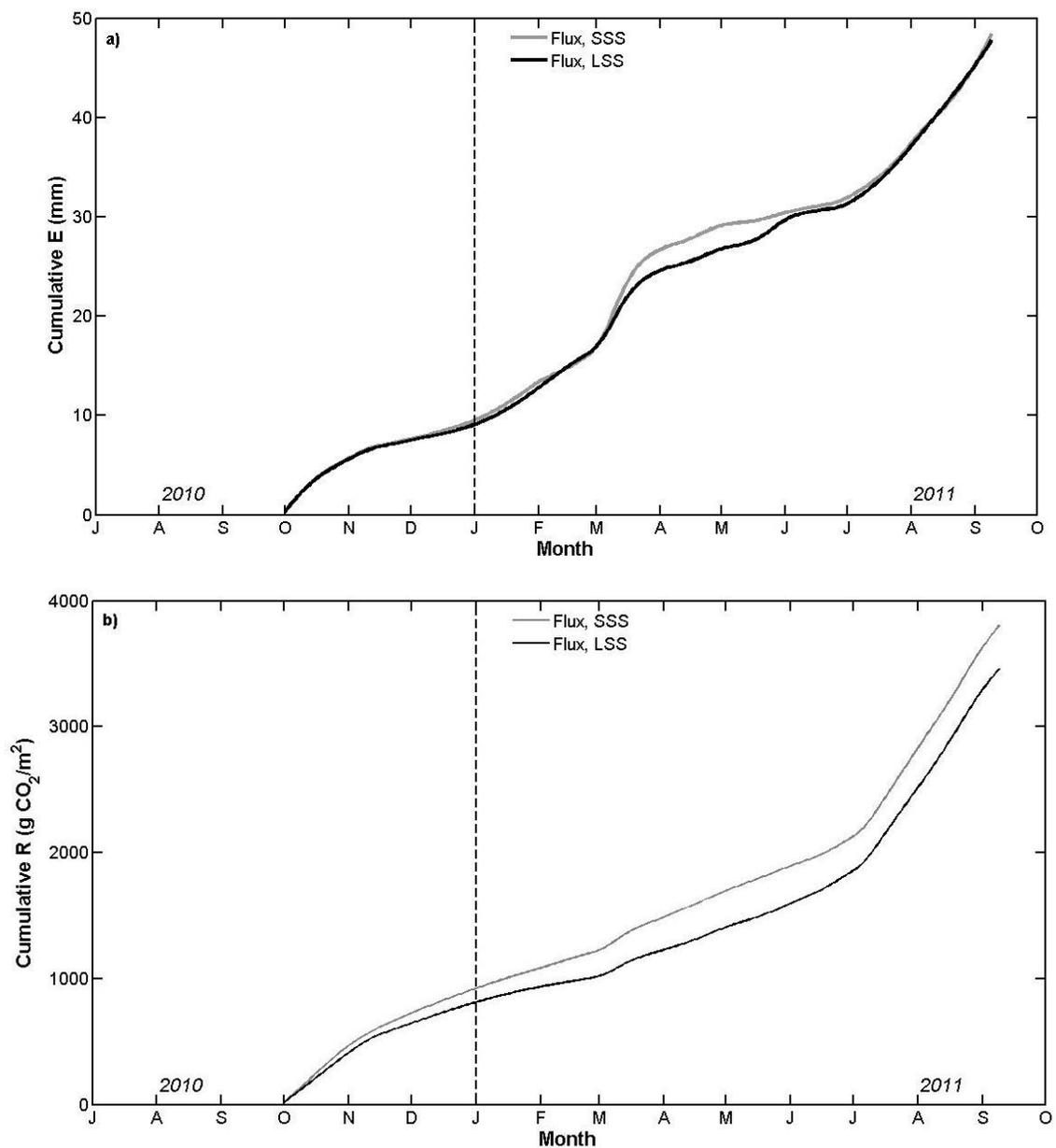


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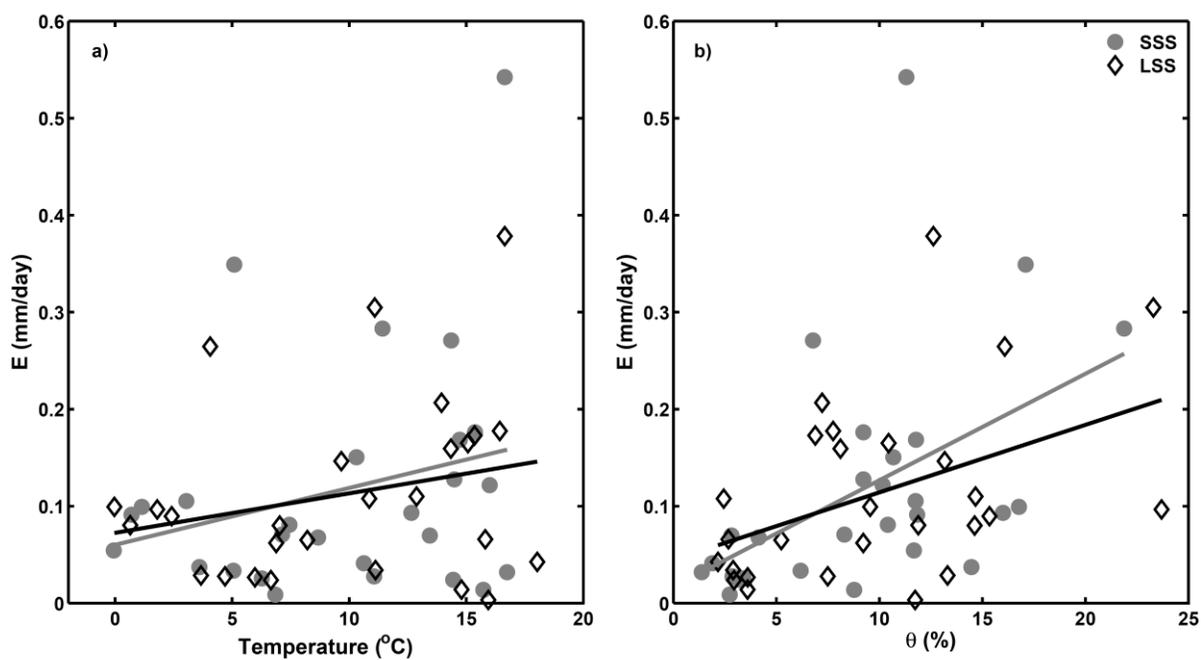


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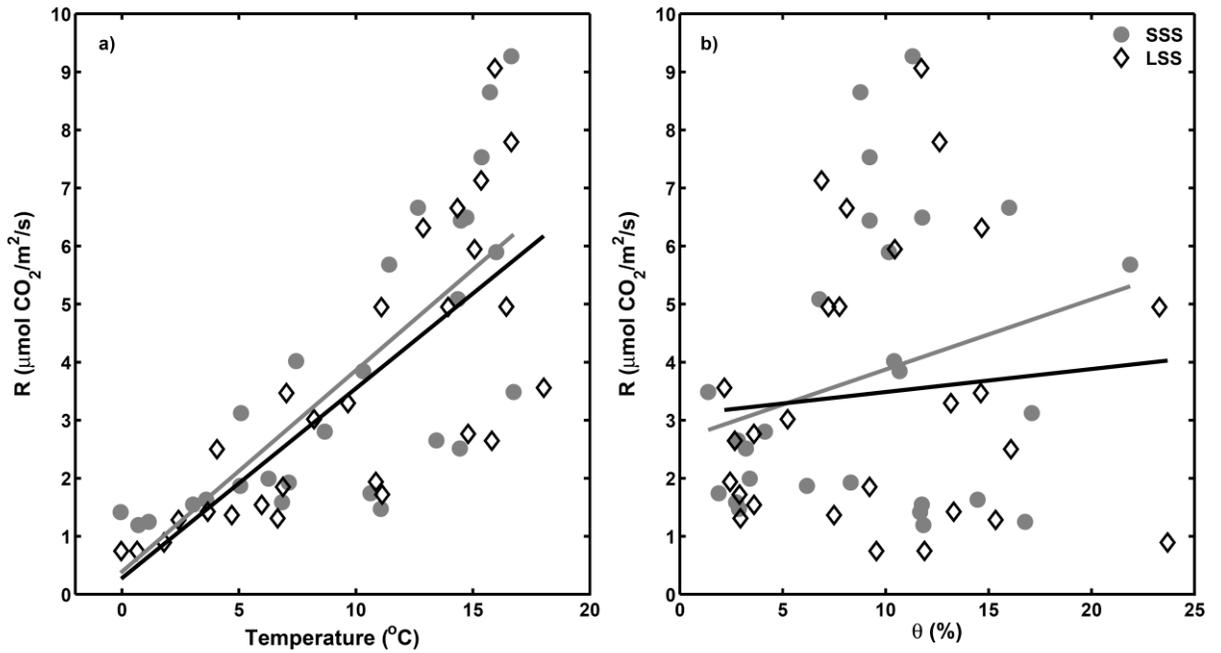


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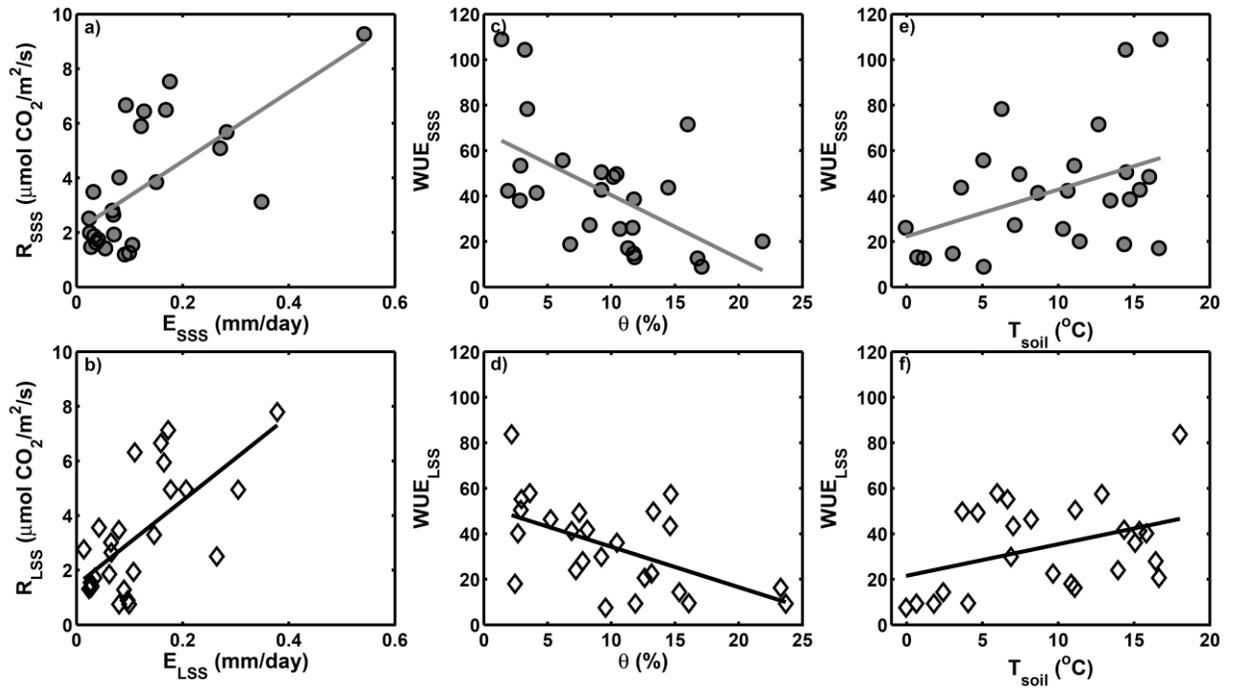


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