Ecohydrologic Dynamics and Social Impacts of Western Juniper in Snow-Dominated Sagebrush Steppe

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by

Ryan J. Niemeyer

Major Professor: Timothy E. Link, Ph.D.

Committee Members: Robert Heinse, Ph.D.; Mark S. Seyfried, Ph.D.;

J.D. Wulfhorst, Ph.D.

Department Administrator: Larry Makus, Ph.D.

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Authorization to Submit Dissertation

This dissertation of Ryan J. Niemeyer, submitted for the degree of Doctorate of Philosophy with a Major in Water Resources and titled "Ecohydrologic Dynamics and Social Impacts of Western Juniper in Snow-Dominated Sagebrush Steppe," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ______________________________ Date:____________
Timothy E. Link, Ph.D.

Committee Members: ______________________________ Date:____________
Robert Heinse, Ph.D.

______________________________ Date:____________
Mark S. Seyfried, Ph.D.

______________________________ Date:____________
J.D. Wulfhorst, Ph.D.

Department Administrator: ______________________________ Date:____________
Larry Makus, Ph.D.

Abstract

Semi-arid social-ecological systems in the western U.S. have undergone drastic changes due to grazing, woody plant encroachment, and urbanization. Specifically in the northern Great Basin, western juniper (*Juniperus occidentalis*) has increased in cover by as much as 10-fold in some regions over the last 140 years. These changes can alter both hydrologic and social characteristics of the social-ecological system. To understand these impacts, I studied both the hydrologic and the social-ecological impacts of western juniper encroachment in the sagebrush-steppe. The hydrologic and social research was carried out in the Owyhees of southwestern Idaho. The objective of the hydrologic research was to understand how western juniper influenced both above and below ground hydrologic processes. This research included field work conducted at Reynolds Creek Experimental Watershed in the Owyhee Mountains and simulations of future climate. This research revealed that juniper not only intercept a large portion of rain and snow, but due to tree wells that form below trees, alter below-canopy snow topography that increases snow deposition below trees. Future climate simulations revealed that while climate primarily fixes the timing of above-ground hydrologic processes (i.e., peak snowpack, surface water input, etc.), changes in land cover have a greater impact on the amount of these fluxes. The below-ground research revealed that western juniper preferentially funnel infiltration at their base, likely due to a combination of roots providing preferential flowpaths and hydrophobic soils concentrating infiltration. Electrical resistivity tomography surveys revealed large juniper can extract moisture in the saprolite and weathered bedrock - as deep as 10 m below the surface. The objective of the social science research was to develop a social-ecological impact assessment that better addressed both the social and ecological aspects of impact assessments required by the National Environmental Policy Act. This research included five workshops and revealed that a deliberative social-ecological assessment process can reveal impacts not otherwise captured with other technical or survey methods.

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Dedication

This dissertation is a direct result of the love of my mother and father. Observing your examples as a fourth grade teacher and school administrator helped teach me critical lessons necessary to be a thoughtful scientist in natural resources: listen first, don't treat people based on their stereotypes, and seek the good of everyone. I am grateful for your example. To you both, my dissertation is dedicated.

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Dissertation Introduction

The semi-arid western U.S. has undergone dramatic social, ecological, and climatic changes over the last century. Euro-American settlement in the mid-nineteenth century initiated livestock grazing, land conversion to agriculture, and fire suppression – land use actions that continue on the landscape to this day and have largely shaped the contemporary semi-arid landscape. Modern day drivers include climate change, exurban development, energy development, and recreational use. In particular, expansion of semi-arid tree species including western juniper (*Juniperus occidentalis*), have increased by 10-fold in many areas. The effects of these drivers of change are of particular concern in their impact on the sage-grouse (*Centrocercus urophasianus*). The sage-grouse was petitioned to be listed and although the U.S. Fish and Wildlife Service ruled the species is not at risk of being endangered in September of 2015, the drivers of change in the northern Great Basin are likely to continue to challenge managers to maintain the species into the future.

To best manage and preserve the western landscapes, it is essential to understand both the hydrologic and social impacts of changes in western juniper cover. From a hydrologic perspective, there are uncertainties as to if and to what extent juniper impact hydrologic processes. Studies of the impact of the removal of Utah juniper (*Juniperus osteosperma*), alligator juniper (*Juniperus deppeana*), and pinyon pine (*Pinus edulis*), semi-arid tree species similar to western juniper, in southwestern Arizona revealed no appreciable gain in streamflow for more than five years after the removal. As a result, some assume that changes in semi-arid tree cover have little or no impact on the hydrologic cycle. Western juniper occupy different climatic regimes than semi-arid trees in the southwestern

U.S. It is therefore essential to understand how western juniper impact hydrologic processes in semi-arid areas.

A large portion, and in some states the majority, of public lands are managed by a federal or state agency. Assessment of impacts on biophysical and human aspects are required by law for any land use on U.S. public lands, but these assessments routinely focus on biophysical assessments and often minimize or disregard altogether social impacts. The National Environmental Policy Act of 1969 (NEPA) was signed into law to ensure that any land use decision on public lands considers potential impacts on the environment, which includes the human environment. Approaches that involve stakeholders have been proposed, although they are often non-participatory technical assessments or merely stakeholder participation without directly referencing the proposed action. There is a need to develop environmental assessments that incorporate the participants directly into the process while assessing the social impacts of land management.

To begin to address some of the knowledge gaps in how western juniper impact the hydrology of semi-arid systems, we assessed how western juniper impact both above-ground and below-ground hydrologic processes. The first chapter quantified the differences in snow deposition between mountain big sagebrush (*Artemisia tridentate*) and western juniper. The second chapter quantified rain and snow interception, throughfall, and rain canopy storage for western juniper and compared snowpack dynamics between western juniper and sagebrush-dominated interspace. This chapter also included an analysis of how these above-grouped processes, including surface water input, change under future warming. The third chapter assessed how subsurface moisture dynamics in shallow and deep subsurface depths differ between western juniper and the low-sagebrush (*Artemisia arbuscula*) dominated interspace. To fill the need to develop a participatory social-impact assessment that incorporate ecological aspects of federal land management projects, our fourth chapter describes a novel social-ecological impact assessment that was implemented for a Bureau of Land Management 1.75 million acre sage-grouse habitat project that focused on western juniper removal.

Chapter 1 - Snow interception in western juniper and mountain big sagebrush

Authors: Ryan J. Niemeyer, Timothy E. Link, Mark S. Seyfried

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Abstract

Woodland encroachment into semi-arid western United States rangelands has modified shrub steppe ecosystems. Despite the importance of hydrologic fluxes in these water-limited systems, few studies have directly compared snow or rain canopy interception across semi-arid tree and shrub species. Only one shrub snow interception study exists for these ecosystems and interception loss estimates are based on snow surveys. Based on previous process-based snow studies, snow interception can be overestimated with snow surveys due to preferential melt below the tree or shrub canopy. To prevent preferential melt from skewing interception estimates from snow surveys, the survey needs to be conducted: a) immediately after a snowstorm and b) for a snowstorm that occurs when no snow was on the ground before the storm. Our study uses snow surveys after a storm with these conditions to compare snow interception between a semi-arid tree and a shrub species. At our study site at the Reynolds Creek Experimental Watershed in southwestern Idaho, after all the winter snow had melted, a snowstorm occurred on 16 April 2013. On the same day we conducted a snow survey among western juniper trees and mountain big sagebrush shrubs to adequately characterize snow interception. Snow water equivalent under juniper trees was 27% (± 15% SD) less than in the open and snow water equivalent under sagebrush shrubs was 12% (± 15% SD) greater than in the open. Juniper tree size was positively correlated with intercepted snow per area unit (p = 0.13) and we calculated plot-level snow interception for juniper of 11.0% for a phase III, dense juniper stand. Future process-based snow interception studies can further elucidate the complexity of snow interception between semi-arid tree and shrub species.

Key words: interception, mountain big sagebrush, snow, throughfall, western juniper, woodland encroachment

1. Introduction

Woodland encroachment in the semi-arid western U.S. has drastically altered rangelands. Over the last 130 years pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodland distribution has increased 10-fold in the western US, encroaching into shrub steppe ecosystems (Burkhardt and Tisdale 1969; Tausch et al. 1981; Tausch and Tueller 1990; Tausch and West 1995; Bunting et al. 1999; Bates et al. 2000; Miller and Tausch 2001; Miller et al. 2000, 2005, 2008; Roberts and Jones 2000; Tausch and Hood 2007; Romme et al. 2009). Western juniper (*Juniperus occidentalis*) specifically occupy 3.6 million ha in Oregon, California, Nevada, and Idaho (Gedney et al. 1999; Miller and Tausch 2001; Azuma et al. 2005), and as much as 90% of those areas were dominated by sagebrush before euro-American settlement in the 1800s (Tausch et al. 1981; Johnson and Miller 2006; Miller et al. 2008). Shrub steppe ecosystems are water-limited, resulting in a tight coupling between hydrologic fluxes and vegetation (Loik et al. 2004; Schwinning and Sala 2004; Huxman et al. 2005). As a result, any change in vegetation can alter hydrologic fluxes (Newman et al. 2006; Wilcox et al. 2011). Replacement of shrub steppe species with tree species can therefore alter soil moisture (Gifford and Shaw 1973; Young et al. 1984; West et al. 2007; Breshears et al. 2009), surface energy balance (Breshears et al. 1997), and erosion processes (Wilcox 1994; Pierson et al. 2007, 2010).

Despite the importance of canopy interception regulating hydrologic fluxes in these semi-arid systems (Wilcox et al. 2003), there is still a lack of understanding about how woodland encroachment alters canopy interception in shrub steppe ecosystems. Canopy interception can be estimated on a plant-level basis by comparing how much precipitation the plant canopy intercepts compared to gross precipitation, or on a plot-level basis by comparing the total plot area interception compared to gross precipitation. In this manuscript we refer to “interception” as merely the ratio of precipitation that falls below a canopy to the soil surface during a storm to the gross precipitation of that storm. Conversely, “interception loss” is the same ratio but over a longer time scale that includes subsequent sublimation, canopy meltwater drip, and water mass release from the canopy. Interception and interception loss are often the same in rain-dominated environments, but in snow-dominated areas they can be drastically different due to the differences in the canopy processes that affect the deportment of snow vs. rain (Storck et al. 2002). Canopy interception loss in rangelands can range from 1% to 80% of the annual water budget, but is typically between 20% to 40% (Wilcox et al. 2003). Piñon and juniper plant-level precipitation interception loss ranges from 14% to 71% (Collings 1966; Young et al. 1984; Eddleman and Miller 1991; Larsen 1993; Taucer 2006; Owens et al. 2006). Only two plant-level interception loss studies exist for western US semi-arid shrub species, the first estimated plant-level interception loss per storm from 44% to 50%, based on rainfall simulation (Collins 1970). The second plant-level shrub interception loss estimate is 11%, based on our back-calculation from plot-level interception, canopy cover, and individual plant storage capacity (West and Gifford 1976). With the wide range of interception loss estimates across semi-arid tree and shrub species, it is not clear how interception could change under woodland encroachment into sagebrush steppe.

While many studies focus on plant-level interception, plot-level interception is also important to understanding hydrologic changes since woodland encroachment can drastically change the total canopy cover of a semi-arid system (Miller et al., 2005; Miller et al., 2008). Woodland encroachment has been classified into three phases of ecological succession based on changes in canopy cover: 1) phase 1 where trees are actively expanding and shrub are still present, 2) phase II where trees are actively recruiting and shrubs have thinned, and 3) phase III where tree recruitment is limited and > 75% of shrubs have died (Miller et al. 2005). In these phases, as tree cover increases shrub cover decreases. Phase I, II, and III correspond to tree (shrub) canopy cover of < 10% (> 20%), 10% to 30% (10% to 20%), and > 30% (< 10%) respectively (Miller et al. 2005 – Fig. 21 and Table 4). For piñon and juniper dominated areas, plot-level annual precipitation interception loss ranges from 7.8% to 25% (Skau 1964; Eddleman 1986; Larsen 1993; Taucer 2006; Owens et al. 2006) and for shrub dominated areas ranges from 4% to 31% (Hull 1972; Hull and Klomp 1974; West and Gifford 1976; Tromble 1983).

An initial survey of semi-arid plant and plot-level interception studies appears to reveal no difference between tree and shrub interception. As a result, others have concluded that interception is similar between western juniper and shrub species (Kuhn et al. 2007). This is counter-intuitive since shrub species have a lower leaf area index (LAI) compared to semi-arid tree species. Shrub species LAI range is 0.03-1.10 m^2 m^{-2} across Wyoming big sagebrush (*Artemisia tridentate* subsp*. wyomingensis*), low sagebrush

(*Artemisia arbuscula*), and mountain big sagebrush (*Artemisia tridentate* subsp*. vaseyana*) (Clark and Seyfried 2001). Semi-arid tree species LAI range is 1.5-2.8 m^2 m^{-2} across western juniper (*Juniperus occidentalis*), pinyon pine (*Pinus edulis*), and one-seed juniper (*Juniperus osteosperma*) (Gholz 1980; Grier et al. 1992). LAI often directly correlates to canopy storage capacity and interception (Link et al. 2004). Since semi-arid trees have a higher LAI than shrub species, we would assume interception loss would be higher in tree species than shrub species, which appears to be contrary to our current state of knowledge. A study that directly compares interception in semi-arid tree and shrub species could clarify this apparent contradiction.

In addition to the lack of research that directly compares interception in semi-arid tree and shrub species, there is a greater dearth of snow interception studies for both species types. Many semi-arid tree and shrub species exist in areas dominated by winter precipitation (Robertson 1947; Hutchison 1965; Romme et al. 2009), making snow interception an important hydrological process. In the only semi-arid tree snow interception loss study, plant-level snow interception loss in western juniper ranged from 45% to 66% (Eddleman and Miller 1991). Hull (1972) and Hull and Klomp (1974), two papers from the same study and referred to henceforth as Hull and Klomp, is the only sagebrush snow interception study. Plot-level snow interception loss in Hull and Klomp ranged from 21% to 39%. Methods differed between the Eddleman and Miller study and the Hull and Klomp study, making direct comparison of the interception estimates challenging. Eddleman and Miller estimated throughfall with wedge-shaped troughs below the canopy that collected all rain throughfall and snow melt under the canopy. They estimated gross precipitation with

US Forest Service type rain gauges outside the canopy. Plant-level interception loss was calculated by comparing gross precipitation and throughfall during snow-dominated months. Conversely, Hull and Klomp calculated interception loss by conducting snow surveys across their plot and estimated plot-level interception loss by comparing areas with and without mountain big sagebrush.

While the trough throughfall collectors in Eddleman and Miller's study can collect all snowmelt that occurs, Hull and Klomp's snow survey method does not collect snowmelt and therefore potentially overestimated snow interception for two reasons. First, vegetation can cause preferential snow melting below a canopy due to plant canopy absorption of shortwave radiation and subsequent emission of longwave radiation below the canopy. This reduces below canopy snowpack not exclusively due to interception. Shrubs specifically can increase below-canopy net radiation, thereby increasing below-canopy melt rates (Robertson 1947; Hutchison 1965; Sturm et al. 2001; Pomeroy et al. 2006). Shrubs also hasten melting because snow has a high albedo that reflects incoming solar radiation and absorbs longwave radiation whereas shrubs have a low albedo that absorbs solar radiation and emits longwave radiation to the surrounding snowpack (Robertson 1947; Hutchison 1965; Pomeroy et al. 2006). Due to solar radiation penetrating the snow, shrubs buried in snow can absorb solar radiation and enhance melt within the snowpack (Warren 1982; Baker et al. 1991; Hardy et al. 1998). Below canopy snowmelt can sublimate, but the majority is delivered to the soil as meltwater (Reba et al. 2012). This elevated snowmelt under and immediately around shrubs can produce a “well” under shrub species, not because of snow interception but because of elevated melt rates (Hutchison 1965). A photo from the Hull and Klomp study during one of their snow survey evidences these wells (Fig. 1.1B).

The second reason snow surveys can overestimate snow interception or interception loss is the presence of shrubs increases snow drifting under the shrub (Fig. 1.1A; Hutchison 1965; Essery and Pomeroy 2004b; Pomeroy et al. 2006; Tedesche 2010), which could cause an apparent negative interception with more snow under the shrub canopy than outside the canopy. Hull and Klomp (1974) cite that "although there is considerable wind and snow drifting in Curlew Valley where the study is located, the tall sagebrush evidently prevented drifting at the experimental site" (p. 25). They only visited their site monthly, therefore any drifting under the shrubs could have been reduced due to preferential melt before when the snow survey occurred. In sum, even though process-based shrub snow studies demonstrate that shrubs can entrap more snow than is present in interspace areas, accelerated melt rates under the shrub can greatly reduce snow under the shrub between when an event occurs and when a snow survey is conducted. Therefore, a snow survey that occurs several days or more after an event, like the Hull and Klomp study, will likely produce interception or interception loss overestimates.

In summary, no rain or snow interception study has directly compared semi-arid tree and shrub species at the same site and the methods of Hull and Klomp confound any immediate comparison of snow interception between semi-arid tree and shrub species. In addition, with the drastic change in canopy cover that occurs with woodland encroachment, it is essential to understand how the encroachment process alters interception. A snow interception study that uses both appropriate methods to estimate snow interception and directly compares semi-arid tree and shrub species is warranted. The main objective of this paper is to compare snow interception between a semi-arid tree and shrub species at the same site. In this context, our research questions are as follows:

1. What is the difference in snow interception between tree and shrub species?
2. Does tree or shrub size increase snow interception?
3. Does semi-arid tree encroachment have a substantial impact on plot-level snow interception?

2. Methods

We conducted the study at the Reynolds Creek Experimental Watershed (RCEW) in southwestern Idaho. The elevation at the research site is 1940 m. The slope is 26% and the aspect is 246°. The wind usually comes from the south by southwest, therefore, snow drifting usually occurs on the north or northeast side of trees and shrubs. Plant species are a mix of western juniper (*Juniperus occidentalis*), low sagebrush (*Artemisia arbuscula*), and mountain big sagebrush (*Artemisia tridentata*). Basic meteorological data, including air temperature, solar radiation, relative humidity, wind speed, wind direction, vapor pressure, and snow depth, were measured with standard methods (Hanson 2001) and a lysimeter measured snowmelt. We constructed the lysimeter with plywood overlaid with an industrial tarp to channel all snowmelt to a tipping bucket. The 250 ml tipping bucket resided in a buried plywood box to prevent freezing. To measure changes in snow depth, we placed two PVC snow depth stakes around the lysimeter. The snow stakes had markings every 2 cm to indicate snow depth. An automated camera took photographs every hour. We used the photographs of the snow stakes to estimate snow depth changes.

2.1 Study Design

The site was visited on 15 April 2013 when no snow was present. A snow event occurred the following day from 400 hours to 600 hours. We conducted a snow survey that same day from 1100 hours to 1745 hours. We measured snow depth with a tape measure under and outside western juniper (henceforth juniper) and mountain big sagebrush (henceforth sagebrush). We chose juniper trees to survey by walking four 200 m transects and identifying the closest tree to the transect every 10 m. If a tree was not within 5 m of these 10 m transect points, no tree was surveyed at that point. We chose sagebrush by random sampling an area that was dominated by mountain big sagebrush. In total, there were 77 juniper and 20 sagebrush sampled.

At each individual juniper and sagebrush plant, we measured snow depth along a small transect on both the north and south sides of each plant (Fig. 1.2). We measured snow depth along the north and south transects at the trunk, one-third of the radius out from the trunk, two-thirds of the radius out from the trunk, at the edge of the canopy, and two measurements 1 m from the edge of the plant canopy in the interspace between surrounding juniper or sagebrush plants (Fig. 1.2). We measured the canopy radius under the juniper from the edge of the trunk to the canopy edge. Since snow buried the sagebrush, we measured the diameter across sagebrush and divided by two to calculate the radius. In sagebrush, due to the shrub being buried, one depth measurement was taken at the center of the sagebrush. For several snow depth measurements, low branches obscured the measurement from being taken. Of the 776 possible depth measurements (97 plants x 8 measurements per plant), this only occurred 3.2% of the measurements (25 measurements).

2.2 Snow Interception

2.2.1 Snow Water Equivalent Estimation

To estimate total storm snow water equivalent (SWE) from the snow depth measurements throughout the day, we estimated snow density throughout the snow survey. We did not use standard methods of using a federal snow tube to estimate SWE and snow density (US Soil Conservation Service 1972) since the snowpack was too shallow for a reliable estimate (Marks et al. 2000). Instead, we calculated snow density throughout the day with continuous snow depth measurements from the photographs and snowpack SWE estimates from the lysimeter. This allowed us to calculate SWE for individual snow depth measurements with a snow density specific to when the snow depth measurement occurred. Depth measurements through time were based on the hourly photographs of snow stakes next to the lysimeter. Total event SWE was 16.5 mm, based on lysimeter output between when the event ended at 600 hours on 16 April and 800 hours on 19 April when a rain event occurred. During that time period, no measureable precipitation occurred at the precipitation gauge. We can assume that nearly all of the snow had melted off the lysimeter before 800 hours on 19 April for two reasons. First, based on the photographs, all the visible snow had melted except for a small patch of snow under a tree. Second, the snow depth sensor at the climate station read “0” before 800 hours on 19 April.

Two possible sources of error to the total storm SWE estimate are either sublimation loss over the 3 d period or snowmelt leaving the snowpack before the end of the snow survey. A 3 yr sublimation study was conducted at RCEW at exposed and sheltered sites had average wind speeds of 4.8 m/sec and 1.3 m·sec^{-1} respectively (Reba et al. 2012), which are both windier compared to our study site with an average wind speed of 0.8 m·sec^{-1}. The calculated mean sublimation loss at the exposed and sheltered sites were 0.39 mm·d^{-1} and 0.15 mm·d^{-1} respectively (Reba et al. 2012). If we assumed our site had the same sublimation rate as their sheltered site of 0.15 mm·d^{-1}, which is likely an over-estimate since average wind speeds were lower at our site, this would produce 0.45 mm of SWE loss due to sublimation between 16 April and 19 April. This is only 2.7% of total storm SWE. The second possible source of error in the total storm SWE estimation is snowmelt that leaves the snowpack before the end of the snow survey. Snowmelt did occur on the lysimeter before the snow survey was completed at 1745 hours on 16 April. Over the 2 h between the beginning of snowmelt output at the lysimeter (1557 hours) and the end of the snow survey (1745 hours), a total snowmelt output of 0.54 mm occurred. This represents a 3.3% loss of total storm SWE. Although this 0.54 mm is incorporated into the 16.5 mm total SWE estimate, it does represent SWE that left the snowpack during the snow survey. To account for this error, the snow density calculation included a loss of SWE for survey points that occurred after 1557 hours. Since both sublimation and snowmelt loss could at most represent a small fraction of total storm SWE, we believe 16.5 mm is a good estimate for total storm SWE.

Assuming total storm SWE is 16.5 mm, we used snow depth measurements from digital images to estimate snow density through time. We estimated snow density at a given time with this equation:

$$density_t = \frac{SWE_t}{depth_{photo,t}} \quad \textbf{[1]}$$

where $depth_{photo,t}$ is the depth of the snow stake by the lysimeter observed in the photo at time *t* and SWE_t is SWE at time *t*. SWE_t was estimated with the total storm SWE of 16.5 mm and subtracting out any lysimeter output before time *t* (i.e. SWE_t until 1557 hours was 16.5 mm). Based on $density_t$, we estimated SWE for each snow depth measurement with a simple equation:

$$SWE_i = depth_{i,t} \times density_t \quad \textbf{[2]}$$

where $depth_{i,t}$ is the snow survey depth measurement at location *i* at time *t*.

2.2.2 Point and Plant-level Interception

Storm snow interception (not interception loss) was estimated by comparing the SWE outside the plant in the interspace to SWE under the plant. The interception equation is:

$$interception = 1 - \frac{SWE_{under\ canopy}}{SWE_{interspace}} \quad \textbf{[3]}$$

For point-level interception calculations, $SWE_{under\ canopy}$ is the SWE estimate for the measured point, and $SWE_{interspace}$ is the average SWE estimate for the two snow depth measurements outside the canopy in the interspace between the plants on the same side (north or south) of the point measurement (Fig. 1.2). Interception is on an $mm \cdot mm^{-1}$ basis and is expressed as a percentage.

For plant-level interception, we used equation 3 and calculated the SWE under the entire canopy from individual point $SWE_{under\ canopy}$. We calculated the SWE under the entire canopy by assigning a percentage of the below canopy area to each snow depth measurement point (Fig. 1.2). We first assumed the measurements at the trunk, one-third radius from trunk, two-thirds radius from trunk, and at the canopy edge represent the inner one-sixth, next one-third, next one-third, and outer one-sixth of the radius respectively. The north and south measurements represented half of each concentric circle (Fig. 1.2). We calculated the area of each half concentric circle from each radius, then subtracted the next inward half concentric circle to calculate the representative area. Therefore the trunk, one-third radius, two-thirds radius, and canopy edge measurements for each north and south side represented 1.4%, 11.1%, 22.2%, and 15.3% of the total under canopy area. Since there was only one trunk measurement for the sagebrush snow surveys, that measurement was assumed to represent the entire inner one-sixth radius area (2.8%). We multiplied the $SWE_{\text{under canopy}}$ for the individual snow depth measurements by the corresponding area percentage (i.e. $SWE_{\text{north, 1/6 radius}}$ by 1.4%, $SWE_{\text{north, 1/3 radius}}$ by 11.1%, etc.), and added up each of these calculations for an area-weighted average $SWE_{\text{under canopy}}$. For the $SWE_{\text{interspace}}$ for the area-weighted interception calculation, we calculated the average SWE for all four of the snow depth measurements in the interspace. For plants where a point measurement was missing, we merely omitted these sections and re-calculated the area-weighted averages without that section.

2.2.3 Plot-level Interception

We estimated plot-level snow interception across the three phases of juniper encroachment and corresponding sagebrush canopy coverage. We estimated plot-level snow interception by multiplying the total average area-weighted interception for each species by a specific canopy coverage percentage. For plot-level interception, we conducted two analyses. First, we calculated separate plot-level interception for pure juniper and sagebrush stands. For both juniper and sagebrush, we calculated plot-level interception for canopy coverage of 5%, 20% and 40%. These percentages correspond to Miller et al.’s (2005) three juniper encroachment phases. Although the encroachment phases do not apply to sagebrush, to make comparisons meaningful between juniper and sagebrush plot-level interception, we used the same three canopy coverage values. Mountain big sagebrush canopy coverage can be as high as 60% and greater than 30% is considered “decadent”, with most canopy coverage values being lower than 30% (Ziegenhagen 2003). Therefore, 5%, 20% and 40% sagebrush canopy coverage falls within the range of low to high mountain big sagebrush canopy coverage. For our second plot-level interception analysis, instead of using pure juniper and sagebrush stands, we used the juniper and sagebrush canopy coverage values for the same juniper encroachment phase, as detailed by Miller et al.’s conceptual model. Therefore the canopy coverage for juniper (sagebrush) include phase I: 5% (30%), phase II: 20% (15%), and phase III: 40% (5%).

2.3 Data Analysis

We compared point-level SWE and interception across juniper and sagebrush at the same measurement locations with 95% confidence intervals. We conducted Student’s *t* tests between sagebrush and juniper both at the same measurement locations to compare point-level interception and for the entire plant to compare plant-level interception. We used a basic linear regression to compare plant-level interception across the range of juniper and sagebrush canopy diameters.

3. Results

3.1 Point-level SWE

SWE in the interspace averaged 14 mm (± 3 mm SD) for the entire snow survey. SWE estimates in the interspace were slightly higher in the sagebrush-dominated area at 17 mm (± 3 mm SD) compared to juniper-dominated areas of 13 mm (± 2 mm SD) (Fig. 1.3). SWE estimates at the same location under the sagebrush and juniper canopy (e.g. comparing *sagebrush* one-third radius north from trunk with *juniper* one-third radius north from trunk) were consistently lower in juniper than in sagebrush at each location (Fig. 1.3) and were all statistically different at $p < 0.01$. For both juniper and sagebrush, when the same location under the north and south sides are compared (e.g. the *north* one-third from radius juniper estimate and *south* one-third from radius juniper estimate), the north side consistently has higher estimates (Fig. 1.3).

3.2 Point-level Interception

Point-level snow interception was much greater in juniper than in sagebrush. Point-level interception is based on equation 3, therefore a positive (negative) snow interception estimate means less (more) SWE under the canopy than in the interspace. The range of the 95% confidence intervals for point-level juniper interception were all greater than zero, except for the range for the canopy edge on the north side (Fig. 1.4). Conversely for point-level sagebrush interception estimates, seven of the eight means were negative (Fig. 1.4). In addition, four of the eight sagebrush point-level interception 95% confidence interval ranges did not overlap positive values (Fig. 1.4). The highest mean point-level interception estimate for the eight point measurements was 48.6% for the juniper-trunk points on the south side. The lowest mean point-level interception was -23.5% for the sagebrush-trunk points on the north side. Comparing point-level interception between sagebrush and juniper at the same measurement locations, all measurement locations were statistically different between the two plants at $p < 0.001$, except on the north canopy edge measurement location ($p = 0.36$).

3.3 Plant-level Interception

Average plant-level interception was 27% (±15% SD) for juniper and -12% (± 15% SD) for sagebrush. Of the 77 juniper plants, interception ranged from -15% to 65%. Of the 20 sagebrush plants, interception ranged from -58% to 9%. The difference between the plant-level interception of the two species was statistically significant at $p < 0.0001$.

3.4 Interception and Plant Size

Juniper diameters ranged from 1.0 m to 12.0 m. Sagebrush diameters ranged from 0.55 m to 1.5 m. Juniper diameter correlated with greater plant-level interception, although the relationship was not statistically significant at $p < 0.05$ with $p = 0.13$ (Fig. 1.5A). Sagebrush diameter correlated with lower area-weighted interception but the relationships were not statistically significant with $p = 0.58$ (Fig. 1.5B).

3.5 Plot-level Interception

Plot-level interception across juniper and sagebrush varied with degree of canopy coverage. Plot-level interception for juniper stands of 5%, 20% and 40% canopy coverage was 1.4%, 5.5%, and 11.0%. Sagebrush plot-level interception across the same three coverage values was -0.6%, -2.2%, and -4.4% respectively. The increasing negative values are due to negative sagebrush interception values, which correspond to sagebrush trapping snow. Plot-level interception for the phase I, II and III for the differing juniper and sagebrush canopy coverage for each phases, was estimated at -1.9%, 3.9%, and 10.5% respectively.

4. Discussion

The difference in point, plant and plot-level interception between sagebrush and juniper suggest that tree encroachment into shrub steppe has a meaningful impact on above ground hydrologic fluxes in these systems. At the plant-level, juniper trees intercepted 27% of the average interspace SWE while sagebrush trapped 12% more than the interspace SWE. For the 16.5 mm SWE for the storm, this difference in interception correlates to a 5.9 mm difference in snow throughfall between the species. The juniper plot-level canopy interception from our study was 1.4% to 11% for 5% to 40% canopy coverage. In another study for a western juniper canopy coverage of 9% to 43%, plot-level snow and rain interception was estimated at 7.8% to 12.8% (Larsen 1993), which is congruent with our results. Conversely, Hull and Klomp sagebrush plot-level snow and rain interception estimates ranged from 17% to 39%, which is dissimilar to our plot-level sagebrush interception of -0.6% to -4.6%. The congruence of our study with Larsen's and the drastic difference between ours and Hull and Klomp evidence that the Hull and Klomp study likely over-estimated plot-level sagebrush snow interception.

Point, plant, and plot-level interception were significantly different between sagebrush and juniper species, however this large difference may not necessarily persist over larger time scales or different climatic conditions. Interception loss for a snow event is one minus the ratio of total snow melt that either enters the soil or is runoff to total storm SWE. Interception loss is often less than interception due to melt drip or canopy unloading of intercepted snow occurring between when a snow event occurs and when the snow melts entirely (Satterlund and Haupt 1970; Hedstrom and Pomeroy 1998; Storck et al. 2002). Based on previous studies, we assume interception loss for the snowstorm in our study was likely lower than the juniper plant-level interception estimate of 27%. However, Eddleman and Miller (1991) observed a 45% to 66% plant-level snow interception loss in western juniper in eastern Oregon. This discrepancy could be due to snow redistribution from our study site reducing apparent snow interception and minimal wind at the Eddleman and Miller site. Wind could reduce apparent snow interception since wind can either increase canopy unloading (Storck et al. 2002) as well as increase scouring of the interspace and adding redistributed snow under the canopy (Pomeroy and Li 2000; Bowling et al. 2004; Essery and Pomeroy 2004b), thereby lowering interception estimates. These redistribution dynamics were apparent in our data (Fig. 1.3) but were not at Eddleman and Miller's site, which could be the reason for the discrepancy for our plant-level interception estimate and their interception loss estimate. In contrast to juniper, sagebrush interception loss was likely positive and therefore greater than the -12% interception estimate. Due to the low profile of the sagebrush plants, many of the plants were buried in snow. During snowmelt after the snow survey occurred, it is likely that a portion of the snow would remain in the canopy and sublimate, thereby increasing the interception loss. Future studies could elucidate interception loss by establishing lysimeters under tree and shrub species to compare interception loss across a much larger time scale and over a broader range of event characteristics.

Despite the uncertainty about the total interception loss for the event, based on point and plant-level interception estimates, juniper trees clearly intercept snow and sagebrush shrubs clearly capture snow. First, in juniper interception was greater at points closer to the trunk than near the edge (Fig. 1.4). Young et al. (1984) similarly observed trunk, half-radius, and canopy edge rainfall interception in western juniper of 69%, 51%, and 19% respectively. In our study, sagebrush showed the opposite relationship, with interception being the lowest closer to the trunk and highest at the canopy edge (Fig. 1.4). Similarly in other studies, while juniper and other tree species consistently have snow interception loss (Eddleman and Miller 1991; Hedstrom and Pomeroy 1998; Storck et al. 2002), the presence of shrub species decreases snow sublimation loss and increases stored snow (Pomeroy and Li 2000; Bowling et al. 2004; Essery and Pomeroy 2004b). A modeling study in the arctic tundra dominated by shrubs predicted that snow gain from redistribution would peak at 30% canopy coverage (Essery and Pomeroy 2004a). These drastic differences between tree and shrub interception may change in areas with deep or persistent snow throughout the winter. However, despite the large difference in the hydrometeorological conditions between these other snow-vegetation studies and our study, overall these other studies support what our study revealed, that tree species can potentially produce a net interception loss of snow, and shrub species can produce a net gain in snow.

A net gain of snow in the sagebrush species is logical considering both the importance of snow redistribution at RCEW and the differences in the morphology of juniper and sagebrush species. Wind redistribution of snow and formation of large drifts is a common phenomenon at RCEW (Reba et al. 2012) as well as much of the semi-arid western

US. (Robertson 1947; Hutchison 1965; Tedesche 2010). Wind typically comes from the southwest at RCEW and drifting usually occurs on the north sides of hills, trees, and shrubs (Winstral et al. 2009). A slight drifting pattern emerged in the point data with more snow deposited on the north sides than south side of both sagebrush and juniper (Fig. 1.3). Since sagebrush is a shrub, their branches are dense and close to the ground. Juniper trees have branches close to the ground, but the density of branches near the ground is much lower compared to sagebrush. As a result, sagebrush shrubs trap more snow that is redistributed by the wind (Fig. 1.3). Drifting under or immediately adjacent to shrubs has also been observed in mountain big sagebrush (Hutchison 1965; Tedesche 2010) and in tundra shrubs (Pomeroy et al. 2006). In our study, shrub size correlated with increased throughfall, but the relationship was not statistically significant (Fig. 1.4). In the arctic tundra, although shrub structure is different, modeled snow dynamics showed an increase in snow accumulation with shrub height (Essery and Pomeroy 2004a; Ménard et al. 2014). Our sample size was adequate, but limited to 20 individual sagebrush shrubs, so additional studies could better elucidate the relationships between shrub size and snow redistribution.

A re-interpretation of the Hull and Klomp study reveals that their monthly snow surveys were likely conducted after a significant amount of snow melt had occurred under the sagebrush. Pomeroy et al. (2006) observed that while snow deposition was greatest in areas with more shrubs, melt rates were also greatest under shrubs. Other studies have shown that buried shrubs enhance snow melt beneath the snow surface (Baker et al. 1991; Hardy et al. 1998) and the majority of snow melt likely reaches the soil rather than sublimates (Reba et al., 2012). These snow deposition and melt/ablation processes can lead to counter-intuitive relationships of sagebrush both trapping more snow than the interspace, while subsequently causing snow to melt out sooner than the interspace. These snow accumulation and melt/ablation processes likely explain the discrepancies between our study and the Hull and Klomp study. While sagebrush likely had low or a net negative interception (i.e. positive throughfall) at the Hull and Klomp site, the snow likely melted out under the shrubs before their snow surveys, producing apparent snow interception by sagebrush. Additional investigations are needed to understand how snow energetics and dynamics vary spatially and temporally during different hydrometeorological events across a mix of shrub and tree canopy structures. These investigations could further assess how woodland encroachment and climate changes will affect hydrological dynamics in semi-arid ecosystems.

5. Implications

Woodland encroachment into sagebrush steppe alters snow interception dynamics. Both increased juniper canopy coverage and larger individual junipers will increase canopy interception (Figs. 1.4 and 1.5A). Juniper trees not only intercepted a large portion of the snow at the plant-level (27%), but sagebrush trapped snow. We calculated that a phase I juniper encroachment stand would trap 1.9% more snow than an area without trees or shrubs at the plot-level, due to a high number of sagebrush in a phase I plot trapping snow. Conversely, phase II and III stands would respectively intercept 3.9% and 10.5% of snow at the plot-level. We also observed the greater the juniper diameter, the greater the plant-level interception, although at $p = 0.13$ this relationship was marginally statistically significant. However, the point-level interception was greatest at the trunk where LAI is highest under the canopy. This suggests that increases in LAI will increase snow interception. This has management implications for woodland encroachment. If woodland encroachment continues to occur into a sagebrush steppe area, a greater fraction of snow could be intercepted and sublimated to the atmosphere due to a) the increase in tree canopy cover, b) the increase in LAI with trees getting older and continuing to grow larger, and c) the decrease of sagebrush plants that trap snow. Not only will woodland encroachment drastically reduce shrub cover across phase I to phase III encroachment, but the hydrological cycle will also likely be altered both as a result of changing snow interception dynamics in addition to transpiration changes. To prevent changes in the hydrology of shrub steppe ecosystems from woodland encroachment, proactive land management must occur.

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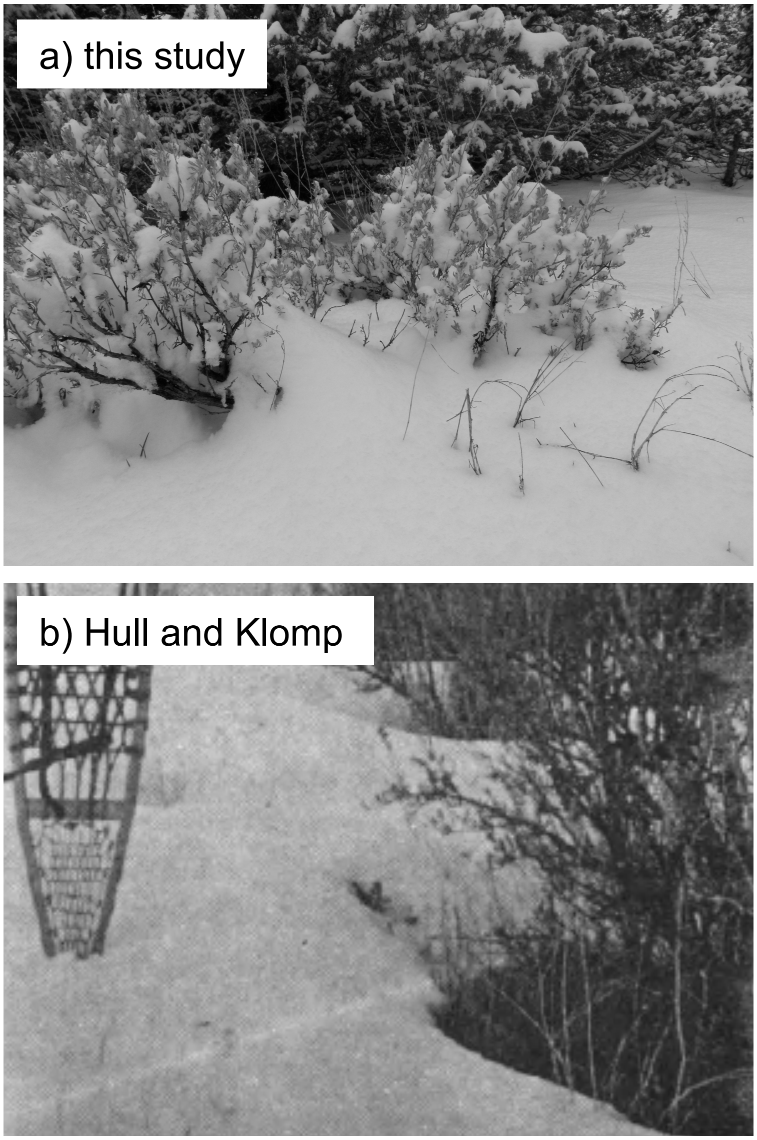

Figure 1.1. Picture of study site during snow survey for A) this study and B) Hull and Klomp (1974) study

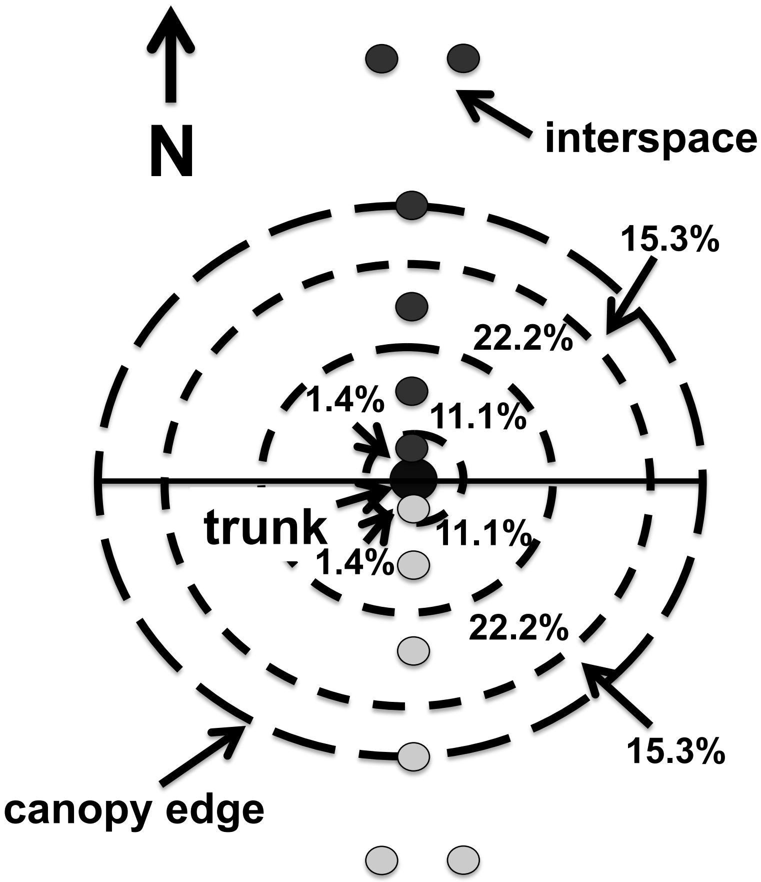

Figure 1.2. Diagram of snow depth sampling design. Dark (light) small dots indicate the north (south) side depth measurements at the trunk, one-third the canopy radius out from trunk, two-thirds the canopy radius out from trunk, and the canopy edge. Two snow depth measurements were taken 1 m outside the tree in the interspace on the north and south sides. Dotted lines forming concentric circles indicate the representative area for each snow depth measurement under the tree. Percentage values are the percent of the total area that each half concentric circle (minus the next inner half concentric circle) represents.

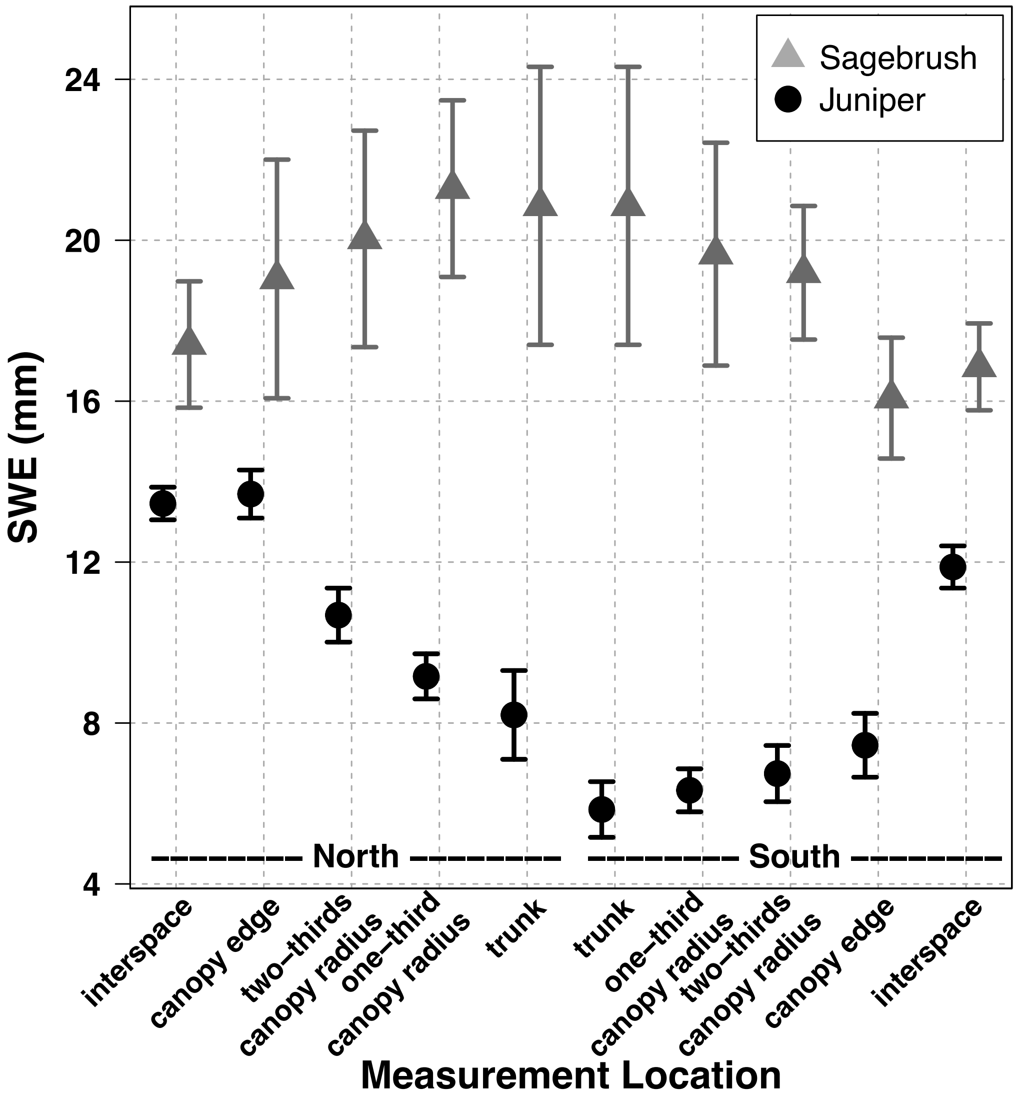

Figure 1.3. Estimated snow water equivalent (SWE) on north and south sides of sagebrush and juniper with 95% confidence intervals.

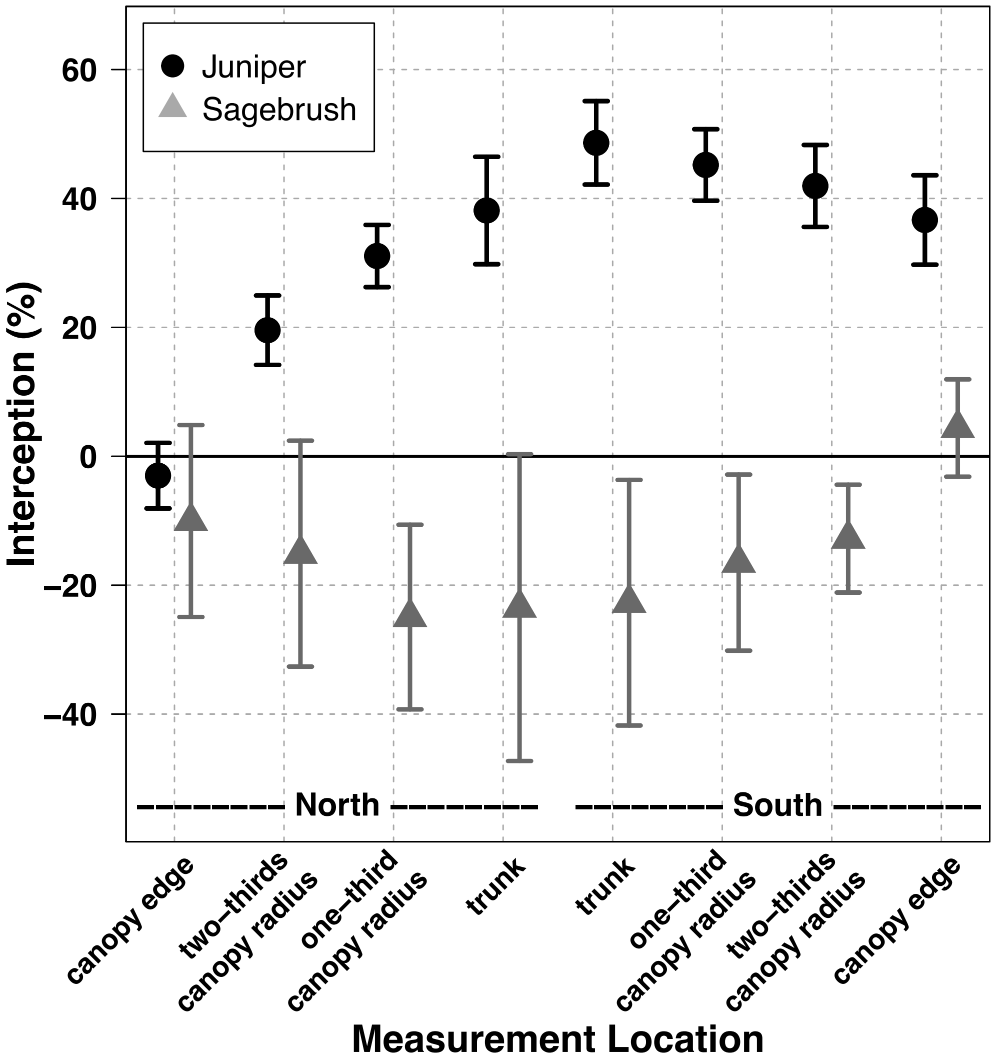

Figure 1.4. Interception at each snow survey location on north and south sides of sagebrush and juniper with 95% confidence intervals.

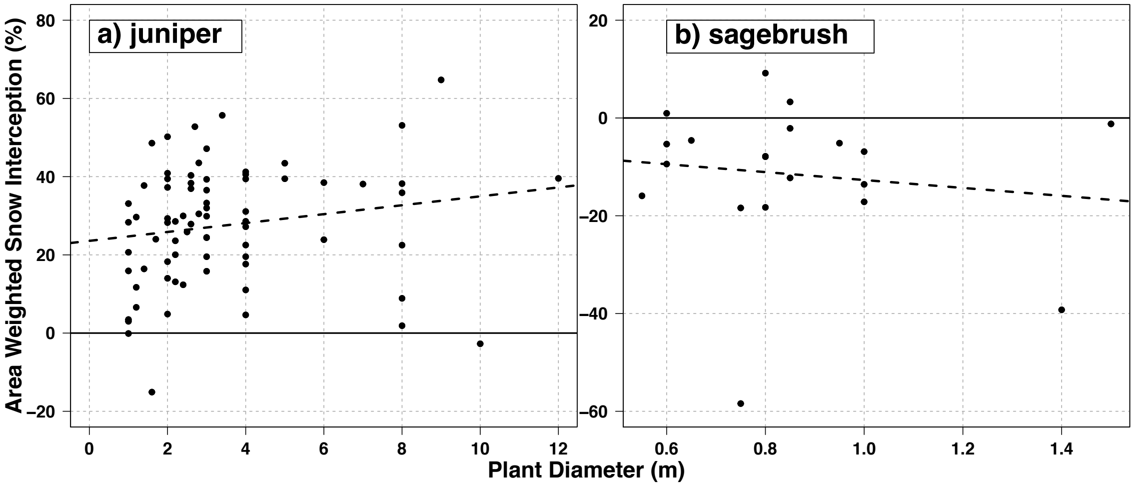

Figure 1.5. Plant diameter and area-weighted snow interception for A, juniper and B, sagebrush. Dotted lines are regression lines for a basic linear model.

Chapter 2 - Interception, throughfall, and snowpack dynamics in western juniper: Potential impacts of climate change and shifts in semi-arid vegetation

Authors: Ryan J. Niemeyer, Timothy E. Link, Mark S. Seyfried, Gerald N. Flerchinger

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Abstract

Shifts in both climate and land cover can both potentially impact above ground hydrological processes. In the western U.S., both climatic shifts from snow to rain-dominated precipitation and land cover shifts of pinyon and juniper species in grass and shrub-dominated landscapes alter interception, throughfall and snowpack dynamics. To better understand how shifts in both vegetation cover and precipitation phase alter above-ground hydrological processes, we assessed differences in rain interception, and snow and rain throughfall in western juniper, how western juniper alters snowpack dynamics, and how these above-ground processes differ across western juniper, mountain big sagebrush, and low sagebrush plant communities. We collected continuous throughfall with four large lysimeters, continuous interspace and below-canopy snow depth data, and conducted periodic snow surveys for two consecutive water years (2013 and 2014). Throughfall, estimated with the lysimeter data, was greater for snow relative to rain events, averaging 74.9% and 54.8% respectively. We validated the Simultaneous Heat and Water (SHAW) model with eight years of continuous snow depth data, two years of interspace and canopy snow depth data, and interspace and canopy lysimeter data. We then simulated above-ground energy and water fluxes for an eight year period with more hydrometerological variability. We simulated surface water fluxes in western juniper, low sagebrush, and mountain big sagebrush cover under both the current and a mid-21st century ensemble projected climate. Comparison of the simulations revealed that changes in vegetation principally change the amount of hydrological fluxes such as surface water input, while the future (warmer) simulations saw shifts in the timing of those fluxes. Information from this study can help managers understand how both shifts in climate and semi-arid vegetation will alter fundamental hydrological processes.

Key words: throughfall, interception, snow, western juniper, woodland encroachment, mountain big sagebrush

1. Introduction

Vegetation canopies assert a first order control on above-ground hydrological processes, therefore any hydrologic analysis of vegetation cover change must consider above-ground processes. In cold regions that receive some portion of precipitation as snow, the above-ground processes principally impacted are interception, throughfall, and snowpack dynamics, and hence timing and amount of surface water input (SWI). First, precipitation interception by vegetation canopies is a major component of the land surface water cycle, consisting of as much as half of the hydrological budget in some systems (Hörmann *et al.*, 1996; Carlyle-Moses, 2004). A large portion of intercepted precipitation is evaporated or sublimated to the atmosphere, defined here as interception loss, and therefore does not become throughfall and enter the soil profile (Calder, 1998). Second, in snow-dominated environments, vegetation cover can alter snowpack dynamics. This occurs both by reducing snow throughfall (Eddleman and Miller, 1991; Storck *et al.*, 2002), and altering snow surface energetics (e.g., net radiation and turbulent energy regimes) which affects snow deposition and snowmelt timing and amount (Golding and Swanson, 1978; Troendle and King, 1985; Ellis *et al*., 2013; Lundquist *et al.*, 2013). Both snow interception and accelerated snowmelt can produce tree wells – areas under tree canopies with less snow than open areas, which in addition to altered wind regimes, can cause snow to be redistributed under shrubs or trees compared to open or interspace areas (Robertson, 1947; Hutchison, 1965; Sturm *et al.*, 2001; Pomeroy *et al.*, 2006). A hydrological analysis of changes in vegetation cover must consider how interception, throughfall, and snowpack dynamics are impacted.

Understanding how precipitation phase (rain or snow) affects interception and throughfall dynamics is especially important since climate change is altering the fraction of precipitation that falls as snow in many regions. Research in the western U.S. shows shifts from snow to rain dominated precipitation regimes (Nayak *et al.*, 2010, Kapnick and Hall, 2012), and these shifts are likely to be even more drastic in the future (Klos *et al*., 2014). These shifts are associated with reduced streamflow (Luce and Holden, 2009; Berghuijs *et al*., 2014). Despite the importance of snow to streamflow in the western U.S. (Service, 2004), there is still a lack of a mechanistic understanding of the hydrological processes that drive these water yield reductions (Berghuijs *et al.*, 2014). A possible mechanistic link is changes in interception and throughfall dynamics. Intercepted rain is stored in the canopy for several minutes and up to a several days, and stemflow can consist of a small or large fraction of total rain throughfall (Eddleman and Miller, 1991; Crockford and Richardson, 2000; Levia, 2004; Carlyle-Moses and Price, 2006; Owens *et al*., 2006), although it is typically smaller in rough-barked trees common in semi-arid areas (Levia and Germer, 2015). On the other hand, intercepted snow can remain in the canopy from days to months (Storck *et al*., 2002; Parajka *et al.* 2012) and stemflow from melted snow is not typically observed or plays a minor role (Young *et al*., 1984; Eddleman and Miller, 1991; Levia, 2004).

Understanding how rain and snow interception and throughfall, as well as snowpack dynamics, differ is especially important in areas undergoing drastic land cover changes. Semi-arid tree-dominated woodlands, including western juniper (*Juniperus occidentalis*) and other pinyon-juniper dominated landscapes are currently the largest forest cover class in the western U.S. (Larson, 1980). This large spatial coverage is partly due to woodland encroachment into grass or shrub-dominated landscapes over the 140+ years that has seen increases by as much as 10-fold in pinyon-juniper coverage in some areas (Tausch *et al*., 1981; Miller *et al.*, 2005; Romme *et al.*, 2009). Assessing shifts from snow to rain interception and throughfall is especially important in western juniper (henceforth "juniper") areas since they principally occur at lower and mid-elevations (Gedney *et al.*, 1999) where the transition from snow to rain dominated regimes has and will likely continue to occur (Nayak *et al.*, 2010; Klos *et al.*, 2014). Land cover in these semi-arid systems will likely continue to shift due to juniper encroachment (Creutzburg *et al*., 2015) as well as large scale juniper removal by management agencies (Bureau of Land Management, 2015). Multiple studies have assessed interception loss in sagebrush spp. and juniper separately for both rain and snow with interception loss ranging from 44% to 55% in sagebrush (Collins, 1970) and 14% to 90% in juniper (Collings, 1966; Young *et al.*, 1984; Eddleman, 1986; Eddleman and Miller, 1991; Larsen, 1993; Taucer, 2006; Owens *et al.*, 2006). Throughfall in juniper can be greater in rain than in snow (Eddleman and Miller, 1991). Both sagebrush spp. and juniper can also alter snow redistribution dynamics, causing snow deposition on the leeward side of the vegetation structure (Tedesche, 2010). Despite the existence of these data, there is a paucity of studies directly comparing above-ground hydrological processes in juniper to sagebrush spp.

The impacts of both changes in vegetation and climate on above ground hydrological processes manifests itself through changes in SWI. While many studies focus on changes in snowpack from shifts in vegetation (Ellis *et al.*, 2013; Lundquist *et al.*, 2013) or shifts in climate (Mote *et al.*, 2005; Kapnick and Hall, 2012), ultimately the timing and amount of SWI exerts primary control on streamflow and ecosystem productivity in many environments (Seyfried *et al.*, 2009; Smith *et al.*, 2011). The timing of SWI is effectively synchronous with precipitation for rain events, but is asynchronous for snow events by hours or even months depending on the timing of snow melt. However, SWI amount may not directly correlate to snow deposition or peak snow water equivalent (SWE) due to snowpack sublimation (Reba *et al.*, 2012) or timing of SWI input (Seyfried *et al.*, 2009). Despite the importance of SWI, few studies focus on how both vegetation and climate shifts alter the timing and quantity of coupled interception, snowpack, and SWI dynamics.

The broad objective of this paper is to understand how shifts from snow to rain and changes in land cover alter above-ground interception, throughfall, snowpack, and SWI dynamics. Furthermore, the existence of western juniper woodlands in the snow-rain transition zones make it especially important to analyze how throughfall dynamics will change across both shifts in precipitation regime and land cover. To this end, the specific objectives of this paper are to (i) understand the differences between rain and snow throughfall in western juniper, (ii) understand how rain canopy storage and evaporation rates in western juniper are influenced by event-scale meteorological conditions, (iii) understand differences in snow accumulation, ablation, timing and amount of SWI, and evaporation and sublimation loss between western juniper, low sagebrush, and mountain big sagebrush.

2. Methods

To assess the effects of climate and vegetation on above-ground hydrological fluxes, we used a combination of observations both to empirically compare processes and to validate a model to assess the effects of different climate and vegetation scenarios on hydrological fluxes.

2.1 Site Description

This study was conducted at the Reynolds Creek Experimental Watershed (RCEW) and Critical Zone Observatory (RCZO) in the Owyhee Mountains, approximately 80 km southwest of Boise, ID, USA. RCZO is a semi-arid watershed with moderate steepness and snow cover typically persisting for 4 to 6 months of the year. The specific site for this study is located at 1940 m above m.s.l. The slope and aspect of the study site are 26% and 246° respectively. Annual precipitation at the nearest gauge, located at a climate station 730 m to the east and 50 m higher in elevation from the study site, was 554 mm. Based on PRISM adjustment of monthly precipitation from the climate station (Daly *et al*., 1994), annual precipitation at the study site is estimated at 490 mm. Wind direction at the site is typically from the south by southwest, producing drifts on the north or northeast sides of topographic features (Winstral *et al*., 2009) or vegetation (Tedesche, 2010). Plant species on the site include a mix of western juniper (*Juniperus occidentalis*), low sagebrush (*Artemisia arbuscula*), and mountain big sagebrush (*Artemisia tridentata*). Equipment was established over an approximate two ha study area that included two areas with juniper: a savannah-like low density area with a canopy cover of 17% and in an adjacent medium density juniper area with a canopy cover of 37%.

2.2 Measurements

Meteorological data collected at a long-term climate station in the medium density juniper area includes air temperature (T_a), shortwave radiation, relative humidity, wind speed (u), wind direction, vapor pressure, and snow depth (D_S), all measured with standard methods (see Hanson 2001 for descriptions). Two trees (designated tree 1 and tree 2) were selected for intensive measurements. Tree 1 had a diameter (height) of 3.2 m (3.7 m) and tree 2 had a diameter (height) of 2.7 m (2.8 m). Based on a vegetation survey, juniper trees at the study area had a median diameter of 2.9 m (n = 84), therefore tree 1 and 2 are representative of the study area. Four large lysimeters, one at each tree and two in the interspace, were used to quantify rain, throughfall, and snowmelt. We constructed lysimeters out of plywood lined with an industrial tarp (see Elder et al. 2014 for a general schematic). The tree lysimeters were constructed to capture all throughfall under the canopy and the interspace lysimeters were a 2.4 x 2.4 m square. Water was funneled to an opening in a buried and insulated plywood box that contained a 250 ml tipping bucket. A volume of tip versus time rating curve was developed for each tipping bucket. Depth of rain, throughfall, and snowmelt were calculated based on the area of the lysimeter and volume of each tip. Freezing was an issue during the winter and we identified and removed erroneous data by comparing lysimeter data to precipitation, D_S, and modeled data. Although not continuous throughout the study period, the lysimeter events allowed for comparison of throughfall dynamics across discrete rain and snow events.

We collected continuous snow measurements by recording hourly digital images of snow stakes under and outside trees with the automated 6 megapixel Moultrie Game Spy M-65. Since snow is most variable on north and south sides, we established two cameras pointed at tree 1 (tree 2) from the east (west) side. Snow stakes consisted of 1.5 m long, 1.3 – 3.8 cm diameter, PVC pipe with depth marks every 5 cm. Due to their small size, we assume these had little impact on snowmelt processes and therefore minimal impact on the lysimeter data. During the first year, we placed two stakes under each tree – one on the north and south sides equidistance from the tree trunk and canopy edge. We also placed two snow stakes outside each tree, 0.5 m to 2.0 m from the canopy edge. During the second year, we placed six snow stakes under each tree, three located on both the north and south side of the tree positioned approximately 15 cm from the trunk, equidistance from the trunk and canopy edge, and approximately 15 cm from the canopy edge. Additionally, four stakes total were placed outside each tree in the interspace on the north and south sides and two on the camera side (east or west) of the tree. Digital photos, by establishing a pixel per cm depth, allowed for D_S measurement resolution of approximately 0.2 cm and manually estimation of D_S. We estimated D_S every hour during snow events and rapid ablation periods, and every 12 hours outside of those periods. Due to camera failure from Dec 5th, 2013 to Jan 30th, 2014, 74% of the active snow season (first snow fall to permanent snowpack melt) was captured.

We estimated rain interception loss (I_{rain}) for individual rain events based on the total precipitation in the interspace (P_G) and throughfall under the tree (P_N) with the lysimeters. We calculated I_{rain} by:

$$I_{rain} = 1 - \frac{P_N}{P_G} \textbf{ [1]}$$

with P_G and P_N as the rain measured in the interspace and throughfall measured under the tree, respectively. P_G and P_N measurements were included from the start of the event to six hours after the rain event stopped to allow for canopy evaporation of intercepted rain.

We estimated the throughfall ratio (TF) both for rain and snow events with the following equation:

$$TF = \frac{P_N}{P_G} \textbf{ [2]}$$

where P_G was based on the average interspace storm a) snow accumulation or b) rain and/or snowmelt measured with the lysimeter. P_N was based on the storm a) snow accumulation under the tree at the particular snow stake (i.e. not averaged for the entire tree) or b) rain and/or snowmelt measured with the lysimeter. First, we calculated rain TF (TF_{rain}) with lysimeter measurements under the tree and in the interspace. Second, we calculated TF with lysimeters for snow events with snow-free antecedent conditions ($TF_{snow,l}$) where the entire snowpack melted out before additional precipitation occurred, verified by the hourly photos. Third, we calculated mixed snow events TF (TF_{mixed}) where part of the event included snow but had some portion that occurred with T_a above 1°C. Fourth, snow TF ($TF_{snow,d}$) was estimated by comparing snow depth at snow stakes for snow events that occurred during the permanent snowpack. $TF_{snow,d}$ was calculated with the ratio of total under tree snowfall to interspace snowfall, both based on D_S measurements before and after the event. Note that in our calculation of $TF_{snow,d}$, P_N and P_G includes both snow that initially falls to the ground as well as deposited snow redistributed by wind. Although this constitutes two different processes, for simplicity we use $TF_{snow,d}$ to incorporate both. To compare TF_{rain} to both $TF_{snow.l}$ and TF_{mixed}, we calculated a P_G-weighted average TF where an increasing weight on the portion of the event P_G to the total P_G.

We conducted several analyses to assess the metereological factors that control both lysimeter-estimated TF (TF_{rain}, $TF_{snow,l}$, TF_{mixed}) and $TF_{snow,d}$. First, we developed two separate multiple linear regressions (MLR) for both lysimeter-estimated TF and $TF_{snow,d}$ with TF as the dependent variable and P_G (D_S outside the tree for $TF_{snow,d}$ MLR), average storm *u* and T_a, and tree type (tree 1 or 2) as the independent variables, in addition to antecedent tree-interspace snow depth difference ($D_{tree\text{-}inter}$) for $TF_{snow,d}$ and VPD for lyimsiter-based TF. We performed a stepwise MLR that removed variables to lower the model Akaike Information Criteria (AIC) score (Burnham and Anderson, 2004). Second, we did a simple linear regression (SLR) between $TF_{snow,d}$ and $D_{tree\text{-}inter}$. To calculate how much additional snow is deposited under the trees due to $D_{tree\text{-}inter}$, we calculated $TF_{snow,d}$ without the influence of $D_{tree\text{-}inter}$ by using the SLR coefficients to remove the influence of $D_{tree\text{-}inter}$ on each $TF_{snow,d}$ estimate. For each storm we then averaged the added snow under the canopy across all snow stakes.

We conducted snow surveys to estimate the spatial variability of D_S across the site. We measured D_S along a 200 m north-south transect that crossed the low density and medium density juniper areas. We established a stratified random sampling design by collecting D_S every 10 m with two north/south or east/west offsets 4 m from the initial point, alternating the offset direction every other measurement. We measured D_S under adjacent trees by locating the closest tree from each initial point, and measuring D_S on the north and south sides at the trunk, between trunk and canopy edge, at the canopy edge, and 1 m outside the canopy edge. If no tree canopy was within a 10 m radius of the initial point, no tree D_S was measured. Our first survey on March 14th, 2013 was along four transects. We conducted snow surveys along one or two of the same initial transects in 2014 on Jan 30th, Feb 20th, and March 12th.

2.3 Canopy Interception Loss Model

We estimated canopy storage capacity (S) and evaporation to rainfall rate during saturated canopy conditions ($\bar{E}/\bar{R}$) by comparing P_N and P_G. The Gash analytical model (Gash, 1979) estimates I_{rain} canopy parameters based on discrete events and has been successfully applied across a range of meteorological and vegetation characteristics (Gash and Morton, 1978; Lankreijer *et al.*, 1993; Jetten, 1996; Schellekens *et al.*, 1999). The model combines mathematical representation of interception processes and an empirical approach based on measured P_G and P_N that span the canopy wetting and saturation period to derive S and $\bar{E}/\bar{R}$ (e.g. Link *et al.*, 2004). We estimated I_{rain} parameters for events with clear canopy saturation inflection points for both tree 1 and 2.

To assess how I_{rain} parameters can change with meteorological characteristics of each storm, we plotted S and $\bar{E}/\bar{R}$ with P_G, VPD, and *u*. We also analyzed the relationship between $\bar{E}/\bar{R}$ and T_a. We plotted I_{rain} with time to understand seasonal dynamics. We plotted I_{rain} through time and not S, since there was a paucity of events that were large enough to estimate S. We used SLR and MLR to test the statistical significance of correlations between I_{rain} parameters and P_G, VPD, and *u*.

2.4 Simulation Approach

To compare differences in above-ground hydrological fluxes under current and future climates and across juniper and sagebrush, we modeled hydrological fluxes with the Simultaneous Heat and Water (SHAW) model (Flerchinger *et al.*, 1996). SHAW is a one-dimensional model that simulates the water and energy fluxes within the soil-plant-atmosphere continuum at an hourly time scale. The model is driven by precipitation, shortwave radiation, *u*, T_a, and relative humidity. The SHAW model has been tested and applied extensively within low and mountain big sagebrush sites at RCZO (Flerchinger *et al*., 1996; Flerchinger *et al.*, 2010). To assess the sensitivity of hydrological fluxes to different vegetation cover characteristics we varied LAI, vegetation height, and albedo across juniper, mountain big sagebrush, and low sagebrush (Table 2.1). These and other parameter values were derived from previous SHAW studies (Flerchinger *et al*., 1996; Flerchinger *et al*., 2010; Chauvin *et al*., 2011) and empirical vegetation studies at RCZO (Clark and Seyfried, 2001).

We simulated the current and future hydrological fluxes with the SHAW model. Current simulations were run with meteorological data from the climate station at the site from 2007 to 2014 water year (WY) and precipitation data from PRISM-adjusted data from the uphill climate station (Daly *et al*., 1994). Future meteorological data was identical to the 2007 to 2014 WY data except T_a was changed. Future T_a was generated using projections from 20 global climate models (GCM) from the Multivariate Adaptive Constructed Analogs (MACA) data set (Abatzoglou and Brown, 2012). For the 8.5 representative concentration pathway for the 4 km or 6 km (GCM resolution varies) tile that overlaps with the study site, we calculated the change in monthly T_a from the current (1990-2005) and mid-century (2046-2065). This change in monthly T_a was then used to change each daily T_a measurement in WY 2007 – 2014. We assumed relative humidity would stay the same and the SHAW model calculates the changes in vapor pressure based on the input T_a and relative humidity. Although precipitation and other meteorological variables may change under future climates, we only modeled changes in T_a and corollary changes in vapor pressure because a) climate predictions show a clear shift in T_a (Hamlet and Lettenmaier, 2007; Abatzoglou and Brown, 2012) and b) precipitation predictions are less certain (Hamlet and Lettenmaier, 2007). The model does incorporate differences in the phase of precipitation with warming T_a, with precipitation being modeled as rain when T_a is above the snow T_a threshold (1 °C).

SHAW model performance was evaluated with the Nash-Sutcliffe model efficiency (Nash and Sutcliffe, 1970) by comparing A) daily simulated D_S with no vegetation to D_S at the climate station (WY 2007 to 2014), B) daily simulated D_S with juniper (no vegetation) to D_S under juniper canopy (interspace) averaged across representative snow stakes at trees 1 and 2, and C) weekly simulated SWI with juniper (no vegetation) to measured SWI at juniper (control) lysimeters. We validated SHAW with no vegetation since the climate station is kept bare and the interspace snow stakes and lysimeters are bare as well. We compared snowpack dynamics, SWI amount and timing, and evaporation/sublimation (ES) loss between the current and future simulations, as well as across the three vegetation types. We also calculated the day 50% of the total WY SWI occurred (SWI 50% day). We used SLRs to compare the timing and amount of SWI to peak SWE.

3. Results

3.1 Throughfall

A total of 11 snow events occurred with snow-free antecedent conditions where the entire snowpack melted before additional precipitation occurred, which allowed for estimation of $TF_{snow,I}$. P_G for these 11 events ranged from 1.1 mm to 13.0 mm (mean = 5.1 mm). The average $TF_{snow,I}$ for these events was 63.1% (n = 16, SD = 34.8%) (Figure 2.1) with two positive $TF_{snow,I}$ estimates. A positive estimated $TF_{snow,I}$ indicates a greater amount of snow deposited under the tree than in the open area. A total of four events included a portion of precipitation falling above and below 1 °C and were classified as "mixed". Average TF_{mixed} was 90.5% (n = 7, SD = 39.6%) (Figure 2.1). TF_{rain} was estimated at 25.1% (n = 29, SD=23.1%) (Figure 2.1). The average TF with snow ($TF_{snow,I}$ and TF_{mixed}) and TF_{rain}, weighted by P_G, was 79.4% and 54.8%, respectively. Comparing the current and future simulated climate, the total seasonal SWE to P_G ratio shifted from 63.6% to 37.3% (Figure 2.2). Calculating the total TF from these monthly precipitation shifts with the PG-weighted TF estimates, the total TF was 400 mm for 1990 – 2005 and 363 mm for 2046 – 2065, a 9.2% reduction from current to future TF.

Comparing $TF_{snow,I}$, TF_{mixed}, and TF_{rain}, both the storm type and P_G impacted estimated TF. For the MLR model with TF as the dependent variable, and the independent variables as T_a, u, VPD, P_G, tree type and storm phase, P_G (p = 0.005) and rainfall events (p = 0.002) were significant. Confirming our assumption of both trees being similar to each other, differences in TF between tree 1 and tree 2 were not significant (p = 0.82). A stepwise MLR of the same statistical model reduced the original six variables to VPD (p = 0.07), P_G (p

= 0.004), as well as rain (p = 0.0001) and mixed (p = 0.31) event type. Furthermore, VPD, P_G, and storm phase explain 3.4%, 9.3%, and 17.0% of variation.

Event-based $TF_{snow,d}$ evidenced a relationship between $D_{tree-inter}$ and estimated $TF_{snow,d}$. $TF_{snow,d}$ increased for events that occurred for larger $D_{tree-inter}$ values (Figure 2.3). This relationship persisted regardless of P_G. Using SLR, the relationship between $TF_{snow,d}$ and $D_{tree-inter}$ was statistically significant (Figure 2.3, $p < 0.001$). Based on a one-way ANOVA, for the 34 snow storms during the second year, event D_S under the tree was statistically different at the snow stakes closest to the trunk compared to the middle and canopy edge snow stakes (p = 0.03), but the latter two were not statistically different (p = 0.26). The five term MLR was significant (p < 0.0001). The stepwise regression retained $D_{tree-inter}$ (p = 0.001), *u* (p = 0.001), T_a (p = 0.11), tree type (p = 0.11), and P_G (p = 0.15).

3.2 Canopy Rain Interception Loss

A total of 29 rain events were captured with a P_G ranging from 0.31 mm to 21.1 mm (mean = 4.9 mm). The average event-based I_{rain} for both trees was 74.9% (n = 52, standard deviation (SD) = 23%) (Figure 2.1). For the 18 (34) rain events larger (smaller) than 5 mm, the average I_{rain} was 48.7% (84.0%,). Plots of the 11 rainfall events large enough to model S indicate clear inflection points in plots of P_G vs. P_N and allowed for I_{rain} parameters to be determined for both trees (i.e. n = 22). These storms averaged 9.3 mm. The average S was 2.0 mm and there was not a statistically significant relationship between P_G (Figure 2.4a) or *u* (Figure 2.4b), although *u* was statistically significant in the MLR (p = 0.02). The relationship between VPD and S was significant (Figure 2.4c). There was an I_{rain} seasonal pattern with maximum I_{rain} during the middle-growing season months of May to September, and lower

I_{rain} in the beginning and end of the growing season (Figure 2.5). In addition, P_G was negatively correlated with I_{rain} (Figure 2.5).

Estimated $\overline{E}/\overline{R}$ during rain events was correlated principally with P_G (Figure 2.4d), which was statistically significant in predicting $\overline{E}/\overline{R}$ in the MLRs ($p < 0.0001$). There was no clear correlation between $\overline{E}/\overline{R}$ and both u (Figure 2.4e) and VPD (Figure 2.4f). However, correlation between $\overline{E}/\overline{R}$ and both u and VPD is greater when only considering events larger than 10 mm (Figure 2.4e,f). T_a is also positively correlated with $\overline{E}/\overline{R}$ (regression not displayed: slope = 0.01 mm hr^{-1} $°C^{-1}$, $p = 0.06$).

3.3 Snow Deposition

$TF_{snow,d}$ was estimated from 65 snow events that occurred as early as September 26th and as late as April 27th. A total of 261 below-tree D_S measurements occurred since each tree had anywhere from two to six snow stakes under the canopy. Total D_S accumulation per snow event outside the tree ranged from 0.7 cm to 30 cm and averaged 5.3 cm. Average event $TF_{snow,d}$ ranged from 0% to 171% with an average of 58.5% (SD = 33.1%) (Figure 2.1). The largest measured winter event during the study period was 30 cm D_S, but snow on the tree branches obscured snow stakes under the trees preventing a below-tree D_S estimate. The largest event where D_S under the trees could be identified was 12 cm D_S and the TF was 49% at the south canopy edge stake and 45% at the north middle canopy stake. Calculated snow deposition due to $D_{tree\text{-}inter}$ was 15.2 cm and 13.9 cm for WY 2013 and WY 2014 respectively, and the complete WY 2014 snow season was not recorded (Figure 2.6).

3.4 Snowpack Dynamics

Snow surveys across the plot in the interspace and under the trees show that in general the continuous measurements were representative of the two ha study area (Figure 2.6). These continuous measurements reveal that snowpack dynamics under the tree and in the interspace comprised almost entirely different snowpack ablation and melt regimes. In WY 2013, under the tree D_S was often less than 5 cm or entirely absent starting in mid-January (Figure 2.6a). Conversely, average D_S in the interspace was persistently deeper and not less than 25 cm until the majority of the snowpack ablation occurred mid-March (Figure 2.6a). In WY 2014, on January 30th snowpack under the tree was absent for six of the eight snow stakes and the interspace average D_S was 9.7 cm (Figure 2.6b). That same year after a large snow event in early February, the snow under trees disappeared almost entirely again before another snow event in late February (Figure 2.6b). Conversely, snow persisted in the interspace through several snow events in late February before disappearing from all the interspace stakes by March 3rd and March 9th for trees 1 and 2 (Figure 2.6b).

3.5 Current and Future Simulations

The Nash-Sutcliffe model efficiency comparing measured D_S at the climate station, D_S in the interspace, and D_S under the juniper canopy with simulated D_S was 0.78, 0.81, and 0.51 respectively. Model efficiency for SWI at lysimeters under the two trees was -0.01 and 0.37, and 0.41 and 0.49 for the two interspace lysimeters were respectively. The average monthly T_a increase between the current and mid-century simulations ranged from 2.2 to 3.2 °C, with January, July, August, and September all above 3 °C. As a result, monthly ratios of simulated SWE to P_G show a clear shift to less snow under a future climate (Figure 2.2).

The average total SWE to P_G ratio from December to March ranged from 0.84 to 0.89 in the current climate, and shifted to 0.47 to 0.57 in the mid-21st century climate (Figure 2.2).

Modeled SWE in juniper compared to the two sagebrush simulations is consistently lower throughout the winter (Figure 2.7). The average peak SWE for the current climate in juniper is 153 mm, compared to 236 mm and 222 mm for mountain and low sagebrush respectively. Juniper therefore have 31% and 35% lower peak SWE than mountain and low sagebrush respectively. This difference in peak SWE between juniper and low sagebrush of 83 mm is 17% of the total annual water budget. Under future simulations, average juniper peak SWE was 46 mm, compared to 67 mm and 74 mm under mountain and low sagebrush respectively. Juniper reduce peak SWE by 30% and 37% compared to mountain and low sagebrush respectively (Figure 2.7). Average snow cover disappearance for the three species were within 2 days of each other for the current climate, and within 12 days of each other for the future climate, with snow disappearance occurring earliest in juniper in both cases (Table 2.2). However, snow disappearance day from the current to future simulations shifted on average 51 days across the three vegetation types (Table 2.2).

Shifts in climate and vegetation both produced differences in timing and quantity of SWI. SWI was greater in both low and mountain big sagebrush, compared to juniper, in both the future and current simulations by an average of 137 mm (Table 2.2). In general, SWI shifted to earlier in the season, with Winter (Nov – Feb) SWI greater in future climate compared to current climate across all vegetation types. Under the current climate, SWI peaked in April, especially in low and mountain big sagebrush (Figure 2.8 a-c) which both had deeper peak SWE compared to juniper (Figure 2.7). These April peaks in SWI in the current simulations for juniper, mountain big sagebrush, and low sagebrush were respectively 34 mm, 104 mm, and 104 mm greater than the March – the next largest SWI month for each simulation. Conversely, average SWI peaked in March in the future climate. These future March SWI peaks were 38%, 44%, and 41% lower than the current April SWI peaks in juniper, mountain big sagebrush, and low sagebrush respectively. These shifts in SWI are reflected in the SWI 50% day which shifted to an average of 45 days earlier across the three vegetation types (Table 2.2).

By comparing peak SWE to both the amount and timing of SWI, we see how a warmer climate impacts SWI timing and quantity. Peak SWE correlates with SWI amount for years when Nov – Mar T_a is on average below 0 °C (Figure 2.9a). But peak SWE is not similarly correlated with SWI when average Nov – Mar T_a is above 0 °C (Figure 2.9a). Conversely, the timing of SWI correlates with peak SWE (Figure 2.9b) regardless of T_a as both cold and warm years fall along the same trend. SWI 50% day occurs earlier in years that are both warmer and with lower peak SWE.

Combined ES loss principally differs in the amount across juniper and the sagebrush species and in timing across both the current and future simulations. ES loss was on average 92 mm greater in the juniper compared to the two sagebrush simulations, but only 19.7 mm greater in the future juniper simulation compared to the current juniper simulation (Table 2.2). In general, from the current to future simulations, ES shifted earlier with increases in February, March, and April and little or no changes occurred in June through November (Figure 2.8d-f). In the juniper simulations, ES loss peaked in June in the current simulation, but peaked in March in the future simulation (Figure 2.8d). Conversely, in mountain and low sagebrush although ES loss increased in November through June between the current and future simulations, the peak monthly ES loss was in June or July (Figure 2.8e,f). Clearly changes in the climate shift the timing of ES loss, but differences in vegetation primarily shift the amount of ES loss.

4. Discussion

I_{rain} and S in juniper were within the range of previous estimates. Our median I_{rain} of 74.9% is similar to other western juniper and similar semi-arid tree species studies that range from 29% to 71% (Young *et al.*, 1984; Eddleman, 1986; Eddleman and Miller, 1991; Larsen, 1993). Our estimate is probably on the upper end of the I_{rain} range because most of the rain events are small (mean = 4.9 mm). Finally, our average S of 2.0 mm was vey similar to Larsen's (1993) average of 1.9 mm, who used simulated rain at 23 mm hr^{-1} for juniper ranging from 2.5 to 10.4 m in diameter.

Our analysis pointed to clear differences in TF due to both precipitation type and P_G. We observed differing TF estimates for TF_{rain} and $TF_{snow,l}$ of 54.8% and 79.4% respectively. The TF group mean for both rain and mixed events in the MLR were statistically different being lower and higher than the overall mean respectively. Conversely, Eddleman and Miller (1991) observed greater TF_{rain} of 48.0% compared to $TF_{snow,l}$ of 39.6%. P_G was also statistically significant in our MLR with increasing P_G corresponding to increasing TF. The fact that P_G was statistically significant is important since future models predict greater winter P_G (Kumar *et al.*, 2012), which would potentially increase TF and thereby offset the decreases in TF due to shifts from snow to rain. Interestingly, in Eddleman and Miller's study of the average P_G was much larger for snow (53 mm) than rain (8.3 mm), despite a lower observed $TF_{snow,l}$ compared to TF_{rain}. A possible reason for differences in the effect of P_G across $TF_{snow,l}$ and TF_{rain} is *u*. Eddleman and Miller surmised that high $TF_{snow,l}$ is due to the lack of wind which allowed for intercepted snow to remain in the canopy for longer time periods to ultimately be sublimated, reducing total $TF_{snow,l}$. Our study supports the potential for wind increasing TF with *u* being significant in the $TF_{snow,d}$ MLR, however it was not significant in the lysimeter-based MLR.

In addition to both precipitation type and P_G driving TF, increases in VPD also alters TF dynamics. First, VPD was correlated with decreasing TF across event type, increasing S (Figure 2.4c), and was retained in the stepwise MLR. VPD is driven in part by T_a, therefore increases in T_a are likely to produce increases in VPD. With the $\bar{E}/\bar{R}$ vs. T_a regression slope of 0.01 mm hr^{-1} °C^{-1}, a 5 °C warming would increase $\bar{E}/\bar{R}$ by 0.05 mm, increasing I_{rain} an additional 1 mm for a a 20 hour storm.

While TF_{rain} and $TF_{snow,l}$ differed, differences in $TF_{snow,d}$ and interspace-canopy snowpack dynamics were apparent. Differences in D_S between the tree and interspace persisted throughout the winter (Figure 2.6). $TF_{snow,d}$ increased for events that were a) windier and b) had greater $D_{tree\text{-}inter}$. We estimated an additional 15.2 cm and 13.9 cm each year was deposited under the canopy due to $D_{tree\text{-}inter}$. This produces a counter-intuitive snowpack dynamic where there can be less snow under the tree but a greater amount of snow can be deposited under the tree than the interspace (Figure 2.3). Similar to other tree and shrub studies in cold environments, tree wells often form under trees due to canopy interception and emission of longwave radiation from tree boles (Robertson, 1947; Hutchison, 1965; Sturm *et al.*, 2001; Pomeroy *et al.*, 2006). Other shrub studies have also observed increased under-canopy snow deposition within these wells around shrubs (Hutchison, 1965; Essery and Pomeroy, 2004; Pomeroy *et al.*, 2006; Tedesche, 2010). Our study is a first step in revealing that there are similar dynamics in juniper. These increases in snow deposition below a tree could potentially provide a soil moisture subsidy that increases localized soil moisture, similar to snow drifting on leeward sides of topographic features (Seyfried *et al.*, 2009). It is also likely that snow energetics plays a primary role in below canopy snow melt and subsequent tree well formation. Future studies could further elucidate the role of snow energetics in snowpack dynamics in juniper and how they differ between juniper and sagebrush.

I_{rain} showed seasonal dynamics with peak I_{rain} in the middle of the summer. There are several possible reasons for this seasonal pattern. First, it is likely due in part to the P_G. Larger events occurred in the late spring and early fall, and P_G is inversely correlated with I_{rain} (Figure 2.1). Second, VPD increases S and higher VPD peaks in the middle of the summer. Third, juniper bud elongation occurs in early spring and their needles die in the fall (Miller *et al.*, 2005). However, the dead needles often do not fall immediately, but can stay attached to the tree for several years (Miller, *personal communication*). Link *et al.* (2004) found that in Douglas fir, there was a clear seasonal component of S linked with bud elongation and needle drop. Future studies could further clarify if this relationship holds in juniper, or if VPD and P_G exerts a stronger control on interception than juniper seasonal needle changes.

Simulations revealed that projected future increases in T_a primarily drive shifts in the timing rather than amount of hydrological fluxes. First, both snow disappearance day and

SWI 50% day were 41 to 56 days earlier between the current and future simulations, with little change in the amount of SWI (Table 2.2). Similarly, ES loss shifted to earlier in the season between current and future climate simulations (Figure 2.8d-f). These shifts to more winter-dominated SWI are congruent a greater portion of winter precipitation occurring as rain in our simulations (Figure 2.2) and Klos *et al.* (2014). The similarity in the snow disappearance and SWI shifts are confirmed by other studies where snow disappearance corresponds to both peak soil moisture and peak runoff (Molotch *et al.*, 2009; Seyfried *et al.*, 2009; Smith *et al.*, 2011). Furthermore, our findings confirm other large scale studies in the western U.S. for both the last century (Regonda *et al.*, 2005) and future simulations (Elsner *et al.*, 2010), which show that with warming T_a, total annual discharge was not greatly reduced but peak streamflow shifting to earlier in the winter.

Contrary to shifts in climate, shifts in vegetation primarily drive shifts in the quantity of hydrological fluxes. Simulated SWI for both the current and future simulations was on average 137 mm greater in both sagebrush species than in juniper (Table 2.2). Only one previous study we are aware of compares open area and forested SWI, and although in a mature conifer forests in humid western Washington state, it shows the same general increase in open area compared to under-canopy SWI (Harr *et al.*, 1989). Finally, ES loss is on average 92 mm higher in juniper than in both sagebrush species (Table 2.2). These similar shifts in SWI and ES loss are linked via interception and throughfall processes. Juniper LAI of 3.0 is greater than LAI in mountain and low sagebrush of 0.9 and 0.3 respectively. This higher LAI corresponds directly to higher S in the model, increasing the amount of intercepted rain and snow lost to the atmosphere and reducing the amount of throughfall reaching the soil. This equates to greater ES loss (Figure 2.8d) and reduced SWI (Figure 2.8a).

One exception to hydrological fluxes shifting in timing across the future and current simulations and in amount across the different vegetation simulations is peak SWE, which shifted both with changes in climate and vegetation. Across the three vegetation scenarios, the average peak SWE from the current to future simulations decreased on average 57.8%. This finding is confirmed by many empirical studies (Mote *et al.*, 2005; Regonda *et al.*, 2005; Kapnick and Hall, 2012) and future simulations (Elsner *et al*., 2010). Peak SWE was also much lower in juniper than in the two sagebrush simulations for the future and current simulations (Figure 2.7). This reduced peak SWE in juniper is due to increased interception and elevated below canopy radiation that increases snowmelt and thereby losses of water from the snowpack. This greater loss of SWE under the canopy is confirmed with the lysimeter data, which although not continuous throughout both winters, when they were operational in the winter during melt events often had almost double SWI in the canopy than the interspace. Other studies comparing tree and interspace or small shrub-dominated open areas, although in large conifer systems, similarly show lower peak SWE under the tree canopy (Golding and Swanson, 1978; Troendle and King, 1985; Ellis *et al.*, 2013; Lundquist *et al.*, 2013).

Above-ground vegetation and climate change studies often focus on changes in peak SWE (Mote *et al.*, 2005; Regonda *et al.*, 2005; Kumar *et al.*, 2012; Lundquist *et al.*, 2013). While these are good first initial steps, these studies did not assess SWI, which does not necessarily correlate directly to SWE since snow deposition (Figure 2.3) and sublimation rates (Reba *et al.*, 2012) can vary between open and under canopy areas. Our study revealed that although peak SWE timing corresponds to timing of SWI (Figure 2.9b), it does not predict total SWI (Figure 2.9a). SWI is a key link between above-ground processes and streamflow generation (Seyfried *et al.*, 2009), and as climate shifts from snow to rain-dominated precipitation and winter SWI increases, it will be important to consider not only change in SWE, but changes in the timing and amount of SWI.

Finally, our study does not definitively reveal a clear mechanism for why greater water yield has been observed during snow-dominated compared to rain-dominated years (Berghuijs *et al.*, 2014). $TF_{snow,I}$ was greater than TF_{rain} and both were significantly different in the MLR. Wind also increased $TF_{snow,I}$. (Figure 2.3), confounding an inference of total TF being greater in snow. Furthermore, in comparing the future and current simulations, reductions in ES loss only changed slightly between current and future simulations (Table 2.2). In contrast, differences in vegetation cover had a much greater impact on ES loss (Table 2.2). Further studies could elucidate the mechanism for observed differences in water yield between rain and snow-dominated years.

5. Conclusions

There are clear differences in above-ground hydrological fluxes between juniper and sagebrush species. Average $TF_{snow,I}$ was 79.4% in juniper compared to TF_{rain} of 54.8%. TF and I_{rain} were both driven by P_G, with increasing P_G increasing TF and decreasing I_{rain}. T_a and VPD also altered above-ground processes, increasing VPD decreased TF and increased I_{rain}, and increasing T_a increased $\bar{E}/\bar{R}$. This has implications for how warming T_a could alter interception dynamics. Snowpack accumulation and ablation regimes were significantly different in the interspace dominated by low sagebrush than under juniper, with snow persisting 13 days longer in the interspace than under the trees and snow being more transient under the tree. It is therefore likely that increases in juniper cover will decrease late season snowpack that produces the delayed release of snowmelt that is key to support regional streams. Also, shifts from juniper to sagebrush decreased SWI by 137 mm, which is 24% of the total water budget.

Dramatic shifts in climate have occurred in many semi-arid systems and will likely continue to occur into the future. Our simulations revealed that warming over the next 40 years could cause the snowpack to disappear 51 days earlier and SWI, a major determinant of peak streamflow, to occur 45 days earlier. Land managers choices for future juniper management activities will therefore directly impact the hydrological fluxes in these semi-arid systems.

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Table 2.1. SHAW above-ground parameter changes across the three vegetation simulations: juniper, mountain big sagebrush, and low sagebrush.

Vegetation	**LAI**	**Height (m)**	**Vegetation albedo**
Juniper	3.0	2.5	0.10
Mtn Sagebrush	0.9	0.77	0.25
Low Sagebrush	0.3	0.18	0.25

Table 2.2. Surface Water Input (SWI) amount and timing for current and future climates for the two eight-year periods. SWI 50% is WY day when 50% of Oct-June SWI occurred. Numbers in parentheses denote standard deviation. Snow disappearance (disap.) day is calculated based on the first day without snow after February 1st. Evaporation-Sublimation (ES) loss is the average annual loss.

	Snow disap. day - current	**Snow disap. day - future**	**SWI-current (mm)**	**SWI-future (mm)**	**SWI 50% - current (days)**	**SWI 50% - future (days)**	**ES loss - current (mm)**	**ES loss -future (mm)**
Juniper	103 (21)	47 (18)	390 (109)	377 (103)	178 (18)	132 (17)	213 (16)	229 (19)
Mtn. sage	104 (20)	52 (21)	511 (121)	492 (112)	183 (18)	142 (14)	114 (16)	138 (10)
Low sage	105 (19)	59 (18)	545 (118)	535 (116)	185 (18)	137 (16)	123 (22)	142 (23)

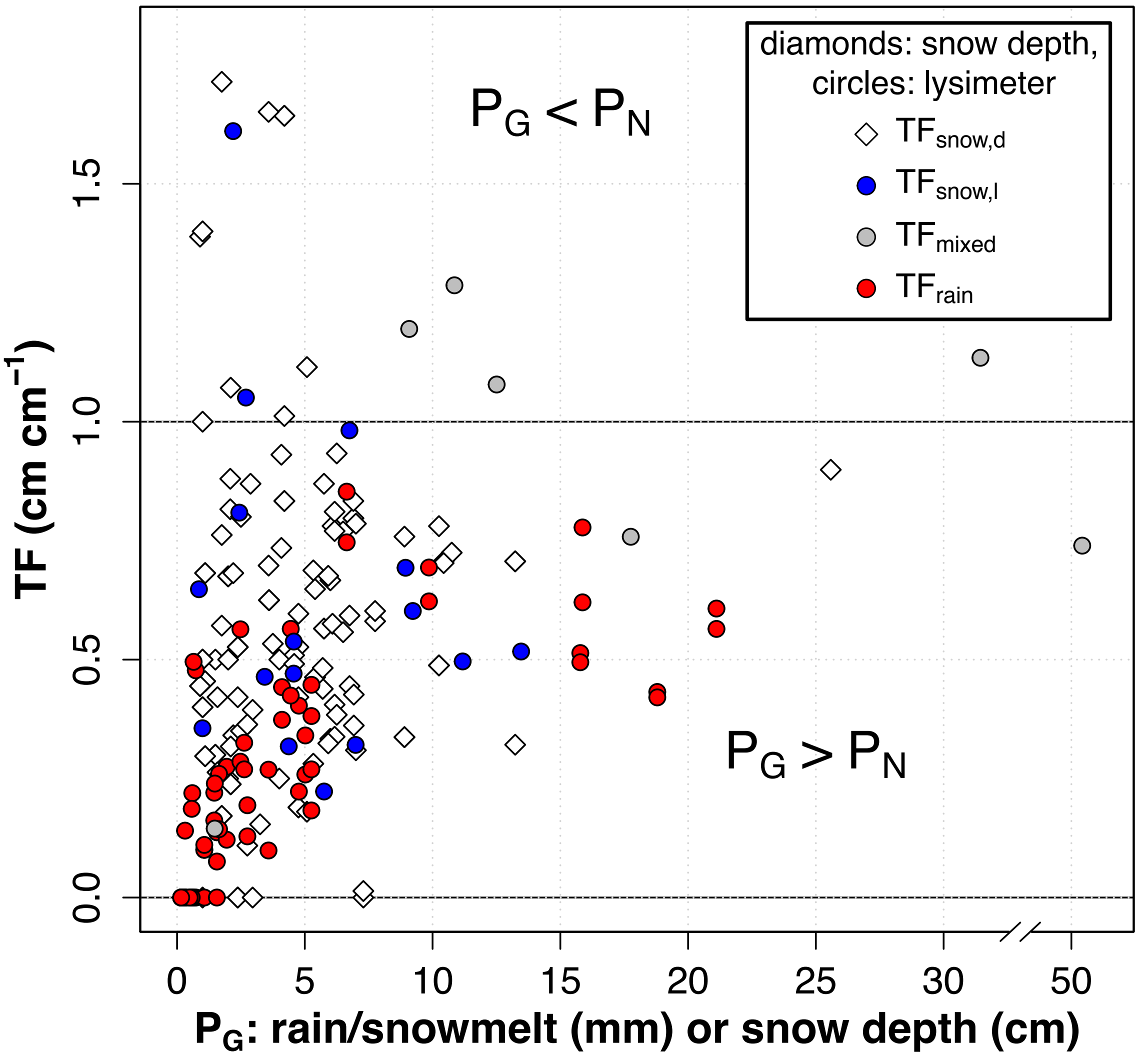

Figure 2.1. Lysimeter-derived throughfall for snow ($TF_{snow,l}$), mixed (TF_{mixed}), and rain (TF_{rain}), and snow depth derived throughfall ($TF_{snow,d}$), relative to total storm lysimeter output (rain/snowmelt) or snow depth (P_G).

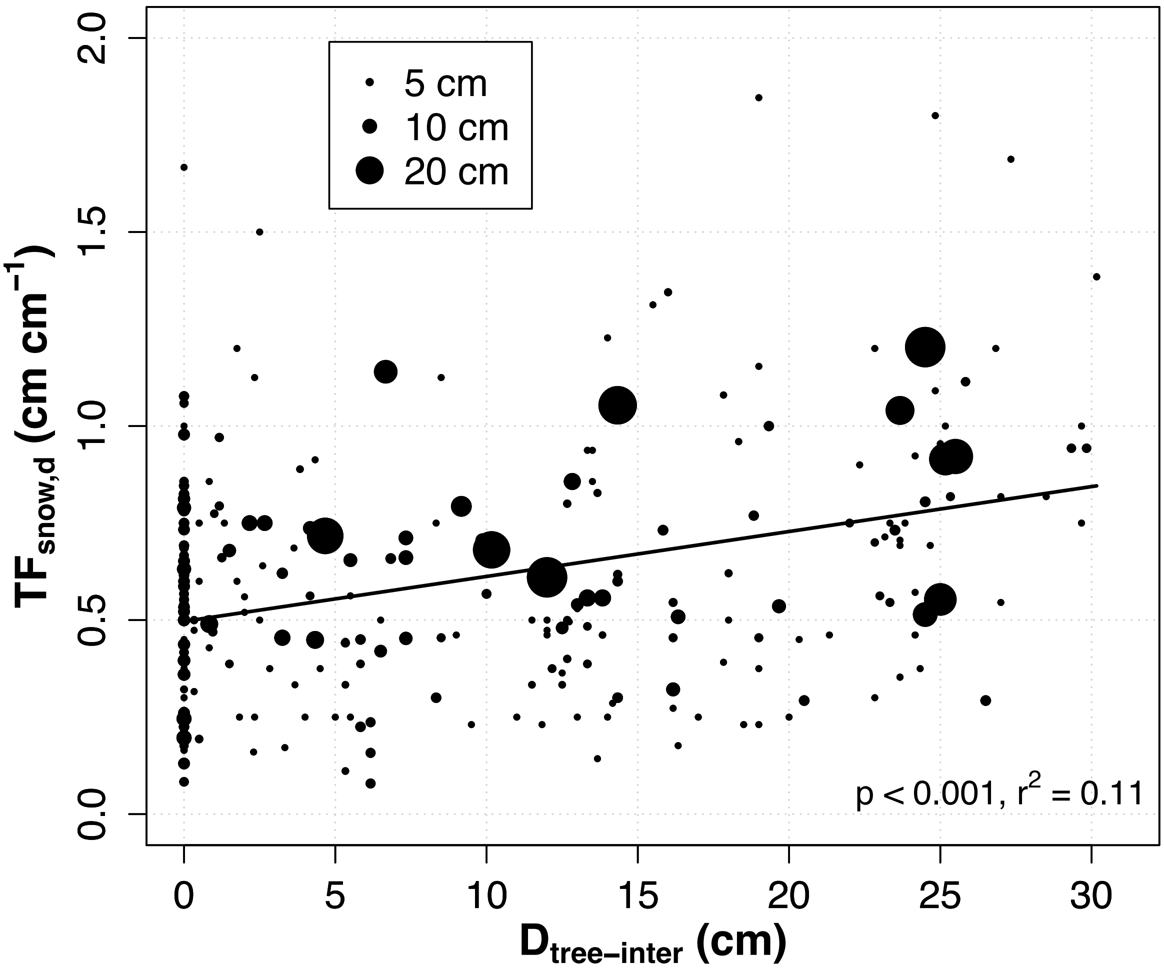

Figure 2.2. Snow depth throughfall ($TF_{snow,d}$) across snow events with a range of pre-event differences in snow depth between the interspace and under the tree ($D_{tree-inter}$), with increasing values representing greater depth of snow in the interspace than under the tree. Circle size denotes interspace storm snow depth.

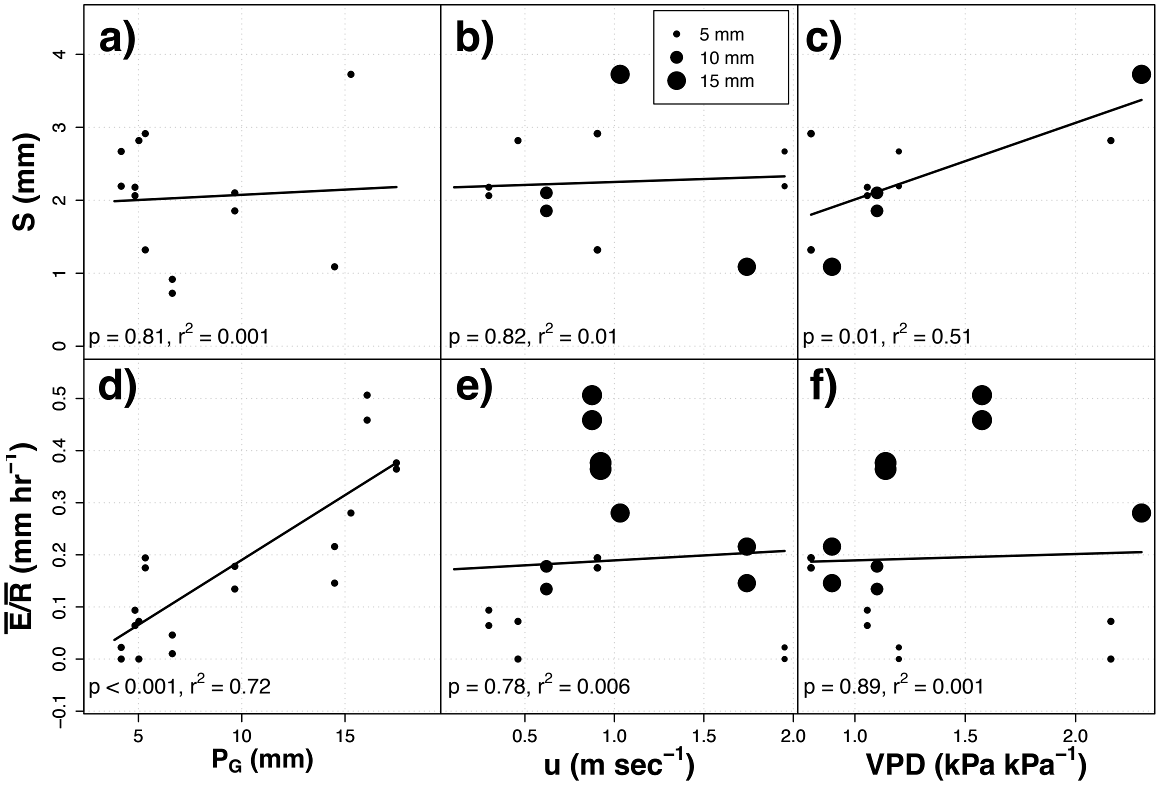

Figure 2.3. The (a,b,c) Canopy storage (S) and (d,e,f) evaporation rate ($\overline{E}/\overline{R}$) estimated with the Gash analytical model for rain events. Canopy storage and $\overline{E}/\overline{R}$ are plotted against (a,d) event size (P_G), (b,e) wind speed (*u*), and (c,f) vapor pressure deficit (VPD). Circle size in *u* and VPD plots correlate to event size.

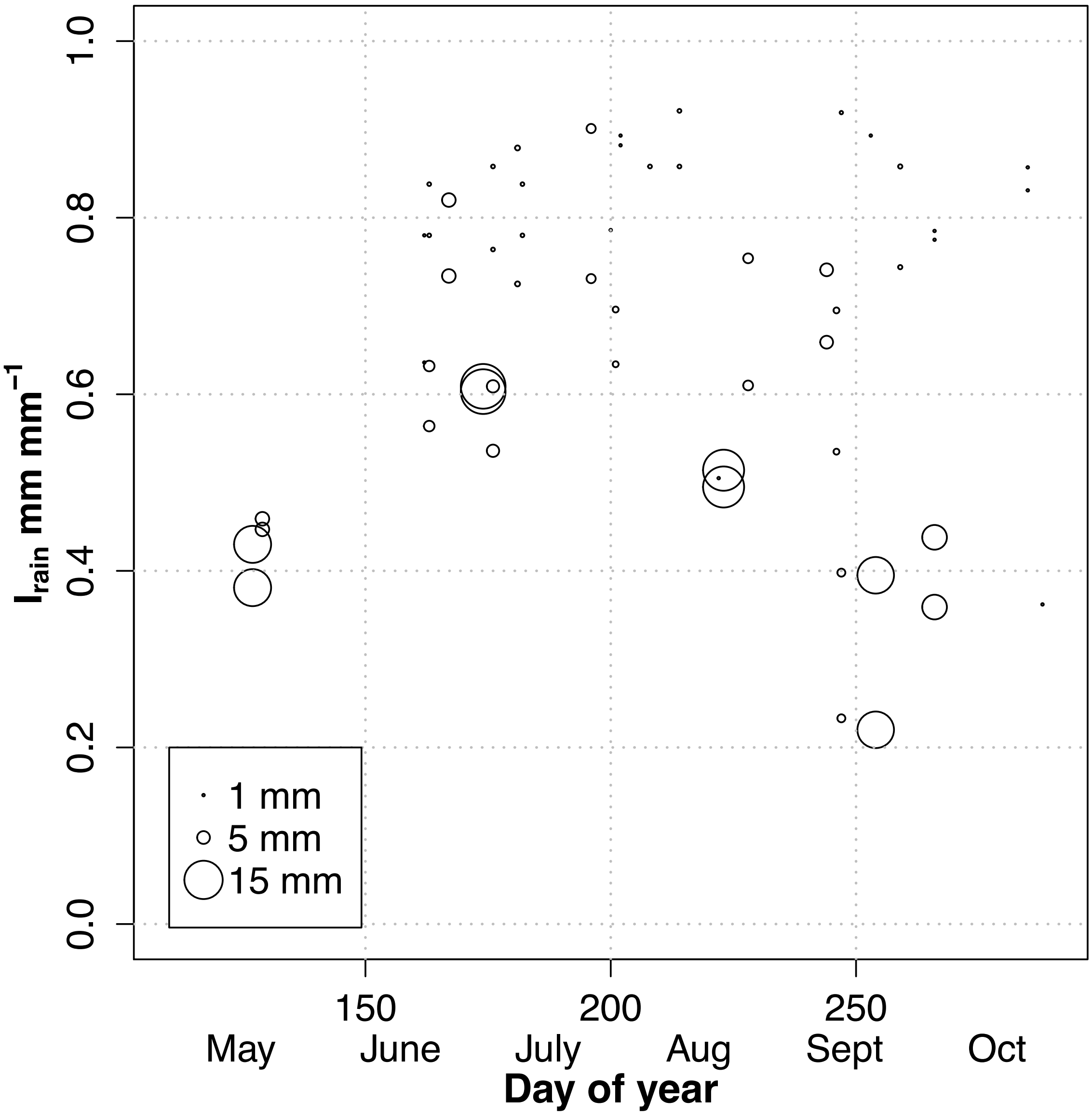

Figure 2.4. Rain interception loss (I_{rain}) from the beginning to the end of the growing season. Circle size denotes event size.

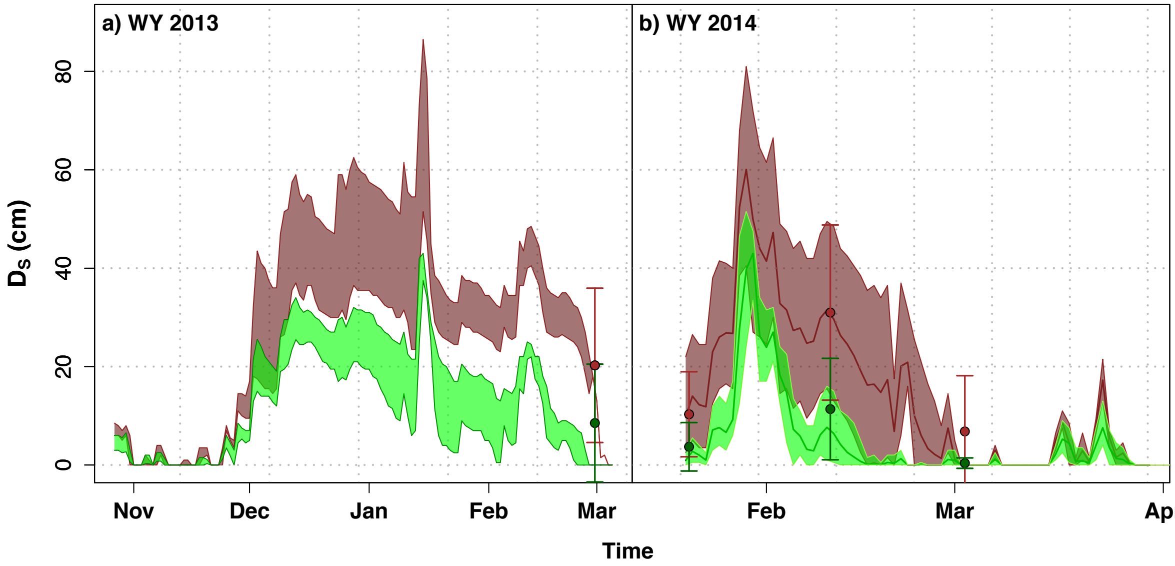

Figure 2.5. Average snow depth in interspace (brown) and under tree (green) for A) WY 2013 and B) WY 2014. Bold line is the average and outside border of the shaded region is the maximum and minimum snow depth. Circles are average snow survey snow depth under trees and in the interspace and error bars are one standard deviation. No average was plotted for WY 2013 due to a camera failure and only two stakes for both the interspace and canopy.

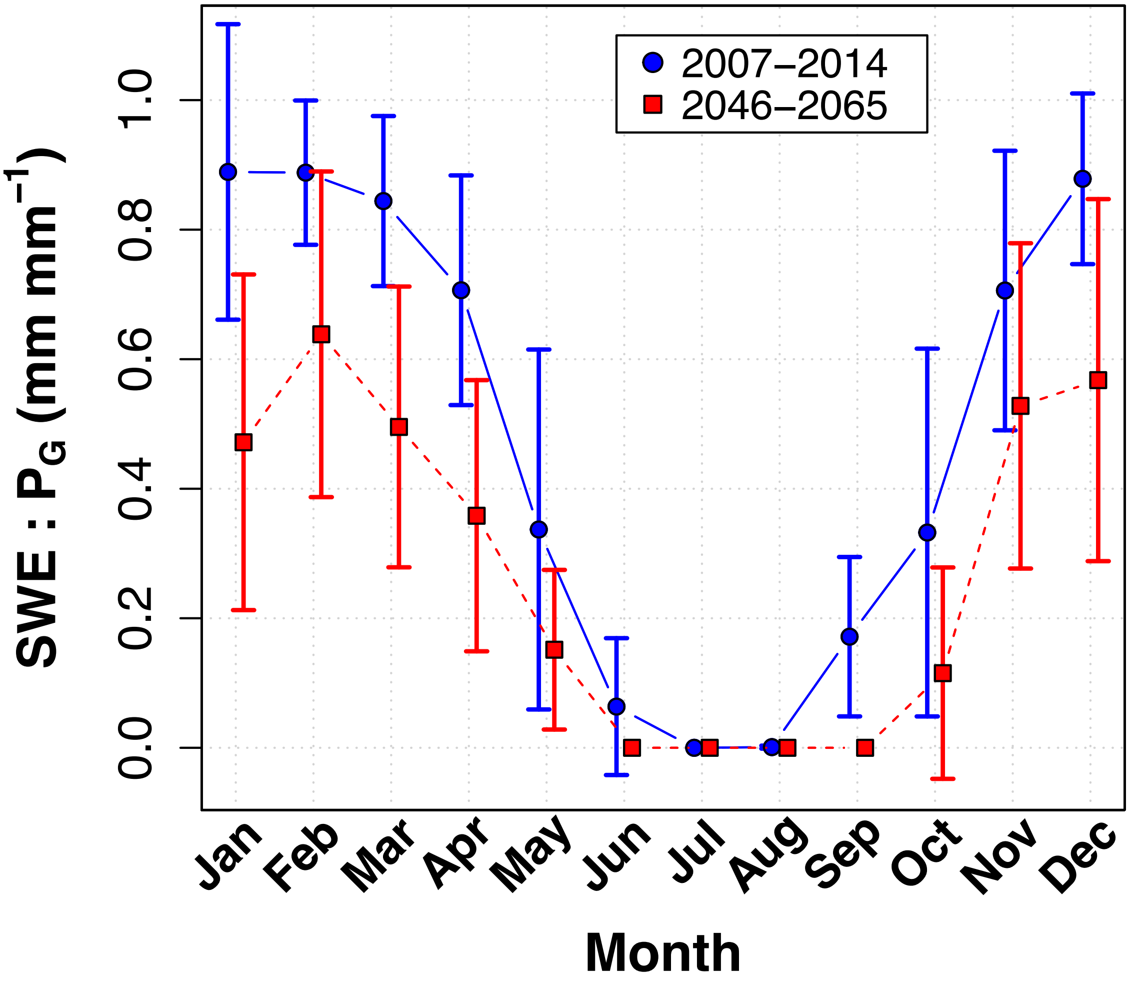

Figure 2.6. Ratio of total monthly precipitation falling as snow (SWE) to total monthly precipitation (P_G) over WY 2007-2014 (blue circles) and under mid-21st century warming (red squares). Points are averages for the eight-year period, error bars denote one standard deviation.

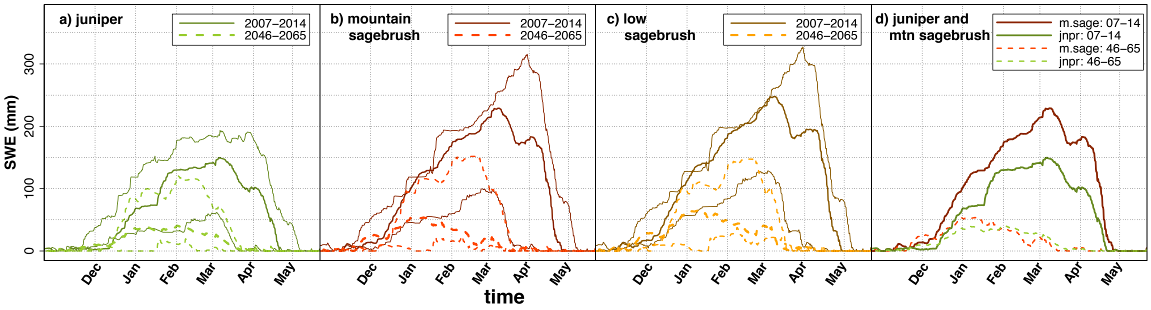

Figure 2.7. Average SWE for WY 2007-2014 (solid) and an 8 year period based on the projected climate in 2045-2064 (dotted line). Plots are for A) juniper, B) mountain big sagebrush, C) low sagebrush where bold line represents SWE through time averaged over the 4 years middle peak SWE years, and lines above (below) represent the two years with the highest (lowest) peak SWE accumulation. Panel D) compares average juniper (bold) and mountain big sagebrush (not bold) SWE for current climate (solid) and 8 year period based on 2045-2064 future climate (dotted).

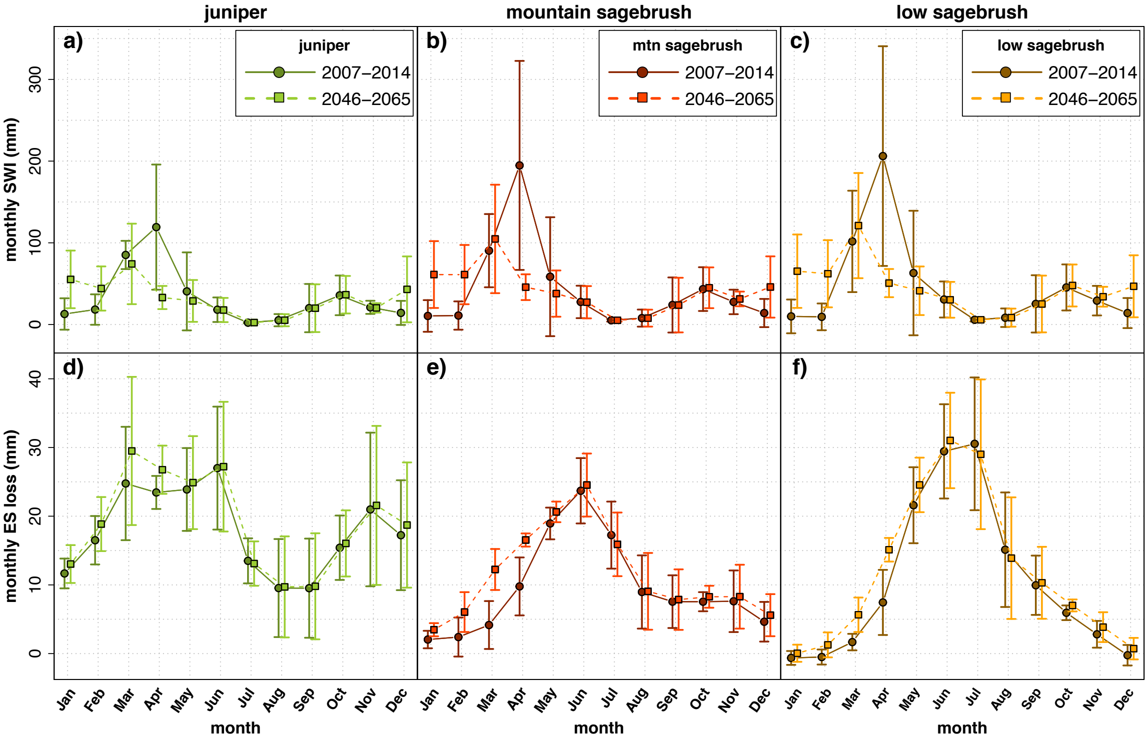

Figure 2.8. Plots of (a,b,c) monthly surface water input (SWI) and (d,e,f) monthly canopy and soil surface evaporation and sublimation (ES) loss in juniper, mountain big sagebrush, and low sagebrush over WY 2007-2014 (current climate) and WY 2046-2065 (future climate). Darker (lighter) colors, circles (squares), and solid (dotted) lines signify current (future) climate. Points are averages for the given period, error bars denote one standard deviation.

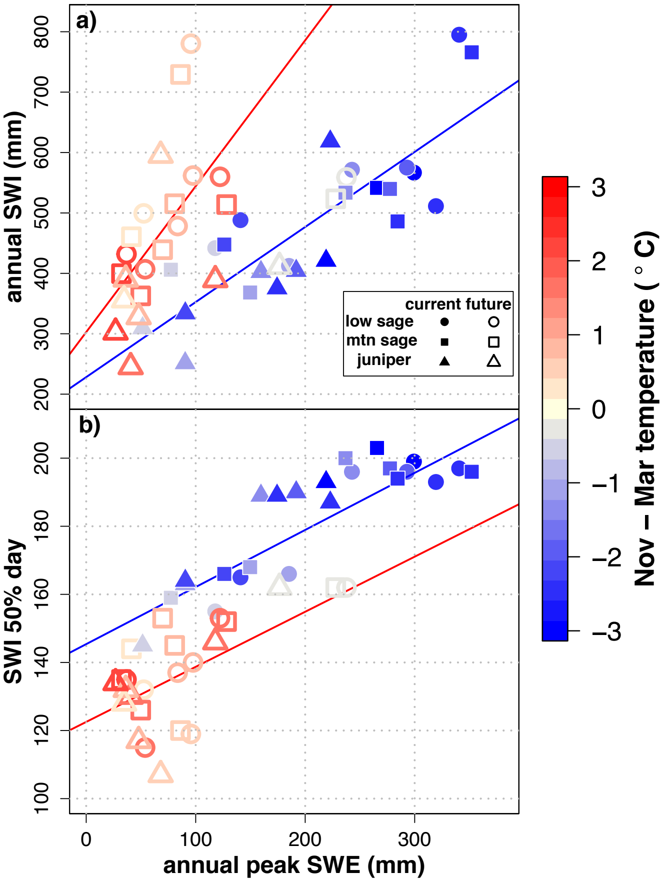

Figure 2.9. The (a) total annual surface water input (SWI) and (b) day of year of 50% SWI (SWI 50% day) vs. annual peak snow water equivalent (SWE). Color denotes the spectrum of November – March temperature with white being zero, colors above zero as red and below zero as blue. Shapes denote vegetation with circles denoting low sagebrush, squares denoting mountain big sagebrush, and triangles denoting juniper. Solid shapes are WY 2007-2014 (current climate) and hollow shapes are under mid-21st century warming (future climate). Blue (red) regression lines are for years with November – March temperatures below (above) 0° C.

Chapter 3 - Spatiotemporal soil and saprolite moisture dynamics across a semi-arid woody plant gradient

Authors: Ryan J. Niemeyer, Robert Heinse, Timothy E. Link, Mark S. Seyfried, Zion P. Klos

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Abstract

Woody plant cover dynamics can alter the timing and amount of moisture accessed by plants in the soil and saprolite. This article links changes in soil moisture dynamics through the growing season across shallow (15 cm) and deep (0.6 – 12 m) subsurface soil and saprolite layers and horizontally across the interspace and canopy. Horizontal interspace and canopy comparison help elucidate how woody plants affect subsurface moisture dynamics. To assess how spatiotemporal subsurface moisture dynamics over two water years in a snow-dominated western juniper stand, we measured continuous soil moisture at 15 and 60 cm and conducted periodic electromagnetic induction surveys and electrical resistivity tomography aimed at moisture changes up to 10 m in depth. Timing of soil moisture dry down at 15 cm was very similar between the canopy and interspace. Conversely, dry down at 60 cm occurred 22 days earlier in the interspace than in the canopy. Analyzing changes in soil moisture after discrete rain events revealed that storm size was the principal driver of increases in soil moisture. As expected, the interspaces showed greater increases in soil moisture at 15 cm, however, when rain events were large enough to produced increase in soil moisture at 60 cm, greater increases typically occurred below the canopy. Soil water holding capacity was a primary driver of areas that were associated with the greatest change in distributed electrical conductivity – an indicator of changes in soil moisture - across the growing season. Vegetation was also correlated with a greater seasonal change in electrical conductivity. The seasonal change in resistivity - measured with the electrical resistivity tomography surveys - suggested soil moisture extraction well into the saprolite, as deep as 10 m below the surface. This change in subsurface moisture primary occurred below medium and large juniper trees. Information from this study can help inform our understanding of the hydrologic impacts of semi-arid land cover and inform future hydrologic modeling efforts.

Key words: soil moisture, saprolite, preferential flow, electromagnetic induction, electrical resistivity tomography, western juniper, woodland encroachment

1. Introduction

The hydrologic impacts of woody plant encroachment in semi-arid environments such as with western juniper (*Juniperus occidentalis*,) expansion into sagebrush ecosystems are poorly understood. Across the western U.S., woodlands have encroached into sagebrush and grassland ecosystems principally due to grazing and fire exclusion (Tausch et al., 1981; Miller et al., 2005; Romme et al., 2009). This has been followed by restoration efforts to remove woody plants (e.g. Bureau of Land Management, 2015). Increases in woody plant cover typically decrease total runoff (Bosch and Hewlett, 1982; Huang et al., 2006; Zégre et al., 2010; Zou et al., 2014; Qiao et al., 2015). However, documented hydrologic responses to woody plant removals have not always been predictable. For example, in some cases reductions in woody plant cover were found to have a negligible effect on streamflow (Clary et al., 1974; Baker Jr, 1984; Baker Jr and Ffolliott, 2000), to increase streamflow in the case of tree die-off (Guardiola-Claramonte et al., 2011), or conversely in the case of woodland vegetation expansion to also increase streamflow

(Wilcox and Huang, 2010). This information leads some to conclude that woody plant removal in semi-arid regions may have negligible impact on streamflow (Hibbert, 1983; Kuhn et al., 2007; Ffolliott and Gottfried, 2012). These uncertainties about woody plant impact on streamflow have motivated this study that aims to improve our process-based understanding of the subsurface hydrological processes in these systems.

The impact of changes in woody plant cover on subsurface water processes is of particular importance in water-limited semi-arid systems. In these systems, both hydrological dynamics in the near-surface soil and in the deep soil/saprolite layers are important. Soil water dynamics in the near-surface control the phenology and plant productivity in semi-arid environments (Loik et al., 2004; Schwinning and Sala, 2004; West et al., 2007; Robinson et al., 2008; Breshears et al., 2009; Penna et al., 2013). Conversely, soil water dynamics in the deep soil and saprolite zones control streamflow generation and groundwater recharge in many systems (Carey et al., 2010; Chauvin et al., 2011; Gabrielli et al., 2012), and provide a moisture pool for some deep rooted semi-arid plants (Breshears et al., 2009) including potential hydraulic lift to draw up deep moisture to shallow soil (Dawson, 1996; Armas et al., 2010). In the semi-arid western U.S. where soil moisture is a limiting factor in primary productivity, understanding the duration of plant available water is particularly important. An earlier reduction in plant available water can increase vegetation vulnerability to drought (Grieu et al., 1988; Littell et al., 2008). Earlier reductions in plant available water could be realized in future summers which are projected to experience less precipitation and increased temperatures (Abatzoglou and Kolden, 2011).

Elucidating how semi-arid woody plants alter subsurface water dynamics is often done by comparing subsurface moisture dynamics at the patch scale. Semi-arid conifer species are often organized into “patches” with the areas covered by trees being the “patches” embedded in an interspace “matrix” that is dominated by shrubs, grasses, and forbes (Miller et al., 2005). The interspace and canopy are often characterized by differences in nutrient dynamics (Padien and Lajtha, 1992), radiation regime (Breshears et al., 1997b; Martens et al., 2000), throughfall (Eddleman, 1986; Eddleman and Miller, 1991; Taucer, 2006; Owens et al., 2006), and snow deposition (Niemeyer et al., in preparation). Theoretical work on interactions between tree and interspace vegetation posits that grasses use shallower soil moisture pools earlier in the growing season, and woody plants using deeper soil moisture pools later in the growing season (Walker and Noy-Meir, 1982; Peláez et al., 1994; Ryel et al., 2008). Empirical work with periodic or continuous soil moisture measurements have shown that indeed woody plants utilize moisture at shallow and deeper layers while grasses and forbs use shallower moisture (Gifford and Shaw, 1973; Young et al., 1984; Sala et al., 1989; Peláez et al., 1994; Breshears et al., 1997a; Seyfried et al., 2005; Breshears et al., 2009). Previous studies have observed both the earlier depletion of soil water depletion in the grass-dominated interspace compared to below juniper canopies (Young et al., 1984) and no difference in soil moisture depletion timing between the canopy and interspace (Breshears et al., 1997a). To adequately understand differences in drought vulnerability between plant species in the canopy and interspace, we must adequately characterize spatiotemporal soil moisture dynamics.

Understanding how shifts in woody plant cover change soil moisture in both space and time requires the triangulation of multiple methods. Assessing differences in soil moisture regimes across canopy/interspace patches or woodland/open plots are often limited to a small number of point-scale soil moisture measurements which are often focused on shallow (< 30 cm) soils (Gifford and Shaw, 1973; Young et al., 1984; Breshears et al., 1997a; Seyfried et al., 2005; Robinson et al., 2010; Roundy et al., 2014). This may adequately capture the changes in soil moisture through time in shallow soil but fails to ascertain how these shifts play out across a canopy-interspace continuum or how these changes play out in deeper layers in the subsurface (Robinson et al., 2008). Deep moisture in the soil, saprolite, and bedrock is inherently inaccessible for investigation using direct-contact sensors and hence is difficult to quantify. Emerging geophysical methods such as electrical resistivity tomography (ERT) and electromagnetic induction (EMI) enable the collection of spatially contiguous datasets both horizontally and vertically (Robinson et al., 2008).

Here we present a study on the differences in subsurface moisture dynamics in space and time between the canopy and interspace. Our approach was to capture both high-temporal resolution soil moisture data, combined with periodic spatially continuous geophysical data. This is the first study in semi-arid woody plant cover to combine both high temporal resolution and broad spatial data to ascertain how canopy and interspace soil moisture dynamics differ. The specific research questions were: a) How does soil moisture use differ between a canopy and interspace? b) How does the depth of soil moisture depletion differ between canopy and interspace? and c) how does the temporal dynamics differ between a canopy and interspace? This study highlights how shifts in woody plant cover could potentially alter the timing and quantity of subsurface hydrologic processes at the patch scale that ultimately drive changes in streamflow at the watershed scale.

2. Methods

To assess how the presence of juniper alters soil moisture in space and time, we used a combination of continuous soil moisture and temperature measurements at shallow (< 1 m) soil depths and periodic geophysical measurements starting at peak soil wetness in early spring, continuing throughout the growing season, and ending at the driest point in the water year before the onset of fall precipitation.

2.1 Site Description

This work was carried out at the Reynolds Creek Experimental Watershed and Critical Zone Observatory (RCZO) in the Owyhee Mountains, approximately 80 km southwest of Boise, ID, USA. RCZO is a semi-arid watershed with moderate steepness and snow cover persisting 4 to 6 months of the year. The specific site for this study (Fig. 3.1, 43.084° N, -116.743° W) was located at 1940 m above m.s.l. The slope and aspect of the site are 26% and 246° respectively. Average annual precipitation at the nearest climate station, located 730 m to the east and 50 m higher in elevation from the study site, was 554 mm. PRISM adjustment (Daly et al., 1994) of monthly precipitation from the climate station from 1962 to 2013 estimated the average annual precipitation at the study site at 490 mm, and annual precipitation for WY2013/14 was 577 mm and 532 mm, respectively. Snow depth, air temperature, relative humidity, and wind speed were measured with a meteorological station at the site with standard methods (see Hanson, 2001 for descriptions). Wind direction at the site is typically from the south by southwest and produces snow drifts on the north or northeast sides of topographic features (Winstral, Marks & Gurney 2009) or vegetation (Niemeyer et al., in preparation). Plant species present include a mix of western juniper (*Juniperus occidentalis*), low sagebrush (*Artemisia arbuscula*), mountain big sagebrush (*Artemisia tridentata*) as well as several grass and forb species. Our sample plot spanned approximately 1.2 ha and covered low and high density juniper areas to the north and south respectively (Fig. 3.1). The high (low) density area was defined by greater (lower) juniper stem density and lower (greater) sagebrush stem density.

2.2 Continuous Soil Moisture Measurements

Continuous soil moisture and temperature sensors were installed in the vicinity of three trees in August of 2012, and one additional tree in June of 2013. The two trees in the high density juniper area were 4.0 m and 3.7 m tall, while the two trees in the low density juniper area were 2.6 m and 3.8 m tall (Fig. 3.1). Soil moisture at each tree was monitored by six sensors. Four sensors were installed at 15 cm both under and outside the canopy on the north side and both under and outside the canopy on the west or east side. Two probes were installed at 60 cm: one in the interspace and one under the canopy, both on the east or west side of the trunk. East and west side interspace sensors locations were chosen based on the least number of junipers in near proximity. The “under canopy” probes were installed at half the distance between the trunk and canopy edge and the interspace probes were located 1 m out from the canopy edge. All east or west probes were 5TM (15 cm probes) or 5TE (60 cm probes) (Decagon Devices, Pullman, WA). All north probes were frequency domain reflectometery (FDR) probes (Stevens Water Monitoring Systems, Portland, OR).

Prior to data analysis, we excluded soil moisture data when the soil temperature dropped below 0° C because probes are only sensitive to liquid water, although it only occurred at 15 cm probes 3.1% of the time since in the winter snowpack insulated the soil and prevented soil freezing. In addition, the collected time-series of soil moisture data had several gaps due to either a) battery failure, b) sensors failing and being replaced. To analyze soil moisture data, we compared the change in soil moisture between the interspace and canopy between storms and across the entire growing season. This continuous data was collected every 30 minutes, but averaged on an hourly basis before analysis. After the FDR probes were installed, the two 15 cm values for the same tree and location (e.g. tree 3 interspace) were averaged during the same time step to analyze differences between location and trees. We estimated the equivalent depth of water stored in the top 90 cm of the soil (S_{90}) on an hourly basis in the interspace and under the canopy as a vertical average using:

$$S_{90} = \theta_{15} \text{ x } 0.3 \text{ m} + \theta_{60} \text{ x } (0.9-0.3) \text{ m} \tag{1}$$

where θ_{15} and θ_{60} is hourly soil moisture (cm^3 cm^{-3}), at 15 cm and 60 cm depths respectively.

Changes in θ_{15}, θ_{60}, and S_{90} were compared to snow depth and precipitation (Fig. 3.2). Snow depth was based on continuous measurements at the climate station and hourly time-lapse photos of snow stakes under and outside the canopy at two representative trees (see Niemeyer et al., in revision for a more detailed description). All hourly snow depth measurements were averaged within either canopy or interspaces. There was a 54 day period from December 6th, 2013 to January 29th, 2014 when both time-lapse camera batteries failed. The gap in the data was filled based on with the snow depth sensor at the site climate station for the interspace, and with simulated data for the canopy. Snow depth simulations were conducted with the Simultaneous Heat and Water (SHAW) model (Flerchinger and Saxton, 1989) (see Niemeyer et al. in preparation for more details).

To analyze the influence of stand location (interspace vs. canopy), weather, and antecedent soil moisture conditions, we calculated the change in soil moisture between before and after a storm. We calculated the change in θ_{15} ($\Delta\theta_{15}$), θ_{60} ($\Delta\theta_{60}$), and S_{90} (ΔS_{90}), after a rain storm that occurred with no snow on the ground. We then plotted these changes in soil moisture across total precipitation (P_G). Because the data displayed heteroscedasticity (not shown) we used the non-parametric regression tree classification (Breiman et al., 1984) based on the following equation:

$$\Delta\theta = P_G + P_{int} + VPD + \theta_{ant} + tree + phase + location \qquad (2)$$

where $\Delta\theta$ is $\Delta\theta_{15}$, $\Delta\theta_{60}$ or ΔS_{90}, P_G is the storm rain depth, P_{int} is the mean rainfall intensity (mm hr^{-1}), VPD is the average storm vapor pressure deficit measured at the climate station (kPa), θ_{ant} is the θ_{15} and θ_{60} S_{90} before the storm began, tree is which of the four instrumented trees the probe(s) were located, phase is the juniper classification (low or high juniper density), and location is if the sensor was in the interspace or under the tree. The variables “tree”, “phase” and “location” were factor variables in the model. To explicitly compare differences in $\Delta\theta$ between the interspace and canopy, we conducted a t-test between interspace and canopy $\Delta\theta_{15}$, $\Delta\theta_{60}$ or ΔS_{90} for the upper P_G quartile, since small P_G

events often show no change in θ and large P_G events typically comprise the majority of the total rainfall.

Rain storms were separated by at least four hours to a) reach a static soil moisture equilibrium and b) not include decreases in the final θ due to evaporation or transpiration. Since most storms were small (< 1 mm), for the top quartile of rain storms, we analyzed the influence of the rain storms on soil moisture by conducting the non-parametric Wilcoxon rank sum test (Wilcoxon and Wilcox, 1964) between paired interspace and canopy $\Delta\theta_{15}$, $\Delta\theta_{60}$ and ΔS_{90} at the same tree.

To assess how the seasonal timing of soil moisture depletion differs between the canopy and interspace, we calculated the day at which θ_{15}, θ_{60} and S_{90} declined to half of the seasonal range ($day_{50\%}$). We estimated $day_{50\%}$as follows:

$$day_{50\%} = [(\max(\theta) - \min(\theta)) \times 0.5] + \min(\theta) \qquad (3)$$

where max(θ) (min(θ)) is the maximum (minimum) θ_{15}, θ_{60} and S_{90} after the snow melted and before the snow first occurred in the fall. Typically it is assumed that halfway between θ at field capacity and θ at plant wilting point is when transpiration begins to decline (Hillel, 1980). Although the maximum S_{90} is likely at θ greater than field capacity, $day_{50\%}$ is still an adequate metric of the timing of soil moisture dry down. Due to the small sample size, we used a Wilcox sum rank test to test for difference between the canopy and interspace $day_{50\%}$.

2.3 Distributed Periodic Measurements

2.3.1 Electromagnetic Induction

To estimate soil moisture across the plot encompassing the low and high density juniper areas (Fig. 3.2), we used electromagnetic induction (EMI). EMI has been used to estimate soil-water properties (Kachanoski and Jong, 1988; Sheets and Hendrickx, 1995; Sherlock and McDonnell, 2003; Corwin and Lesch, 2005; Abdu et al., 2008). EMI can be exploited to ascertain spatial difference in soil texture (Doolittle et al., 1994; Triantafilis et al., 2001; Triantafilis and Lesch, 2005) and changes in soil water content in both space and time (Sherlock and McDonnell, 2003; Abdu et al., 2008; Tromp-van Meerveld and McDonnell, 2009). Changes in soil moisture are based on when measurable differences in soil electrical conductivity occur between wetter and drier soil states. Geo-referenced (SX BlueII, Geneq, Montreal, Canada) soil apparent electrical conductivity (EC_a) was collected with a CMD-1 electromagnetic induction (EMI) conductivity meter (GF Instruments, Brno, Czech Republic). The instruments has both a vertical co-planar ($EMI_{0\text{-}150}$) and horizontal co-planar ($EMI_{0\text{-}75}$) configurations which have approximate depths of exploration of 0 to 75 cm and 0 to 150 cm, respectively (McNeill, 1980). The two depths were chosen to assess surface soil moisture with the $EMI_{0\text{-}75}$ and the entire root zone with the $EMI_{0\text{-}150}$ (Corwin and Lesch, 2005). The measured EC_a represents an integrated conductivity across the soil depth of exploration (McNeill 1980).

EMI surveys were conducted on four dates during the summer dry down in 2013 (Fig. 3.2). We walked thirteen 200 m north-south transects spaced 5 m apart. A GPS was used to remain on the transect line. When a large tree was encountered, we walked around it, making effort to remain as close to the transect as possible. The instrument was held approximately 8 cm above the ground. Data underwent a quality control by removing measurements that had atypically high in-phase values observed when the instrument was above conductors such as stabilizing wires for the climate station or metal rods found at the site. Typically only a total of 5 to 15 values for each data set were removed. We transformed the raw EC_a data to a reference 25° C temperature based on the soil temperature at 60 cm for EMI_{0-150} and 15 cm and 60 cm for EMI_{0-75}. Soil temperatures at 60 cm were averaged across all measurements at the four instrumented trees. We used a standard conversion function for this transformation (Sheets and Hendrickx, 1995; Reedy and Scanlon, 2003).

We used kriging to interpolate the data to a 2 m resolution. Many environmental variables are positively skewed and require transformation (Goovaerts, 1997), we therefore used a normal-score transformation, which is often used for EC_a data (Abdu et al., 2008; Tromp-van Meerveld and McDonnell, 2009). We back transformed the normal-score kriged EC_a values for plotting purposes. We used the automap package in R (Hiemstra et al., 2009) to fit the semivariogram with an exponential, spherical, or stein model, depending on which provided the best statistical fit.

2.3.2 Rock and Soil Characteristics

To accurately interpret EC_a data, “soft” subsurface including soil and rock data are required (Sherlock and McDonnell, 2003; Abdu et al., 2008). To link soil physical properties to the EC_a data, we used the spatial statistical algorithm in the ESAP software package to collect soil samples across the entire EC_a distribution (Lesch et al., 2000) to select eight soil sample locations. Soil physical properties were characterized down to 90 cm or refusal by sampling at depth ranges of 0 to 10 cm, 10 to 30 cm, 30 to 60 cm, and 60 to 90 cm in April 2014. We were only able to sample to 65 cm for one sample, 72 cm for one sample, and 75 cm for two samples. Particles larger than 2 mm were removed prior to soil analysis (Natural Resources Conservation Service, 1999). After sieving the soil we estimated sand, silt, and clay with the sedimentation method (Gee and Or, 2002) and soil organic matter (SOM) with the loss on ignition method (Nelson et al., 1996) . For each depth we calculated VWC with the gravimetric method and bulk density assuming a particle density of 2.65 g cm^{-3}. We also measured the electrical conductivity of the soil solution (EC$_e$). To estimate clay content and bulk density across the site, we used an exponential model to perform universal kriging at 2 m resolution.

Distributed variables to assess controls on changes in EC$_a$ over the entire plot included tree canopy height, rock content, and snow survey data. Tree canopy height was calculated from LiDAR data flown in July of 2010, where we derived a ground layer and a canopy layer, and subtracted the two for a canopy height model (Hudak et al., 2002). We conducted the snow survey on March 14th, 2013; based on the continuous snow depth sensor at the climate station, this was approximately 15 days after the peak snow water equivalent date, and 67% of peak snow depth. We measured snow depth along four 200-m north-south transects that were 20 m apart and spanned the plot, every 10 m. For each survey point, we measured a set of two either north/south or east/west offsets 4 m away from each point. We established a stratified random sampling design by alternating the offset direction every other measurement. To measure snow depth under adjacent trees, we located the closest tree from each initial point, and quantified the canopy radius. On the north and south sides of the tree we measured snow depth at the trunk, half of the radius out from trunk, at the canopy edge, and 1 m outside the canopy edge. If no tree canopy was within a 10 m radius of the initial point, no tree snow depth was measured. Rock content was estimated along transects based on surface rock coverage and subsurface exploration. First, we walked three north-south transects and three east-west transects to characterize the surface rock coverage. This included percent soil cover, percent rock cover, and rock size. We then inferred sub-surface rock content based on a) the surface rock content from the survey and b) subsurface exploration. Subsurface exploration included multiple auger samples both for the eight samples and other samples collected throughout the study period and across the study site. Second, it included four pits with 1.2 m width, 0.8 m length, and 0.8 m depth dug in the high density juniper area to install buried tipping buckets. The rock content was classified into 9 different classes that ranged from 0 to 35% rock content by volume.

To interpolate the canopy height, rock content, clay, sand, and snow depth data, the same previous kriging methods were used to perform universal kriging on a 2 m resolution grid. We calculated water holding capacity (WHC) for each grid by entering the clay and sand content into the Rosetta Pedotransfer Function (Schaap et al., 2001) to generate θ at both field capacity (θ_{fc}) and plant wilting point (θ_{pwp}). WHC was calculated by:

$$\mathrm{WHC} = (\theta_{fc} - \theta_{pwp}) \times (1 - \mathrm{rock}) \tag{4}$$

where rock is the rock content, which we assume has negligible water storage.

We conducted two statistical analyses with interpolated EC_a data. The first was to assess the controls on EC_a, the second to assess the controls on change in EC_a (ΔEC_a). To evaluate the controls on EC_a, we conducted a univariate regression analysis with EC_a as the dependent variable and θ, rock content, clay content, and sand content as independent variables. The second analysis was to assess the ΔEC_a from May to September, and from August to September. These two time periods were chosen to assess changes in moisture across the entire season for the former, and during the late season when vegetation was closest to drought stress, for the latter. To assess ΔEC_a we conducted a multiple generalized least squares multiple regression model that includes spatial covariance. We used a generalized least squares model since the errors can be correlated or have unequal variance (Goovaerts, 1997). The model was as follows:

$$\Delta EC_a = WHC + snow + canopy\_height \tag{5}$$

where canopy_height is the LiDAR derived canopy height and snow is the interpolated snow data. We also conducted a simple linear regression to assess the influence of proximity to vegetation and ΔEC_a.

2.3.3 Electric resistivity tomography and seismic surveys

We conducted ERT surveys in August of 2013 (dry) and May of 2014 (wet) to assess changes in the resistivity related to subsurface moisture seasonal dynamics (Daily et al., 1992; Zhou et al., 2001). The resistivity survey was conducted with a multi-channel ERT system GeoTom MK-RES/IP/SP (GEOLOG2000, Starnberg, Germany) along 4 sequential lines of 25 electrodes for a total transect length of 99 m. We used a combination of Wenner, dipole-dipole, and Schlumberger electrode arrays with 1 m spacing and 10 pseudosection levels. Relative elevation for the topography correction was collected at a centimeter resolution with a total station. Inverse solution reconstruction with the apparent resistivity data was conducted with BERT software (Günther et al., 2006). For inversion, we combined datasets of all three arrays to maximize the accuracy of the reconstruction (Friedel et al., 2006).

To help constrain the depths of soil, saprolite, and weathered bedrock, we conducted a seismic survey in September 2014 along the ERT transect. We used a 96-channel seismograph with 10 Hz geophones at 1 m spacing. A 10 lb sledge hammer and aluminum plate were used for the source and shots were taken every 5 m. Inverse reconstruction of seismic data was constructed with fat-ray wavepath eikonal travel time inversion with Rayfract software package (RAYFRACT, Vancouver, Canada). We assumed 2,000 m sec^{-1} as the boundary between saprolite and moderately weathered bedrock (Begonha and Braga, 2002; Olona et al., 2010; Befus et al., 2011; Holbrook et al., 2013) and 700 m sec^{-1} was a cutoff for soil to saprolite layer (Befus et al., 2011).

We validated the ERT and EMI surveys by comparing the August 2013 ERT and EMI surveys. We averaged the resistivity values from the top 1.5 m of the ERT inversion and the interpolated EMI_{0-150} data that overlapped the ERT transect.

3. Results

3.1 Soil Moisture

Figure 3.2 b and c show the summer dry down in soil moisture occurring at similar periods in shallow soil but earlier in the interspace than under the juniper canopy. Based on a Wilcox rank-sum test, the canopy and interspace $day_{50\%}$ at 15 cm did not statistically differ (p=0.58), as the average $day_{50\%}$ for the canopy and interspace were day 234 and day 239 of the water year respectively. Conversely, at 60 cm the soil moisture dried out later under the tree compared the interspace with a $day_{50\%}$ of 287 and 265 respectively, which were statistically different (p=0.05). The average $day_{50\%}$ of the S_{90} in the interspace was day 260, compared to day 275 under the canopy, which was marginally statistically different (p=0.08). This suggests that soil moisture at the surface is evaporated or transpired initially at the surface, while deeper moisture pools are used later in both the canopy and interspace.

In Figure 3.3, we see that storm size drives $\Delta\theta_{15}$, $\Delta\theta_{60}$ and ΔS_{90}, but varies at different depths and locations (canopy vs. interspace). These data included 148 discernable storms over the measurement period when there was no snow on the ground, the total of which was 264 mm of rain. The median storm was 0.2 mm, but upper quartile was 1.4 mm to 29.6 mm. This upper quartile comprised 86% of the total precipitation. A between canopy and interspace t-test for $\Delta\theta_{15}$, $\Delta\theta_{60}$ and ΔS_{90} for this upper P_G quartile was only significant for $\Delta\theta_{60}$ (p=0.03) with $\Delta\theta_{60}$ canopy values being greater than interspace $\Delta\theta_{60}$ values. Canopy ΔS_{90} was greater than interspace ΔS_{90}, but only marginally statistically significant (p=0.13). Conversely, interspace $\Delta\theta_{15}$ was greater than canopy $\Delta\theta_{15}$, although not statistically significant (p=0.81).

The regression tree in Figure 3.4 confirms the importance of P_G in driving changes in soil moisture, being all three nodes in the $\Delta\theta_{60}$ tree, the root and a secondary node in ΔS_{90}, and being the root node in the $\Delta\theta_{15}$ tree (Fig. 3.4). Increases in soil moisture increase with P_{int}, although this is likely in part related to the fact that P_{int} is linearly correlated with P_G (R^2

= 0.60, p<0.0001). P_{int} was also retained in the $\Delta\theta_{15}$ tree, although it was a tertiary node and for low $\Delta\theta_{15}$ values. VPD was a secondary node in $\Delta\theta_{15}$ tree for larger $\Delta\theta_{15}$ values, where increasing VPD decreased $\Delta\theta_{15}$. VPD was also a tertiary node in the ΔS_{90} tree, although counter-intuitively increasing VPD correlated with increased ΔS_{90}.

3.2 Electromagnetic Induction

Figure 3.5 show that as the dry season progresses, EC_a gradually decreases at both shallow and deeper layers in the soil. The median for both the $EMI_{0\text{-}75}$ (0 – 75 cm) and $EMI_{0\text{-}150}$ (0 – 150 cm) configurations reduced almost by half from May to September, going from 28.6 to 12.0 mS m^{-1} and from 41.5 to 21.6 mS m^{-1}, respectively. The frequency distribution of EC_a further narrowed as the dry season progressed (Fig. 3.5), with the range from Q1 to Q3 shrinking in both the $EMI_{0\text{-}75}$ from 17.6 to 7.3 mS m^{-1} and in the $EMI_{0\text{-}150}$ from 23.2 mS m^{-1} to 12 mS m^{-1}. Interestingly, despite the large summer rain storm between the August and September survey, the median, Q1, and Q3 values all decreased across the surveys in both the $EMI_{0\text{-}75}$ and $EMI_{0\text{-}150}$.

Univariate data analysis of EC_a and soil properties showed that the greatest correlation with EC_a was a negative correlation with sand content (R^2=0.92) as shown in Figure 3.6. EC_a was also positively correlated with θ and clay content (Fig. 3.6). On the other hand, rock content ranged from 0 to 35% and was not correlated with EC_a. Considering that soil moisture is the only time-variable property significantly correlated with ECa, we reason that temporal changes in EC_a are a good predictor of θ changes across the study site. For the kriged predictor variables, SWE ranged from 0 cm to 29 cm and the average for pixels with snow was 8.05 cm. WHC in the top 150 cm of the soil ranged from 43.2 cm to 67.2 cm and the mean was 52.0 cm. LiDAR derived vegetation canopy height ranged from 0 to 9.6 m, the mean for pixels greater than 1 m (i.e. pixels with juniper tree present) was 2.8 m.

We then used fitted semivariogram models to interpolate EC_a measurements using spherical and stein models (for semivariogram parameters see Table 3.1). These maps shown in Figure 3.7 revealed consistently higher EC_a in both $EMI_{0\text{-}75}$ and $EMI_{0\text{-}150}$ in the lower juniper density area of the plot compared to the lower density area. Areas with high conductivity were areas with high clay content and low rock content, and conversely areas with low conductivity were areas with lower clay content and higher rock content. These areas in the southern part of the plot had ECa lower than 40 mS m^{-1} for the $EMI_{0\text{-}150}$ throughout the study period. The stream channel in the middle of the transect for the $EMI_{0\text{-}150}$ shifted from high conductivity (> 100 mS m^{-1}) to low conductivity (< 50 mS m^{-1}).

Comparisons of seasonal changes in EC_a with interpolated snow depth, WHC, and canopy height revealed that WHC was the primary control on ΔEC_a (Table 3.2). WHC was significant for all models at $p<0.0001$. Canopy height was only significant ($p<0.1$) for the $EMI_{0\text{-}75}$ configuration from May to June and June to August, and the relationship changed from positively correlated to negatively correlated respectively (Table 3.2). Snow was a significant ($p < 0.05$) variable for the $EMI_{0\text{-}75}$ and ΔEC_a from May to September model.

Comparing ΔEC_a in $EMI_{0\text{-}150}$ to presence of juniper canopy, there was a significant correlation between the canopy height and ΔEC_a from August to September (Fig. 3.8B, Fig 3.9). For the ΔEC_a for the $EMI_{0\text{-}150}$ configuration, the larger the adjacent canopy height was, the greater the ΔEC_a (Fig. 3.9). Conversely, for the ΔEC_a from May to September, there is no apparent correlation between ΔEC_a and proximity to juniper trees (Fig. 3.8A).

3.3 Electrical Resistivity Tomography

ERT inversion results are depicted in Figure 3.10. Along the ERT transect, total canopy coverage (m^2) of all trees within 5 m of the transect per 1 m of transect was greater in the high density juniper area (0 – 35 m) at 5.1 m^2 m^{-1}, compared to 1.7 m^2 m^{-1} in the low density juniper area (60 – 100 m) (Fig. 3.10A). Furthermore, the total cumulative height of all junipers within 2 m of the transect is 36.3 m in the high density area, and 10.7 m in the low density juniper area. The number of sagebrush in the high density area was 0.49 shrubs m^{-2} compared to 1.93 shrubs m^{-2} in the low density area (Fig. 3.10A).

The seismic data along the same transect revealed a relatively consistent boundary between soil and saprolite and a varying boundary between soil and weathered bedrock (Fig 10B, 11). The depth of the soil ranged from 1.3 m to 3.0 m and was on average 2.1 m in the high density juniper segment of the transect (0 – 35 m) and 1.7 m in the low density juniper segment of the transect (60 – 100 m) (Fig. 3.10B, 11). The average saprolite and weathered bedrock boundary was 12.9 m (Fig. 3.10B, 11). Comparable to the soil and saprolite boundary, the depth to the saprolite and weathered bedrock boundary was similar across the high density and low density juniper areas at 15.4 m and 13.4 m respectively. The saprolite and weathered bedrock boundary was shallowest near the stream channel (as shallow as 8.0 m).

Time-lapse ERT surveys during wet (May) and dry (August) revealed areas of both low and high resistivity (Fig. 3.10C,D). Much of the high density juniper area was dominated by low resistivity subsurface. Conversely, much of the low density juniper area was dominated by high resistivity values. The differences between the wet and the dry ERT surveys produced consistently negative change in resistivity values below the high juniper areas and below trees (Fig. 3.10E,11). Comparing the change in resistivity averaged over the high density juniper area (0 – 35 m) and low density juniper area (60 – 100 m) in Figure 3.12A shows that this relationship persists across all depths measured. The greatest change in resistivity for both low and high density juniper areas was at 4 – 6 m depths (Fig. 3.12A). Conversely, the lowest changes in resistivity in both areas were in shallow (< 2 m) and deep (> 10 m) depths. Furthermore, we visually see that a subsurface either directly under a clump of medium trees (15 – 35 m) or in proximity to a large juniper tree (0-5 m; 45 – 55 m) resulted in the greatest increase in resistivity at depth (Fig 3.11). Analyzing the relationship between the presence of trees and change in resistivity in a linear regression, we see that the presence of more trees and taller trees across the entire plot correlates to greater increase in resistivity (Fig. 3.12B). Finally, note that several areas decreased in resistivity between the wet and dry season (Fig. 3.10E, Fig 3.11).

Confirming the high and low resistivity measurements at the surface along the ERT transect were in fact real, the EMI_{0-150} interpolated data was well correlated with the top 1.5 m ERT survey, with the slope of -9.9 mS log ohm^{-1}, at $p<0.0001$ and $R^2 = 0.70$. This confirms that some of the heterogeneities across the plot are real instead of an instrument error.

4. Discussion

Our original hypothesis was that soil moisture after a rain storm would increase more in the interspace than under the canopy due to canopy interception. Statistically there was no difference in change in shallow moisture ($\Delta\theta_{15}$) after a rain storm between the canopy and interspace. However, there was significantly greater increase in deeper moisture ($\Delta\theta_{60}$) under the canopy. This is counter-intuitive since juniper canopy interception and canopy storage capacity is often high and assumed to be much greater than grass or sagebrush species as described in the relevant literature (Eddleman and Miller, 1991; Larsen, 1993; Owens et al., 2006; Kuhn et al., 2007; Ffolliott and Gottfried, 2012). What could lead to this counter-intuitive increase in $\Delta\theta_{60}$ below the juniper canopies following a rain storm? There are three plausible causes: 1) hydrophobicity funneling infiltration to deeper layers, 2) roots and other preferential paths increasing deep infiltration, and 3) increased infiltration due to stemflow. In regards to the first possible cause, Madsen et al. (2008) and Robinson et al. (2010) both observed elevated soil hydrophobicity compared to the interspace directly under Utah juniper (*Juniperus osteosperma*) and pinyon pine (*Pinus edulis*). We observed hydrophobicity below several juniper canopies at our site (water drop penetration greater than 1 min, data not shown). Although hydrophobic soils may appear to decrease infiltration, they can increase preferential infiltration as suggested by Robinson et al. (2010). The authors observed preferential flow causing deeper infiltration under tree canopies than in the interspace. Regarding the second possible cause, roots may facilitate increased infiltration since roots provide “pathways” for water to bypass the soil matrix. Roots have been observed to facilitate deeper infiltration in pinyon and juniper trees (Dasgupta et al., 2006) and in other ecosystems (Johnson and Lehmann, 2006; Niemeyer et al., 2014). Third, stemflow may result in elevated $\Delta\theta_{60}$. Stemflow concentrates (funnels) water at the tree base and increases preferential flow (Levia and Germer, 2015). However, multiple juniper and pinyon studies have quantified stemflow to be less than 5% of total precipitation (Eddleman and Miller, 1991; Owens et al., 2006). Considering observed hydrophobic soils below the canopy and the low potential for large amounts of stemflow, we partially attribute elevated $\Delta\theta_{60}$ under the canopy after a storm principally due to increased preferential flow due to hydrophobic soils and root facilitation. Figure 3.13 is a conceptual diagram for how these potential below and above ground processes interact. Semi-arid trees intercept more water than the interspace (Eddleman, 1986; Eddleman and Miller, 1991; Taucer, 2006; Owens et al., 2006), and this likely results in greater amount of total infiltration in the interspace. However, our study shows that infiltration penetrates deeper in the soil profile under the canopy (Fig. 3.3B), likely due in part to all hydrophobic soils and preferential infiltration pathways along roots.

A total of 80% of events have a lower change in moisture (ΔS_{90}) estimate than the total rainfall (P_G) estimate (Fig. 3.3C). Both the canopy and the perennial vegetation in the interspace result in some interception loss, which will reduce the amount of precipitation that enters the soil. In addition, summer rain events that are often convective events with more localized rainfall patterns and the interpolation from the uphill station to the site station (across 0.8 km) could result in overestimates of P_G. Third and the more likely reason is that the summer rain storms principally wet up the top of the soil, so estimates of S_{90} are biased towards changes in θ at 15 cm and 60 cm where it is likely the soil between the surface and 15 cm is where the “missing water” is stored.

The observation that $day_{50\%}$ in the interspace occurs earlier than under the canopy was also noted by other studies. During two years of soil moisture data collection, Young et al. (1984) similarly found that soil moisture below juniper trees at 7.5 cm depth was depleted more slowly than in the interspace. Breshears et al. (1998) modeled soil moisture at 2 cm based on soil temperatures and observed drying to occur earlier in the interspace than under the tree canopy. Interestingly, Roundy et al. (2014) in their measurements in the top 30 cm observed more days with a matric potential greater than -1.5 MPa after a juniper removal treatment (chaining and burning) compared to control plots with juniper. However, their study only assessed affects after 3 years of treatment. A longer time period after treatment with greater increases in herbaceous cover may decrease the differences between the control and treatment.

It can be inferred form our results that semi-arid woody plants have potential to transpire subsurface moisture from deep layers. In our study, Figure 3.12 reveals that there is a greater reduction in subsurface moisture in areas dominated by junipers compared to those dominated by low sagebrush. This is not surprising considering juniper initially develop deep tap roots and then add above ground biomass (Young et al., 1984; Kramer, 1990; Barrett, 2007). Roots are both a mechanism for how moisture moves to deep layers since infiltrating water often follows large roots (Johnson and Lehmann, 2006; Niemeyer et al., 2014) and a mechanism for how moisture can be transpired from those deep layers. There is a call by many to retain any junipers on a landscape that are older than 150 years and pre-date euro-American settlement (Miller et al., 2005). Regardless of reasons for preserving or removing these trees, our study reveals that large juniper trees do take up subsurface moisture both layers as deep as 12 m and laterally beyond their canopy.

Our study also demonstrates what other observational field studies have shown, that juniper thrive on rocky soils with low WHC (Miller et al., 2005). Studies of western juniper have observed that during pre-Euroamerican settlement in the western U.S., the trees were predominantly found in rocky ridge tops where fire does not propagate as easily. Likely these areas have lower WHC than soil in the mid-slope and valley and must extract water in the saprolite or weathered bedrock in deeper layers. Our study provides process-based evidence that indeed juniper trees extract water from deeper, non-soil layers. Interpolated WHC data revealed lower WHC in the upper 90 cm of the soil in the dense juniper area than the sparse juniper areas (Table 3.2). This suggests that the soil moisture required to sustain the juniper in the dense area must be obtained from deeper layers, both because of lower WHC at the upper 90 cm and because the trees are more dense (i.e., increased transpiration demand). The ERT surveys largely corroborated that both large juniper and small juniper clusters cause moisture to be extracted as deep as 10 m (Fig. 3.12). That juniper can extract deep moisture means it may be more drought-tolerant than other species.

Based on our results, there is a need to focus on deep moisture pools in addition to shallow soil moisture pools. Soil moisture at the surface is a crucial driver of primary productivity (Loik et al., 2004; Schwinning and Sala, 2004) and most studies of woody plants in semi-arid regions have focused on shallow moisture layers (Breshears et al., 1997a; Robinson et al., 2010; Roundy et al., 2014). Our study revealed shallow soil moisture regimes (i.e. at 15 cm) are quite similar, but have greater differences in moisture dynamics within deeper layers. As drought risk increases with a changing climate, there is greater need to understand what moisture pools trees use and how this increases their resilience to drought.

The EMI surveys revealed that soil moisture in the upper 150 cm is principally driven by soil and climate factors. First, the soil sample analysis with EC_a measurements revealed EC_a was negatively correlated with sand content (Fig. 3.4), a principal determinant in WHC. Second, the multiple generalized least squares analysis of the distributed data revealed that WHC was the principal driver of temporal changes in EC_a (Table 3.2). In addition, some aspects of the plot drove temporal shifts in EC_a. Similar to Western et al. (1999), EC_a was more variable during the wet season and became more elevated around the stream channel and other features as the dry season progressed (Table 3.1). The fact that there is no clear spatial pattern around tree location and density in ΔEC_a from May to September (Table 3.2, Fig 8A) could be that principal differences in soil moisture change is at deeper (> 150 cm) layers (Shaw and Gifford, 1973). This is supported by the fact there was only small absolute differences between the tree and interspace ΔS_{90} from May to August (Fig. 3.2). The ΔEC_a from August to September was correlated with proximity to larger trees (Fig. 3.8B, Fig. 3.9), although canopy height was not significant in the generalized least squares model (Table 3.2). Finally, some areas saw an increase ΔEC_a in the later month (Fig. 3.8). Similarly, some areas in the ERT survey saw a decrease in resistivity (Fig. 3.11). This could be due to subsurface ion accumulation (Friedman, 2005).

5. Conclusion

Throughout the western U.S., woody plant species have encroached into historical grasslands and sagebrush (Romme et al. 2009), and there are ongoing large efforts to remove these woody plants to restore rangelands (e.g. (Bureau of Land Management, 2015). To understand how shifts in semi-arid land cover alters the hydrologic cycle, our study used both continuous shallow (< 1m) measurements and periodic geophysical surveys to assess how subsurface moisture dynamics differ between juniper and sagebrush (interspace). Our study shows that western juniper transpire moisture from deep layers of the subsurface. It also revealed a counter-intuitive relationship between juniper and infiltration: that soil moisture penetrates deeper under the canopy than in the interspace. These are first steps in understanding the hydrologic processes that drive changes in streamflow observed in semi-arid woody vegetation studies. Furthermore, this advance in the understanding of semi-arid ecohydrologic processes can help inform future hydrologic models to predict how future climate and vegetation impacts soil moisture and streamflow. This is especially important considering that climate change could impact the timing, intensity, and phase of precipitation.

There still remains a need for future research in understanding the impact of semi-arid land cover change on subsurface moisture. Since our work was carried out in two years with slightly above normal precipitation, above normal temperature, and below normal snow pack, further research is needed to understand how changes in subsurface moisture differ from wet to dry years and if trees consistently access deep moisture pools. Future research could also elucidate the horizontal subsurface impact of semi-arid woody vegetation, and in particular at what horizontal distance and what depths do woody plant roots access moisture, since juniper roots have been found to have lateral roots that extent well past the canopy edge (Barrett, 2007). Despite these knowledge gaps, it is clear that semi-arid trees alter the soil moisture regime and significantly impact the terrestrial hydrologic cycle of these systems.

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Table 3.1. Semivariogram parameters for fitted EC_a models for both EMI0-75 and EMI0-150 for each month.

	$EMI_{0\text{-}75}$ **(0 – 75 cm)**					$EMI_{0\text{-}150}$ **(0 – 150 cm)**				
Month	**Model**	**Nugget**	**Range (m)**	**Sill**	**Kappa**	**Model**	**Nugget**	**Sill**	**Range (m)**	**Kappa**
May	Spherical	0	9.7	0.53	-	Stein	0.03	0.44	19.4	10
June	Spherical	0.06	18.1	0.59	-	Spherical	0.002	0.62	16.1	-
Aug	Stein	0.03	11.4	0.50	10	Stein	0.03	0.54	11.0	10
Sept	Stein	0.02	12.8	0.47	1.1	Stein	0.01	0.48	14.7	1.6

Table 3.2. Multiple generalized least squares regression coefficients for ΔEC_a models for both $EMI_{0\text{-}75}$ and $EMI_{0\text{-}150}$. Canopy height (canopy_height) is derived from LiDAR data, water holding capacity (WHC) is calculated with a pedotransfer function from interpolated maps of sand and clay, and snow is from interpolated snow surveys.

ΔEC_a Model	**Variables –** $EMI_{0\text{-}75}$ **(0-75 cm)**			**Variables –** $EMI_{0\text{-}150}$ **(0-150 cm)**		
	canopy height	WHC	snow	canopy height	WHC	snow
May – June	0.009+	0.383***	0.0004	-0.003	0.297***	0.0004
June – August	-0.009+	1.743***	-0.003	-0.004	1.406***	-0.001
August – Sept	0.002	0.101***	0.0008	0.002	0.138***	-0.0004
May – Sept	0.001	2.247***	-0.003*	-0.0003	1.848***	-0.002

+=p<0.1, *=p>0.05, **=p<0.01,***=p<0.001

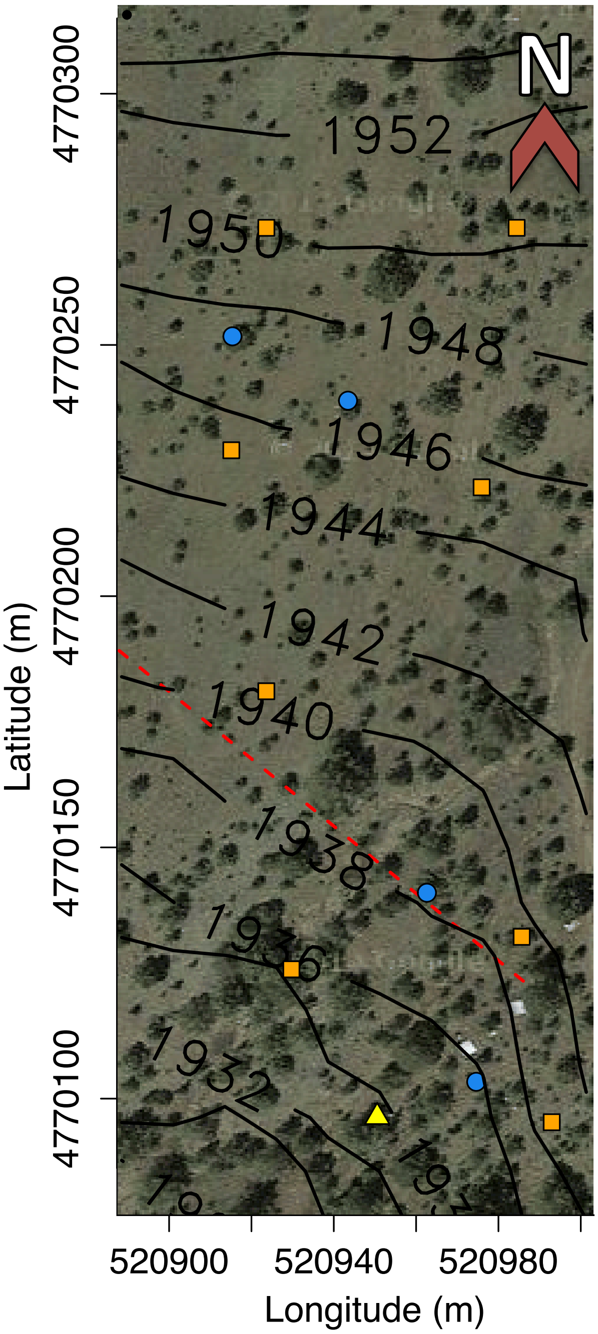


Figure 3.1. Aerial photo of study site with elevation contours in meters (black lines), trees with soil moisture probes (blue dots), climate station (yellow triangle), soil sample locations (orange squares) and ERT transect (dotted red line). The map area is the approximate boundary for the EMI survey. The “0” point of the ERT transect is on the east (right) side of the transect.

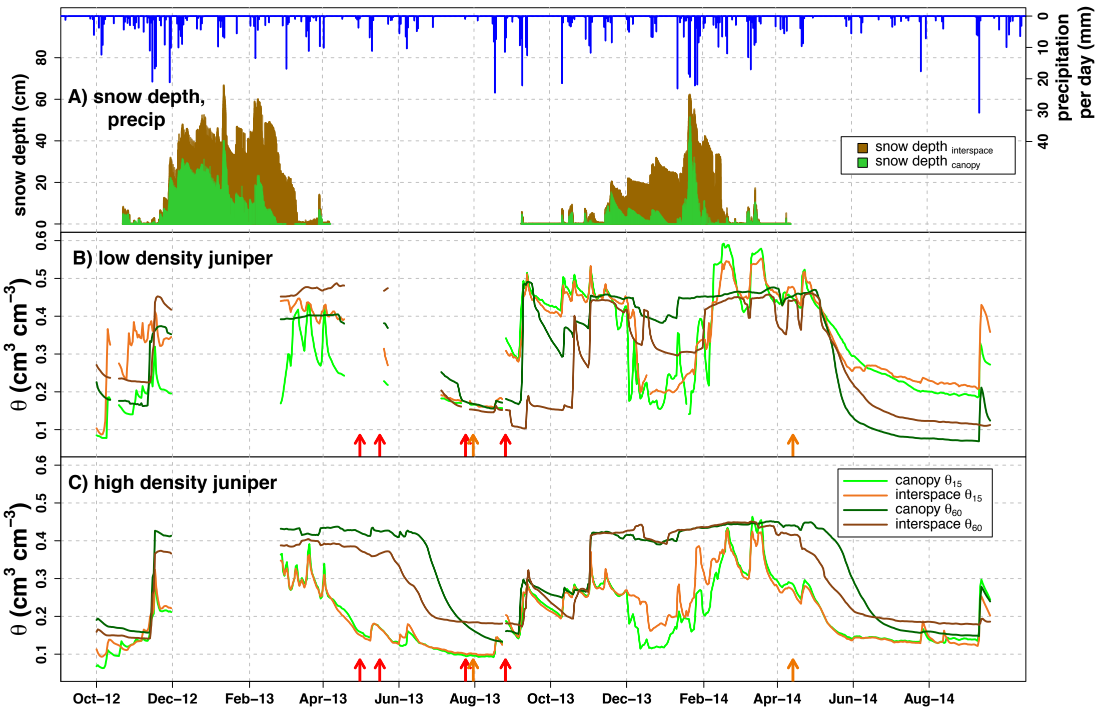


Figure 3.2. This figure contains A) snow depth and precipitation per day, volumetric water content at 15 cm (θ15) and 60 (θ60) cm soil depth measured at under the canopy and in the interspace at two trees in the B) low density juniper and C) high density juniper. These θ data are an average for both trees in each density area. Red (orange) arrows indicate when EMI (ERT) surveys occurred.

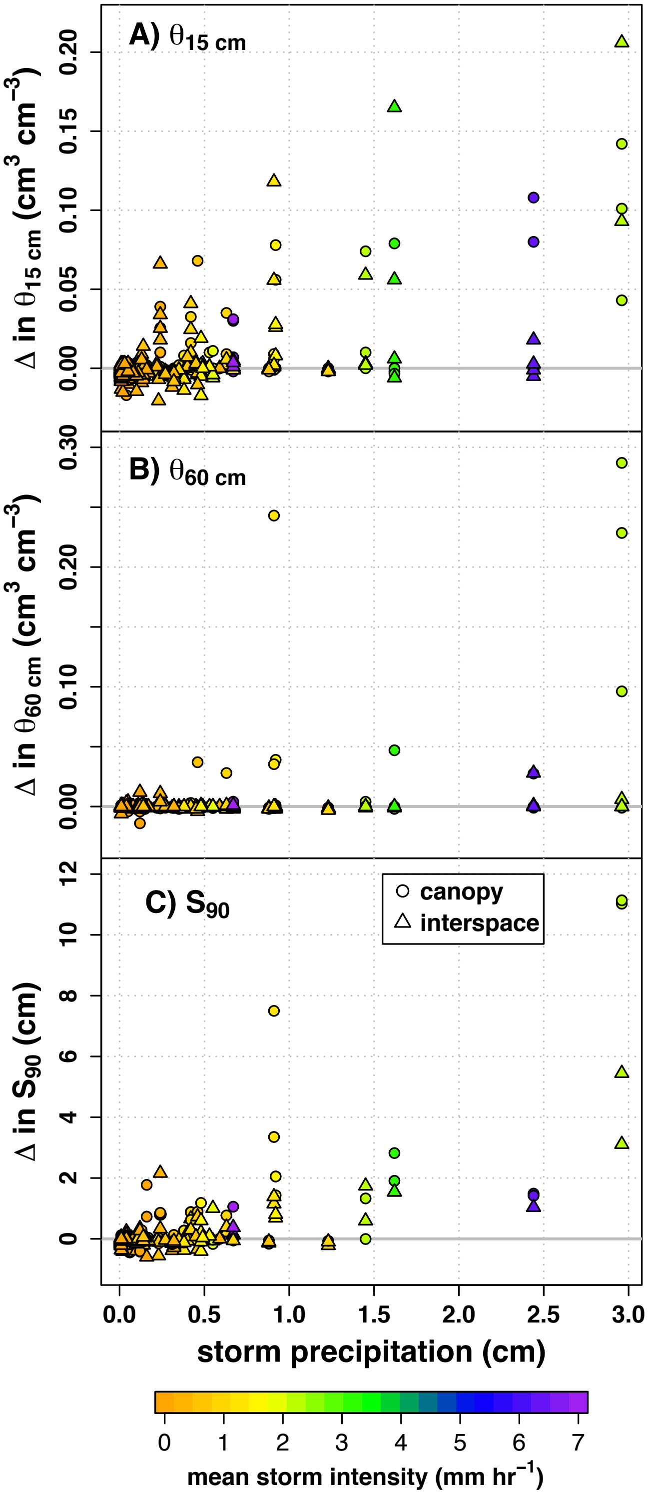
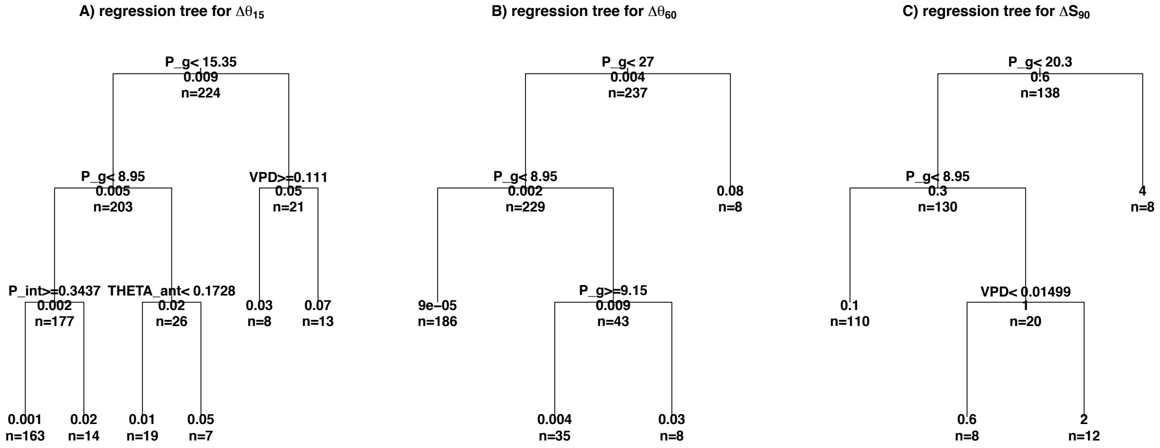


Figure 3.3. Plot of $\Delta\theta$ at 15 cm (A) and 60 cm (B) and ΔS_{90} (C) after rain storms plotted against total storm precipitation, colored with average rainfall intensity.


A) regression tree for $\Delta\theta_{15}$

B) regression tree for $\Delta\theta_{60}$

C) regression tree for ΔS_{90}

Figure 3.4. Regression tree for A) $\Delta\theta_{15}$, B) $\Delta\theta_{60}$, and C) ΔS_{90} after a rain storm, across storm, soil, and site characteristics. Tree branches are uniform for improved visibility.

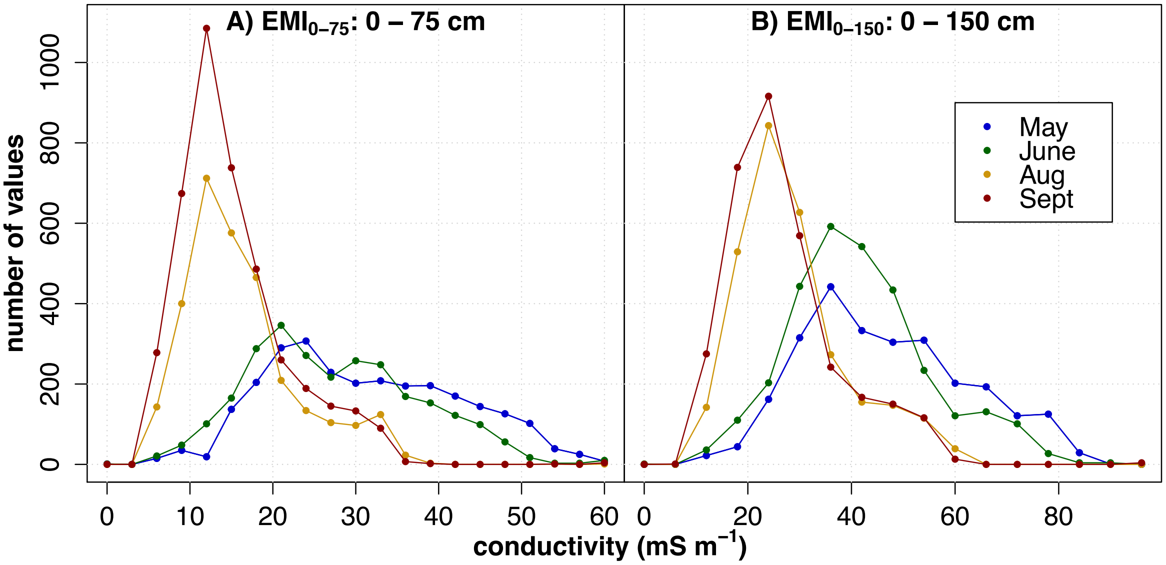
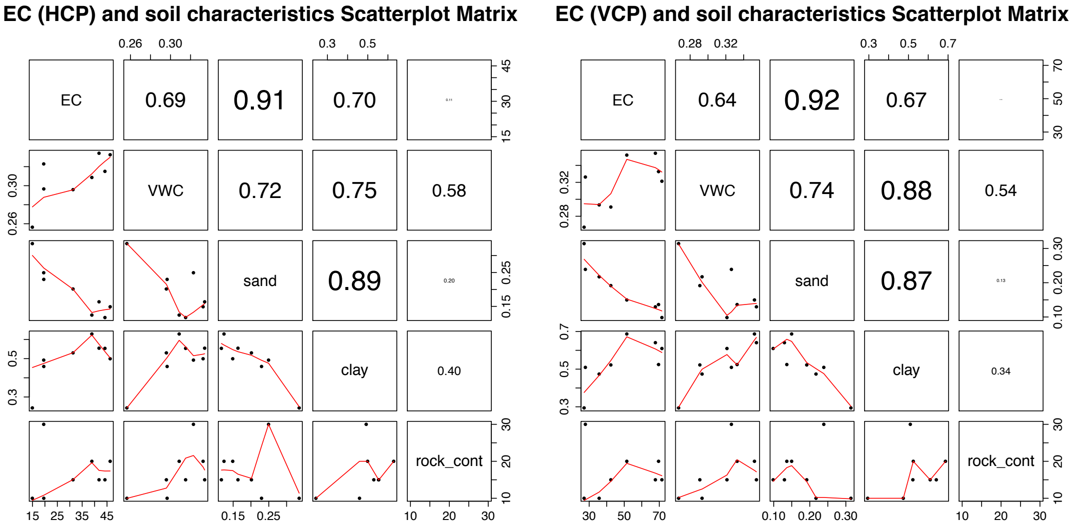


Figure 3.5. Histograms of EC_a data for both $EMI_{0\text{-}75}$ and $EMI_{0\text{-}150}$ across May, June, August, and September.


EC (HCP) and soil characteristics Scatterplot Matrix

EC (VCP) and soil characteristics Scatterplot Matrix

Figure 3.6. Scatterplot matrix of EC_a and soil characteristics for soil sample sites.

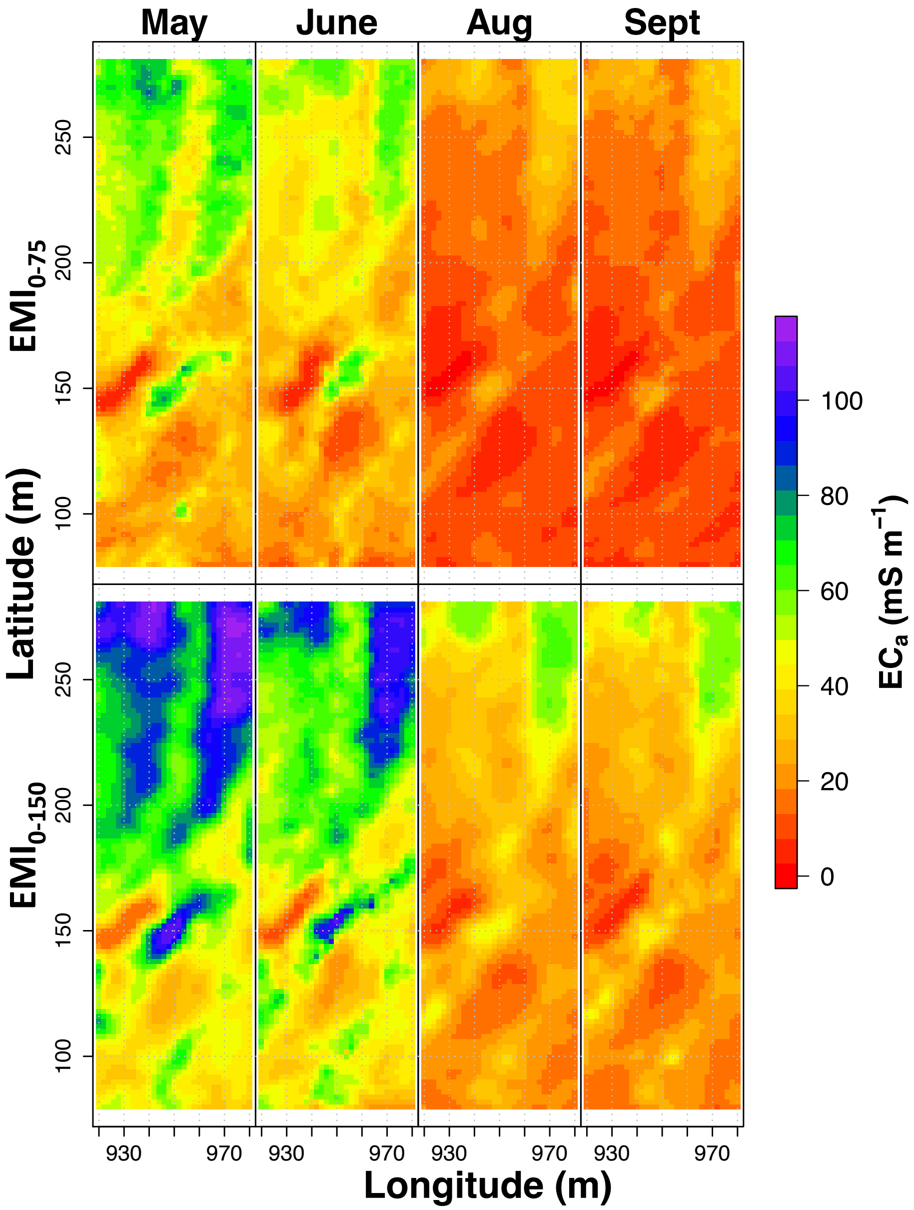


Figure 3.7. Maps of EMI inversions for $EMI_{0\text{-}75}$ (0 – 75 cm) and $EMI_{0\text{-}150}$ (0 – 150 cm) in sequential months from May, June, August, and September.

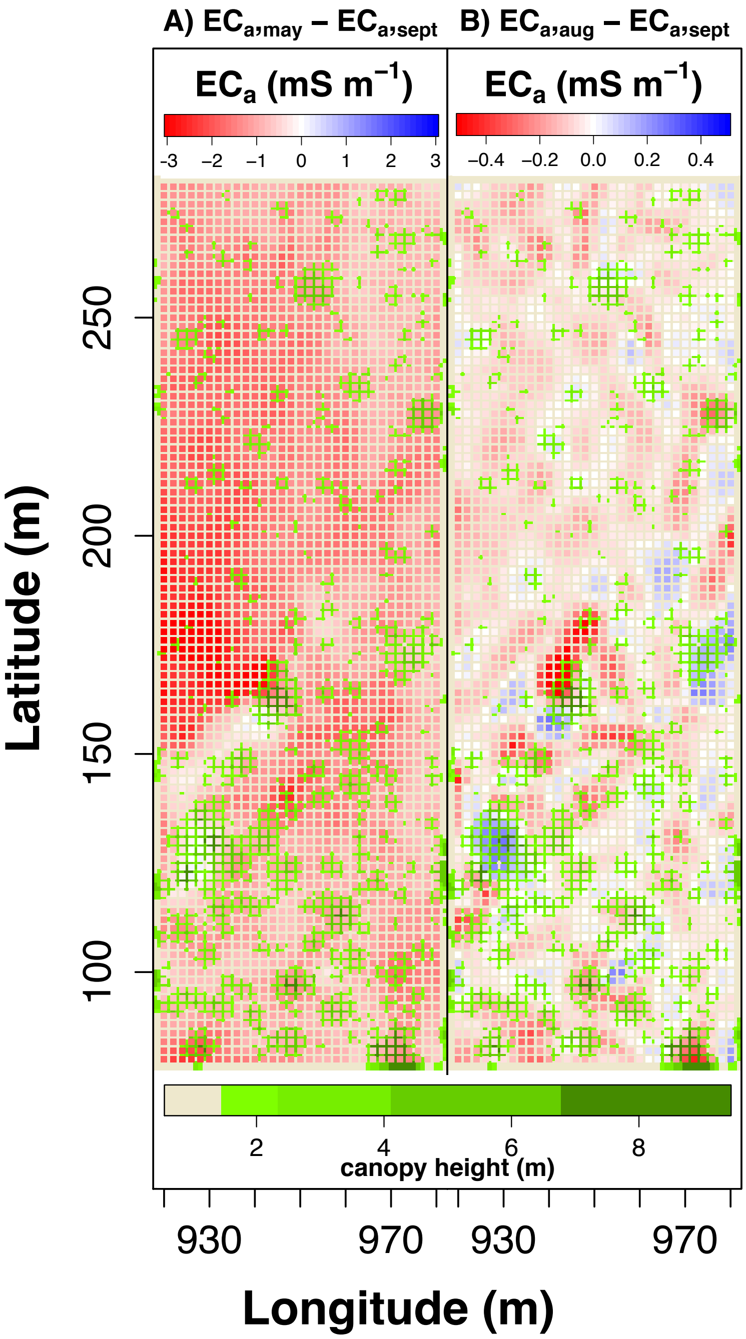


Figure 3.8. Absolute (A) and percent change (B) in EC$_a$, both normalized (divided by) the earlier EC$_a$ survey. Tree canopy height plotted in the background.

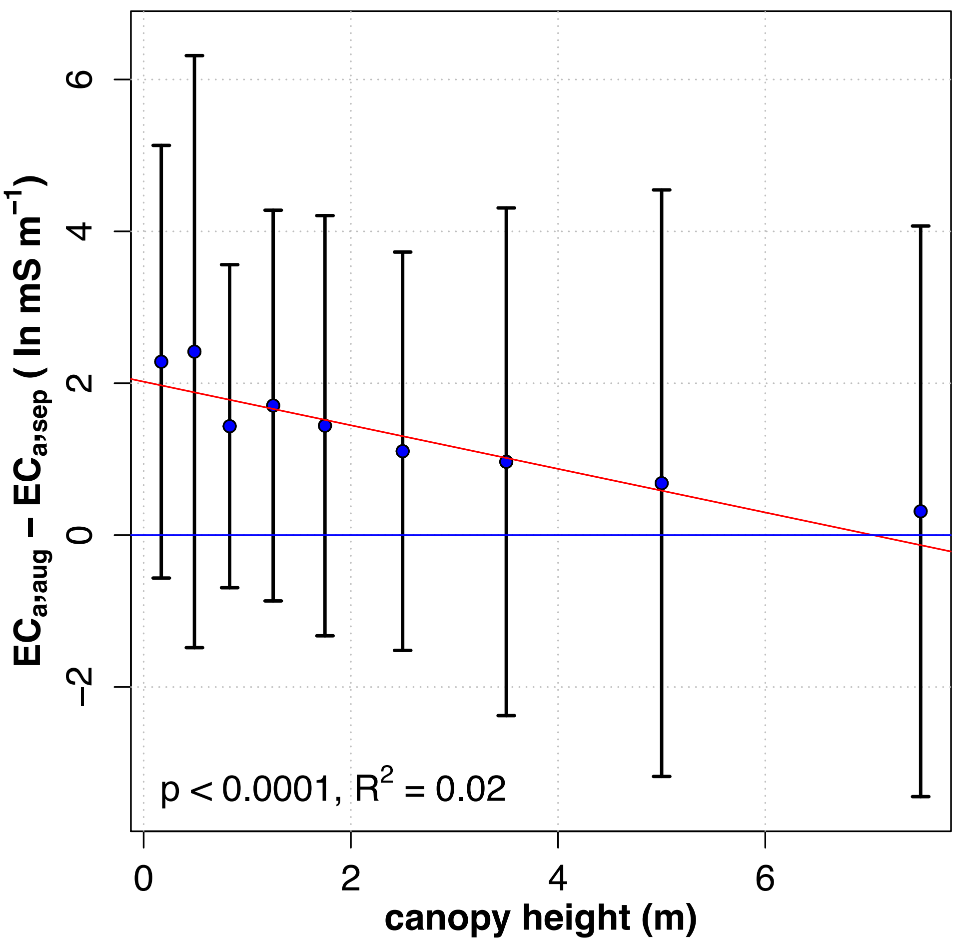


Figure 3.9. Relationship between the max canopy height of adjacent cells and the natural log of the change in $EMI_{0\text{-}150}$ EC_a from August to September. Error bars are 1 standard deviation. Red line is linear regression trend line between the two variables.

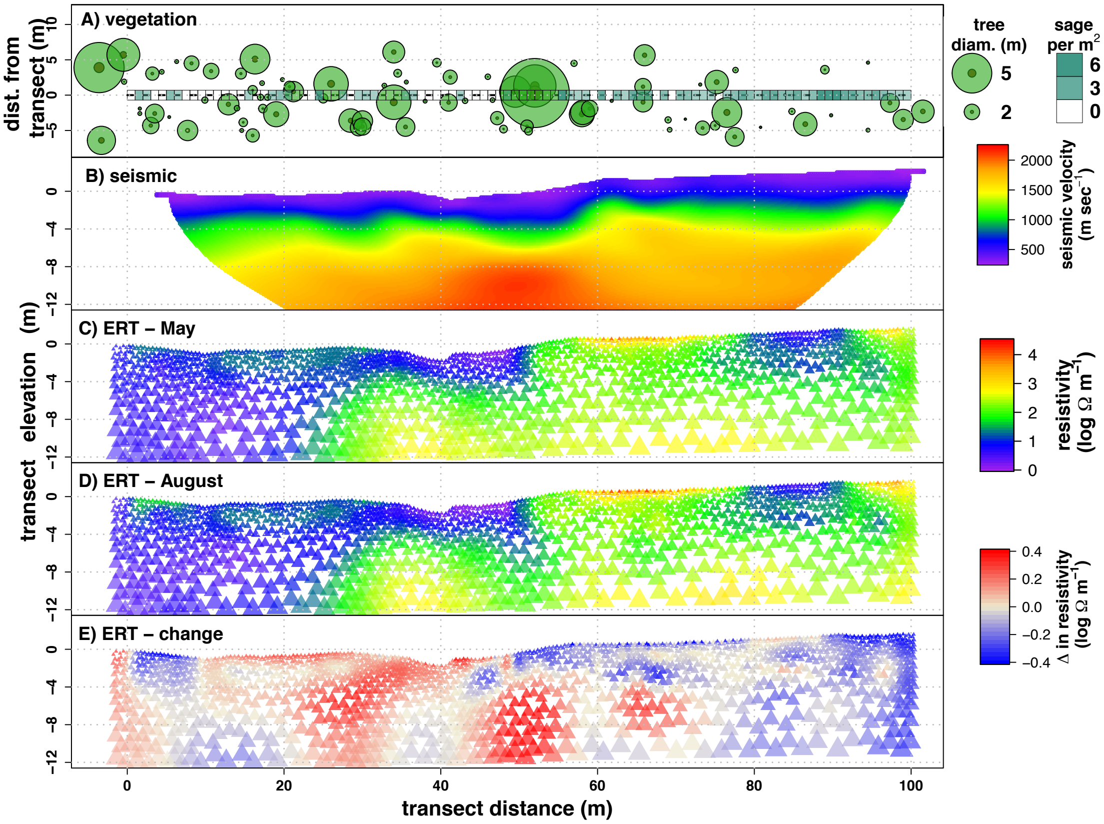


Figure 3.10. This figure shows A) tree location and diameter as well as sagebrush density along the ERT transect, B) inversions of seismic data, C) inversion from ERT survey in May 2014, D) inversion from ERT survey in August 2013, and E) change in resistivity from ERT inversions from May (wet) to August (dry) data.

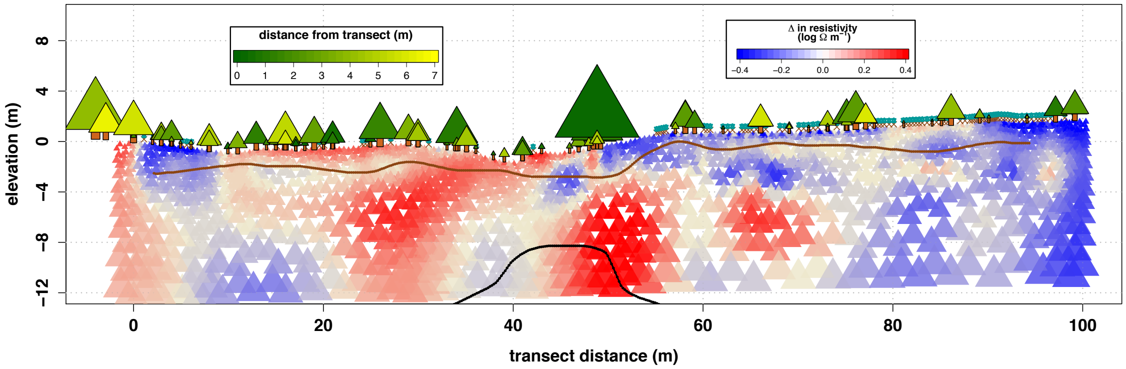


Figure 3.11. Change in ERT between May and August, with contour lines delineating the soil – saprolite layer (brown line) and the saprolite – weathered bedrock layer (black line). For juniper canopy and trunk (green triangles and brown rectangles) and sagebrush canopy and trunk (teal asterisk and brown "x"), both the canopy height and diameter are plotted approximately to scale. All juniper within 5 m of the ERT transect are plotted.

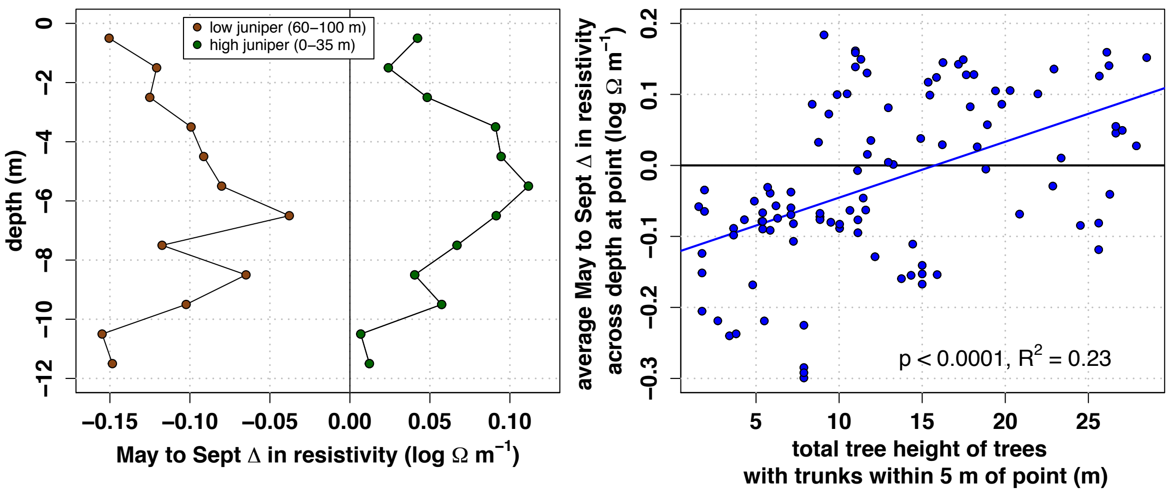


Figure 3.12. Vertical average change, across the low vs. high areas (maybe 0 – 35), and 60 – 100 – that would be across the two plateaus of low and high density juniper.

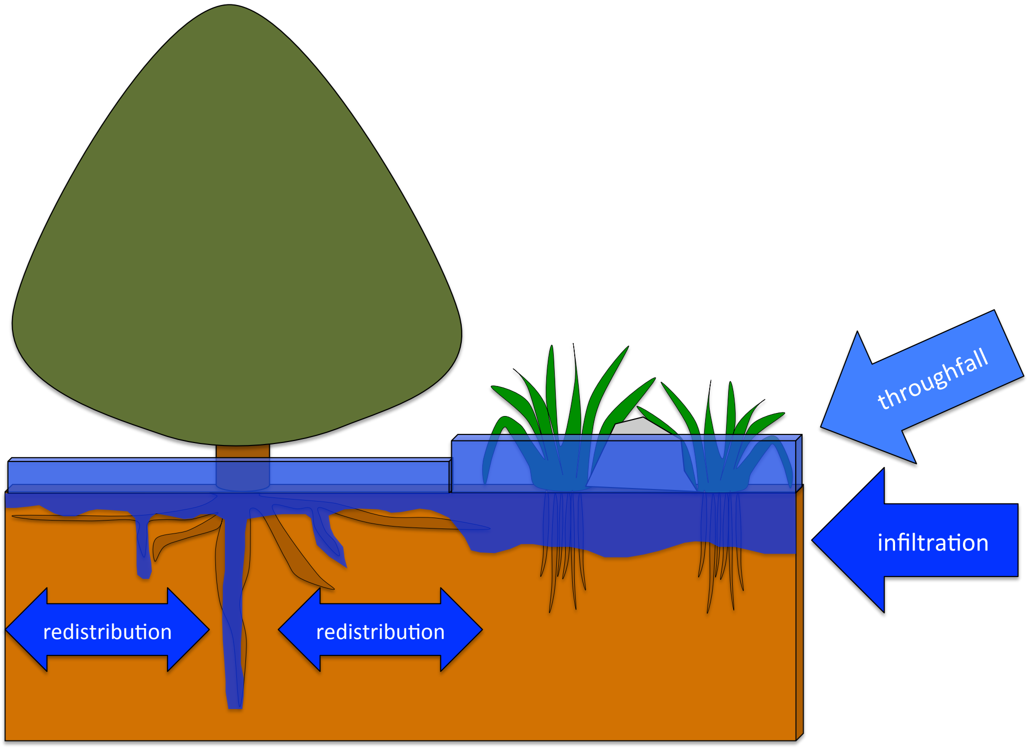


Figure 3.13. Conceptual figure of throughfall and infiltration processes between the canopy and interspace. More throughfall occurs in the interspace due to juniper canopy interception, therefore greater total infiltration occurs in the interspace. But due preferential infiltration and roots providing pathways for preferential flow, infiltration occurs deeper in the soil profile.

Chapter 4 - A social-ecological impact assessment for public land management: application of a conceptual and methodological framework

Authors: Amanda Bentley Brymer, Joseph D. Holbrook, Ryan J. Niemeyer, Alexis A. Suazo, J.D. Wulfhorst, Kerri T. Vierling, Beth A. Newingham, Timothy E. Link, and Janet L. Rachlow

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Abstract

According to the U.S. National Environmental Policy Act of 1969 (NEPA), federal action to manipulate habitat for species conservation requires an environmental impact statement (EIS), which should integrate natural, physical, economic, and social sciences in planning and decision-making. Nonetheless, most impact assessments focus disproportionately on physical or ecological impacts rather than integrating ecological and socio-economic components. We developed a participatory social-ecological impact assessment (SEIA) that addresses the requirements of NEPA and integrates social and ecological concepts for impact assessments. We cooperated with the Bureau of Land Management in Idaho (USA) on a project designed to restore habitat for the Greater Sage-Grouse (*Centrocercus urophasianus*), which is a candidate species for listing under the Endangered Species Act. We employed questionnaires, workshop dialogue, and participatory mapping exercises with stakeholders to identify potential environmental changes and subsequent impacts expected to result from the removal of western juniper (*Juniperus occidentalis*). Via questionnaires and workshop dialogue, stakeholders identified 46 environmental changes and associated positive or negative impacts to people and communities in Owyhee County. Results of the participatory mapping exercises showed that the spatial distribution of social, economic, and ecological values throughout Owyhee County are highly associated with the two main watersheds, wilderness areas, and the historic town of Silver City. Altogether, the SEIA process revealed that perceptions of project scale varied among participants, highlighting the need for specificity about spatial and temporal scales. Overall, the SEIA generated substantial information concerning potential impacts associated with habitat treatments for Greater Sage-Grouse. The SEIA is transferable to other land management and conservation contexts as it supports holistic understanding and framing of connections between humans and ecosystems. By applying this SEIA framework, land managers and affected people have an opportunity to fulfill NEPA requirements and develop more comprehensive management plans that better reflect the linkages of social-ecological systems.

Key words**:** deliberative workshops; impact assessment; National Environmental Policy Act; NEPA; PPGIS; public lands; public participatory GIS; social-ecological systems workshops; public participatory GIS; PPGIS; woodland encroachment

1. Introduction

When federal actions aimed at species conservation are anticipated to cause significant impacts to the environment, land and resource managers in the U.S. are required by the National Environmental Policy Act of 1969 (NEPA) to assess potential impacts, develop mitigation strategies, and report their findings in an environmental impact statement (EIS). NEPA stipulates an interdisciplinary approach so that the entire environment is included in planning and decision-making (CEQ 2007). Even so, a typical EIS tends to comprise more ecological than social impacts, and assessments that integrate ecological and social concepts to identify impacts on multiple scales are uncommon (see Burdge 2002, Whitfield et al. 2011).

A social impact is defined as a physical or cognitive effect experienced by humans and their communities and caused by a change in the social or ecological environment (Vanclay 2002). Traditionally, secondary sources such as Census data were analyzed to identify potential social impacts (Becker 1997), but secondary data can be inappropriate when sources are outdated or lack information on specific community needs or cultural issues (Esteves et al. 2012). Consequently, typical social impact assessments (SIA) often lack current, primary data (Lockie 2001) and rarely invite stakeholders to actively engage in planning or assessment processes (Vanclay and Esteves 2011).

Effective SIA facilitates the evaluation and management of social issues associated with planned interventions (e.g., management or land use change) and are participatory, supportive of people affected by interventions, and increase people's capacity to respond to change (Vanclay 2003, Esteves et al. 2012). However, Esteves et al. (2012) identified a set of issues that persist in SIA, including inadequate public participation and analyses that do not identify spatial or temporal distributions of impacts. Research has demonstrated that dialogue-based approaches to SIA such as interactive community forums and participatory modeling can help to overcome these limitations by providing a more comprehensive and deeper understanding of values, place meanings, and perceived impacts (Becker et al. 2003, Harris et al. 2012, Whitfield and Reed 2012). Rather than predicting impacts from secondary data sources, an emerging paradigm of SIA seeks a community-based process that empowers affected people with 1) improved understanding of a project, and 2) increased capacity to negotiate outcomes with the project managers or developers (Vanclay and Esteves 2011).

Reconciling the shifting SIA paradigm and the requirements for NEPA processes highlights the need for novel methodological approaches that can capture social dynamics like political tensions among different interest groups, as well as diverse perspectives on changing ecological conditions. The design of such approaches should assist public land managers in developing socially and ecologically comprehensive management plans that aid in decision-making and ultimately help achieve conservation goals. Our research objective was to develop a social-ecological impact assessment (SEIA) that addresses the requirements of NEPA and embodies the emerging SIA paradigm calling for more participatory, dialogue-based approaches. Our conceptual framework builds on previous work (i.e., Slootweg et al. 2001, de Groot et al. 2002, 2010, Vanclay 2002) by merging ecosystem service concepts with social process concepts to better represent the interdependent relationships between humans and ecosystems. The methodological approach directly engages diverse stakeholders and builds on previous work (i.e., Becker et al. 2003, Gunderson and Watson 2007, Harris et al. 2012, Lowery and Morse 2013, Whitfield and Reed 2012) by deliberating project alternatives to identify stakeholders' perceptions of potential impacts, and by adding a spatial dimension with participatory mapping to include values across the landscape and project area.

We apply the SEIA to a high-profile conservation context in the western U.S.: Greater Sage-Grouse (*Centrocercus urophasianus*; hereafter Sage-Grouse) habitat restoration. As of January 2015, the Bureau of Land Management (BLM) has been developing a draft EIS focused on improving habitat for Sage-Grouse by removing conifer trees. Sage-Grouse are a sagebrush ecosystem obligate and candidate species for listing under the Endangered Species Act (USFWS 2010) due to >50% habitat loss since the mid-1800s (Knick et al. 2003). We embedded our integrated SEIA into the BLM's active NEPA process, illustrating the potential of this approach for other EIS processes aimed at species conservation on public lands.

1.1 Proposed action: sage-grouse habitat restoration

The proposed study region for the treatments of Sage-Grouse habitat was in Owyhee County in southwestern Idaho, USA (Fig. 4.1). Owyhee County is comprised of 76% public land (managed mostly by BLM), 2,092 km^2 (11%) of which is designated wilderness (Owyhee Initiative 2012). Agriculture comprises 26.1% of total employment in Owyhee County with two-thirds of that sector engaged in ranching (University of Idaho Extension 2015). Most ranches are not economically viable with private land alone; these operations rely on permitted grazing on BLM allotments (Bartlett et al. 2002). Although the Owyhee region is vast and rural, it is in close proximity to the greater Boise metropolitan area (Mackun and Wilson 2011), from where many people travel for hunting, fishing, rafting, bird watching, hiking, and off-highway vehicle riding.

The habitat treatment plan proposed by the BLM was termed the Bruneau-Owyhee Sage-Grouse Habitat (BOSH) project, and the project goal is to improve or maintain Sage-Grouse breeding habitat (i.e., area surrounding leks) by removing western junipers (*Juniperus* spp.). Conifers, including junipers and pinyon pines (*Pinus* spp.), are dominant trees in Great Basin woodlands that have expanded into sagebrush habitats (Tausch et al. 1981, Romme et al. 2009). Tree expansion can negatively affect Sage-Grouse breeding habitat (e.g., Baruch-Mordo et al. 2013), which has prompted management actions to remove conifers.

The BOSH project proposes to remove low-density western juniper (*Juniperus* spp.) stands that are within 10 km of 63 active Sage-Grouse leks within Owyhee County (Fig. 4.1). The BLM and Idaho Department of Fish and Game (IDFG) define active leks as those that have been visited by at least two male Sage-Grouse in at least one of the last five years. The BLM chose the 10 km buffer because approximately 80% of hens nest within 10 km of their lek. The proposed project boundary covered 708,200 ha (1.75 million acres) of southwestern Idaho and included 93,078 ha (230,000 acres) of wilderness. Proposed treatments included cut and scatter, mastication, and jackpot burning. Cut and scatter involves cutting down trees and scattering the branches, while mastication uses heavy machinery that shreds the above ground tree biomass and spreads the mulch (Cline et al. 2010). Jackpot burning involves burning the cut trees when fire risk is low (Huffman et al. 2009). In accordance with NEPA, the BLM developed treatment alternatives that included: 1) no action: no juniper removal, 2) full-suite: cut and scatter, mastication, and jackpot burning where deemed necessary and appropriate, and 3) cut and scatter: cut and scatter where deemed necessary and appropriate.

2. SEIA Development

2.1 Conceptual Framework

To build the SEIA framework, we merged previously developed conceptual frameworks that emphasize the connection between humans and ecosystems. First, we applied concepts from the de Groot et al. (2002, 2010) ecosystem services framework that provides a standardized typology for describing and classifying ecosystem functions, goods, and services: 1) provisioning, 2) processing, 3) supporting, and 4) cultural. Second, we used Vanclay's (2002) conceptualization of social processes to integrate economics, governance, and empowerment concepts with ecosystem services concepts. The combination of these concepts provides a more comprehensive framework for assessing potential social-ecological changes and impacts in complex systems. These aforementioned concepts have been defined and discussed in community development contexts, but have rarely been integrated in a regulatory context on U.S. public lands.

We adapted a flow diagram from Slootweg et al. (2001) to serve as a guide for the identification and description of cause and effect pathways and to aid in the articulation of potential impacts to people and communities. For example, removal of juniper (*Juniperus* spp.) trees from a landscape exemplifies an intervention that causes social-ecological change (Fig. 4.2). A person might perceive that a reduction in juniper cover will lead to improved sagebrush habitat for sagebrush obligate species, and for people who appreciate sagebrush obligates, an improvement in obligate species habitat might lead to a positive perception of juniper removal (Fig. 4.2). Examples illustrating two additional pathways are provided and described in the flow diagram (Fig. 4.2).

2.2 Methodological Approach

The SEIA approach merges a deliberative workshop setting and participatory mapping activities to better understand differing perspectives among people who live and work in the Owyhee region and to identify spatial dimensions of their values. Public participation GIS (PPGIS) is a method to spatially represent public knowledge, place meanings, or values by including members of the public in the mapping process (Talen 2000, Brown 2005). We merged participatory, qualitative approaches to SIA (Becker et al. 2003, Harris et al. 2012) and PPGIS methods (Gunderson and Watson 2007, Lowery and Morse 2013) because 1) there is a need and legal mandate to involve the public in planning processes (Brown and Weber 2011, Brown and Donovan 2013), and 2) human-ecosystem interactions and planning are inherently geospatial. These methods have rarely been applied together to understand potential impacts as required by NEPA on U.S. public lands.

We implemented two workshops to foster discussion about the alternatives drafted by the BLM, general social, economic, and ecological values, and benefits people receive from the ecosystem (i.e., the Owyhee region). In the first workshop, we structured questionnaires and dialogue directly around the conceptual framework and flow diagram. Using a workshop protocol similarly structured to interactive community forum formats (Becker et al. 2003), participants were prompted to deliberate the proposed juniper treatment alternatives, how each alternative might cause changes to ecosystem services, (e.g., provisioning, processing, supporting, and cultural services), and/or changes to social processes (e.g., economic, institutional and legal, or empowerment processes), and how those changes might positively or negatively impact people and communities. In the second workshop, we asked participants to spatially draw values associated with social, economic, or ecological characteristics or processes fundamental to their relationships to the ecosystem.

3. Methods

The sampling frame included local, state, and federal resource managers, as well as organizations involved in a long-term collaborative effort in the Owyhee region (i.e., The Owyhee Initiative), which served as a clearinghouse of parties interested in resource management in the Owyhee region. Prior to our agreement with the BLM, a working group comprising managers from the BLM and Idaho Fish and Game, restoration conservationists from governmental and non-governmental organizations, and representative from the Owyhee County Sage-Grouse Local Working Group had already been formed by the project lead (hereafter Group 1). To broaden the range of perspectives for the SEIA, we purposively sampled 27 stakeholder groups whose members are concerned with ecosystem functions in the Owyhee region to create an additional workshop group (hereafter Group 2). Group 1 and Group 2 separately participated in a two-workshop series. Each workshop spanned an average of 5 hours. We followed ethical guidelines for working with human subjects, and the University of Idaho Institutional Review Board approved our project #12-357 (Appendix C).

3.1 Deliberative Workshops

The first workshop began with an overview presentation of the BOSH project and four rounds of questionnaires with subsequent deliberation (Appendix A: Table A1). The first round assessed participants’ baseline perceptions of the current structure and function capabilities of the Owyhee region in terms of ecosystem services and social processes, while the subsequent three rounds of questions revealed participants’ perceptions of future structure and function of the Owyhee region under the three BOSH project alternatives.

Quantitative and qualitative analytical approaches were employed. Questionnaires included seven questions related to ecosystem services and social processes. All four questionnaires were identical, but while completing the four questionnaires participants were asked to consider the structure and function in the present state (i.e. baseline) and in the future under the three project alternatives. For the present state and future conditions under each alternative, participants rated items from 0 – "as bad as it can be" – to 10 – "as good as it can be." To compare the perceived benefits or costs of juniper treatment, we normalized each participant's ratings by subtracting their "baseline" rating from the three alternative ratings. The last question related to the level of acceptability for each treatment in wilderness areas, which was different than the other questions because there was no baseline condition and the scale was from 0 – "extremely unacceptable" to 5 – "extremely acceptable." Thus, we analyzed the wilderness question separately. Data were analyzed with R statistical software (R Core Team, 2014).

Workshop dialogue was recorded and transcribed for analysis in NVivo 10 (QSR International Pty Ltd. Version 10, 2012). First, the integrated social-ecological conceptual framework was used to categorize participant responses into statements about particular ecosystem services and social processes. Second, an inductive approach was used to review the transcriptions and allow descriptions of potential impacts to emerge from participants' deliberations. For a social-ecological impact to be included in the analysis, it had to 1) be explicitly stated, and 2) include the direction of effect (e.g., positive/better, negative/worse, or no change).

3.2 PPGIS Workshops

We implemented a qualitative approach to PPGIS (e.g., Brown and Pullar 2012, Lowery and Morse 2013). We presented participants with laminated 61 x 91 cm aerial photographs (USDA, National Agriculture Imagery Program 2011) at a scale between 1:400,000 and 1:500,000. We asked each individual to map areas throughout Owyhee County that they perceived as valuable for social, economic, and ecological reasons. Next, we presented a separate set of maps that displayed the BOSH project boundary and asked participants to identify areas where they did not want the project executed and to explain why. We then took photographs of each map to create a county value map by digitizing polygons within ArcGIS 10.1 (ESRI 2012). Each polygon had attributes indicating the group and participant number and whether it was based on social, economic, or ecological justification. We analyzed overlapping polygons in ArcGIS (Honeycutt 2013) across a 30 m^2 grid overlaid on Owyhee County and the BOSH boundary.

4. Results

The sample consisted of 24 participants in total. Twenty participants completed all four questionnaires, three participants completed questionnaires but were unable to participate in the workshops, 19 participated in the deliberative workshops and 10 participated in the PPGIS workshops (eight participated in both). As self-described, participants represented diverse occupations and user groups including non-government conservationist (4), wildlife biologist (4), livestock rancher / land owner (3), government conservationist (2), supervisor (2), natural resource manager (2), restoration coordinator (1), range management specialist (1), archaeologist (1), cartography technician (1), retired fire fighter (1), self-employed individual (1), and one individual who did not self-identify an occupation.

4.1 Questionnaire Results

The average observed range of responses for all four questionnaires was 81.6% (Fig. 4.3), indicating that the sample of participants revealed a broad range of perspectives. On average, participants' ratings for future social-ecological conditions in the Owyhee region under the no action alternative were 1.4 points (SD 1.9) lower than their baseline ratings. This suggests most workshop participants perceived that if there were no action to remove juniper trees, future social-ecological conditions in the Owyhee region would deteriorate. Participant ratings for the full-suite and cut and scatter alternatives were on average 1.4 points (SD 2.8) and 0.3 points (SD 2.3) higher than their baseline ratings, respectively. This suggests many workshop participants perceived that implementation of either treatment alternative would improve future social-ecological conditions, but for some participants the full-suite alternative will lead to a higher degree of improvement, bringing the Owyhees closer to “as good as it can be.” Some social conditions (e.g., economic, institutional and legal, and empowerment processes) were rated higher in a future with either the full-suite or cut and scatter alternative by almost all participants (Fig. 4.4e, f, & g), in contrast to some ecological conditions (e.g., supporting service: open space, cultural service: opportunities for spiritual enrichment and recreation), which were rated inconsistently across participants (Fig. 4.4c & d). On the acceptability of juniper removal within wilderness, participants' responses displayed substantial variation indicating little consensus.

4.2 Deliberative Workshop Results

Workshop participants described 46 environmental changes and associated positive or negative impacts that they anticipate to result from the BOSH project alternatives (see Appendix B: Table B1, Table B2, and Table B3 for example quotations). Of the 18 changes to ecosystem services and social processes anticipated from the no action alternative, fifteen changes were perceived to lead to negative impacts and three changes were perceived to lead to positive impacts to people and their sense of well-being (Table 4.1). For example, if there is no action to remove juniper from the landscape, people anticipated experiencing negative impacts due to reduction of watershed functionality, loss of biodiversity and habitat (particularly Sage-Grouse habitat), diminished spiritual experience, less opportunity in the local economy, and less opportunity for stakeholder collaboration. Positive impacts were expected to derive from the availability of areas without juniper removal for control group studies and from the improvement of overall enjoyment of the Owyhee region. The most striking split in opinion among participants related to perceived impacts that no action will have on their overall enjoyment of the Owyhee region. Some participants enjoy the Owyhee region when they know it is managed and junipers are removed – particularly due to the belief that reduced juniper cover improves Sage-Grouse habitat. Other participants emphasized that junipers are native and that we are managing too much. For them, the knowledge that nothing is being done to remove juniper is comforting and improves their overall enjoyment of the Owyhees.

We found participants’ perceptions of potential social-ecological changes and subsequent impacts from the full-suite and cut and scatter alternatives to be mostly similar, though a few key differences stood out. Workshop participants described five similar environmental changes that they perceived could be caused by both alternatives leading to negative impacts: increased fire danger, degraded wildlife habitat, diminished viewsheds, and worsened agency reputation and diminished management effectiveness, primarily for the BLM. Workshop participants described three similar environmental changes that they perceived could be caused by both alternatives leading to positive impacts: improved watershed functionality, improved wildlife habitat, and more opportunity in the local economy. For the full suite, some participants anticipated additional positive impacts, some of which included improved management, viewsheds, general enjoyment of the Owyhee region, and the maintenance of culture tied to cowboys and Sage-Grouse.

Contrary to those who anticipated both alternatives to cause certain social and ecological changes, other participants described that in a future under the full suite alternative, there would be no change in some people’s ability to make a living, no change in management, and no change in viewshed or spiritual experience. The split in opinion about anticipated environmental changes was based on participants’ varying perceptions of project scale and juniper removal tools. For example, some participants expressed concern that mastication would be applied across the entire project area, while others understood that mastication was proposed for roadsides only.

4.3 PPGIS Workshop Results

The PPGIS workshop comprised mapping activities based on two key questions: 1) “What areas across Owyhee County are important to you for social, economic, and/or ecological reasons?”, and 2) “Within the BOSH Project boundary, where do you not want juniper removed?" Results from the first mapping activity (hereafter county values map) show that the overall distribution of perceived values (social, economic, and ecological combined) throughout the Owyhee region is highly associated with the two main watersheds (Owyhee and Bruneau-Jarbidge), wilderness areas (e.g., Owyhee River and near Juniper Mountain), and the town of Silver City, Idaho (Fig. 4.5). Silver City is a historic mining town with a deep history and many cultural traditions. The Owyhee and Bruneau-Jarbidge watersheds are within significant portions of the Owyhee River and Bruneau-Jarbidge wilderness areas (see point 1 and 2 in Fig. 4.5a).

When we separated social, economic, and ecological values into three county value maps, the social (Fig. 4.5b) and ecological (Fig. 4.5d) values displayed similar patterns. However, we found more polygons per participant for ecological than social values. The polygons characterizing economic values were quite different than social and ecological values, and there were fewer polygons per participant for economic values (Fig. 4.5c). Economic values were mapped in a general sense (i.e., perhaps less precise) relative to the other values.

Justifications for the location of social, economic, and ecological polygons were diverse. Social polygons were generally drawn around areas that participants value for the ranching or cowboy culture and tradition, and watershed- or wildlife-based recreation. Economic polygons were mapped to highlight the value of the ranching and farming industries, as well as tourism and the military. Ecological polygons were drawn across areas that participants found valuable for resource connectivity, wildlife and fisheries habitat, and biodiversity.

The second mapping activity (hereafter no treatment map) served as a social setting filter, much like the ecological filter that narrows the scope of issues related to an intervention (Slootweg et al. 2001). The majority of participants indicated that the BOSH project will be positive and therefore did not draw any polygons; these participants support juniper removal over the entire project area. Some suggested no treatment around Riddle, Idaho, because this area would be a lesser priority due to their perceptions that essentially no junipers are present. Others identified areas near Juniper Mountain, Idaho, because they are culturally valuable to Native Americans. Finally, some participants indicated they are against executing the BOSH project entirely because they questioned the BLM's ability to complete the project goals without unintended consequences (e.g., spreading invasive species and half-finished projects).

5. Discussion

We combined a conceptual framework and multi-method process that upholds the requirements of NEPA and generates a more holistic understanding of social-ecological impacts associated with habitat conservation plans. In the context of our project, the general discussion of perceived impacts from juniper removal alternatives were difficult to understand without incorporating spatial data. Incorporating the spatial dimension of participants' environmental values via mapping allowed land managers to understand where interests and concerns were located within the Owyhee region. This information can be useful for identifying and prioritizing the most relevant issues to address with mitigation strategies. In our case, potential impacts associated with watersheds, wilderness, and historic towns were the top priorities for the BLM to address with mitigation. Mapping data can also serve project managers as a decision-making tool concerning where to stage juniper removal phases since the 1.75 million acre project area will not be treated simultaneously. Moreover, by coupling dialogue data and spatial mapping we were able to identify the relative scope of potential impacts associated with participants' values. For instance, our data suggest that the scope of impacts is narrower within the BOSH project boundary compared to the scope of potential impacts at the county level. Collectively, these data provide BLM managers with a better understanding of how proposed land actions influence social perceptions, which will allow for the development of a more holistic environmental impact statement for Sage-Grouse conservation.

Our SEIA process also advanced some of the major shortcomings of conventional EISs, including the lack of social-ecological integration. Rather than consider characteristics of the social system separate from the ecological system, we merged ecosystem service concepts and social process concepts to achieve an integrated framework that represents the complexity of interdependent social-ecological systems. The SEIA conceptual framework was intuitive to the study participants, and most agreed that it was a useful tool for articulating ways that juniper removal alternatives could impact their lives. The range of topics covered in the workshops demonstrated the importance of a social-ecological framework for public lands where individual and community well-being depend upon the environment. Most EISs to date are relatively devoid of social impacts, much less integrated with ecological and/or biophysical concepts in public land management contexts (Slootweg et al. 2001, Burdge 2002, Whitfield et al. 2011). Given that NEPA requires an interdisciplinary approach for the preparation of EISs (42 U.S.C. § 4331), the lack of social impacts puts current practice into question.

In addition to improving social-ecological integration, there is a need to add a spatial dimension to environmental assessments – specifically, the identification of areas that are socially, economically, and ecologically valuable. Values are the fundamental building blocks of perceptions about how one might be impacted by a management intervention and environmental change, and visualizing this information on a map is helpful because public land management is done in a spatial context (Lowery and Morse 2013). During PPGIS activities, we observed workshop participants discussing areas of value and finding common ground around rivers and wilderness. Participatory mapping also allowed for clarification of misconceptions about the project, identification of unnecessary project boundaries, and deliberation of areas to prioritize or disregard for juniper removal. These observations are consistent with previous research on qualitative approaches to PPGIS that reported benefits, such as positive synergy among participants and clarified perceptions of project scale (Lowery and Morse 2013).

The PPGIS activities coupled with deliberative workshops also addressed the need to improve the role of affected people in impact assessment processes. Deliberations of potential impacts revealed a key point: addressing multiple spatial and temporal scales throughout a project can clarify project purpose and inform a more comprehensive design of mitigation strategies. The benefits of these workshops are consistent with previous research that observed improved opportunities for community members to share their perceptions about proposed actions and potential futures in a deliberative setting (Becker et al. 2003, Harris et al. 2012). Typical scoping processes, during which people write or call the planning agency with their concerns, normally do not identify such nuances. A deliberative approach to SEIA can enhance scoping in a NEPA process by providing an opportunity for people to elaborate their concerns or support for a project, as well as to identify a comprehensive list of issues to address with mitigation strategies.

The novelty and strength of this approach is the application of a social-ecological conceptual framework within a deliberative setting that includes questionnaires, dialogue, and PPGIS. By merging the integrated conceptual framework and methodological approach, the SEIA process enabled triangulation of multi-scale social-ecological impacts associated with the proposed BOSH project. In addition, discrepancies in perceptions of the scale of the project emerged from the dialogue in the deliberative setting. For example, when anticipating changes to a viewshed as a result of juniper removal, participants described different perceptions of trail-level, ridge-line, horizon, and aerial views. While an agency may frame a proposed project in one scale, we observed participants framing potential impacts of the BOSH project in several scales, which fostered some ongoing confusion and is indicative of how even interested publics may misgauge project goals and objectives. Precisely characterizing scale is a recognized issue in the field of ecology (e.g., Levin 1992), but our data suggest the same level of precision is needed when discussing social-ecological impacts associated with land management actions.

6. Conclusion

Social-ecological systems are complex, as are the perceptions of humans who endeavor to manage and conserve our shared resources. This SEIA supports holistic understanding and framing of connections between humans and ecosystems, and enables land managers and affected people to co-develop more comprehensive management plans and conservation goals. The SEIA is not designed to replace a traditional ecological impact assessment for which ecological and biophysical monitoring data are analyzed, nor do we intend for SEIA to replace traditional economic impact assessments. Rather, SEIA is meant to complement other assessments by defining the connections between people and their environment and highlighting how those connections might be weakened or strengthened by land management decisions. We support the notion that impact assessments are context-dependent (Vanclay 2002), and we recommend a modification of social-ecological concepts in the framework and/or the tools for data collection depending on environmental characteristics, politics, and power dynamics specific to the project area (Ross and McGee 2006). Continued applications of integrated frameworks such as SEIA within public land management would better satisfy NEPA requirements and assist the design of more complete mitigation strategies. The advancement of conservation efforts relies in part on our ability to comprehensively assess social and ecological consequences of human interventions on public lands (e.g., *sensu* Brashares et al. 2014). The SEIA we conducted and described here contributes to this broader conservation goal.

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Table 4.1. Perceived changes to social processes and ecological services, and the direction of subsequent impacts, concerning the Bruneau-Owyhee Sage-Grouse Habitat (BOSH) project in Owyhee County, USA.

	Direction of Effect		
Process/Service	Positive	Negative	No Change
Social			
Economic processes	*No Action:* -None described *Full Suite:* -More opportunity for local economy -Ability to make a living: improved *Cut and Scatter:* -More opportunity for local economy	*No Action:* -Less opportunity for local economy -Tension on livestock operators *Full Suite:* -None described *Cut and Scatter:* -Weakening of local livelihoods -Reduced range and grazing	*No Action:* -Same opportunity for local economy *Full Suite:* -No change in ability to make a living *Cut and Scatter:* -None described
Institutional and legal processes	*No Action:* -None described *Full Suite:* -Improved management *Cut and Scatter:* -None described	*No Action:* -Disheartening to land managers -Endangered listing of Greater sage-grouse *Full Suite:* -Worse management -Worsened agency reputation *Cut and Scatter:* -Diminished management effectiveness	*No Action:* -None described *Full Suite:* -No change in management *Cut and Scatter:* -None described
Empowerment processes	*No Action:* -None described *Full Suite:* -None described *Cut and Scatter:* -None described	*No Action:* -Less opportunity for stakeholder collaboration *Full Suite:* -None described *Cut and Scatter:* -None described	*No Action:* -Same opportunity for stakeholder collaboration *Full Suite:* -None described *Cut and Scatter:* -No change in stakeholder decision-making
Ecological			
Provisioning	*No Action:* -Impact to ecosystem	*No Action:* -Decline of historic plant	*No Action:* -None described

	Full Suite: -Improved range and grazing *Cut and Scatter:* -Improved ecosystem health and characteristics -Increased water availability	communities *Full Suite:* -None described *Cut and Scatter:* -None described	*Full Suite:* -None described *Cut and Scatter:* -None described
Processing	*No Action:* -None described *Full Suite:* -Increased watershed functionality *Cut and Scatter:* -Increased watershed functionality	*No Action:* -More difficult to balance or restore landscape/ecological processes -Reduced functionality of watershed *Full Suite:* -Increased fire danger *Cut and Scatter:* -Increased fire danger	*No Action:* -None described *Full Suite:* -None described *Cut and Scatter:* -None described
Supporting	*No Action:* -None described *Full Suite:* -Increased biodiversity -Improved wildlife habitat -Improved sage-grouse habitat *Cut and Scatter:* -Improved wildlife habitat	*No Action:* -Loss of biodiversity and habitat -Loss of sage-grouse habitat *Full Suite:* -Degraded wildlife habitat *Cut and Scatter:* -Degraded sage-grouse habitat -Increased cover for sage-grouse predators	*No Action:* -None described *Full Suite:* -None described *Cut and Scatter:* -None described
Cultural	*No Action:* -Availability of areas without treatment for study -Improved general enjoyment of the Owyhees *Full Suite:* -Improved general enjoyment of Owyhees	*No Action:* -Loss of open space -Limits on recreation -Less aesthetic enjoyment -Diminished hunting -Diminished spiritual experience *Full Suite:* -Recreation: disrupted -Degraded viewshed	*No Action:* -No change for general enjoyment of the Owyhees -No change in spiritual experience *Full Suite:* -No change in solitude -No change in recreation -No change in viewshed

	-Improved hunting -Improved viewshed -Improved spiritual experience -Maintained culture tied to cowboy and sage-grouse *Cut and Scatter:* -None described	*Cut and Scatter:* -Degraded viewshed	-No change in spiritual experience *Cut and Scatter:* -No change in general enjoyment of the Owyhees

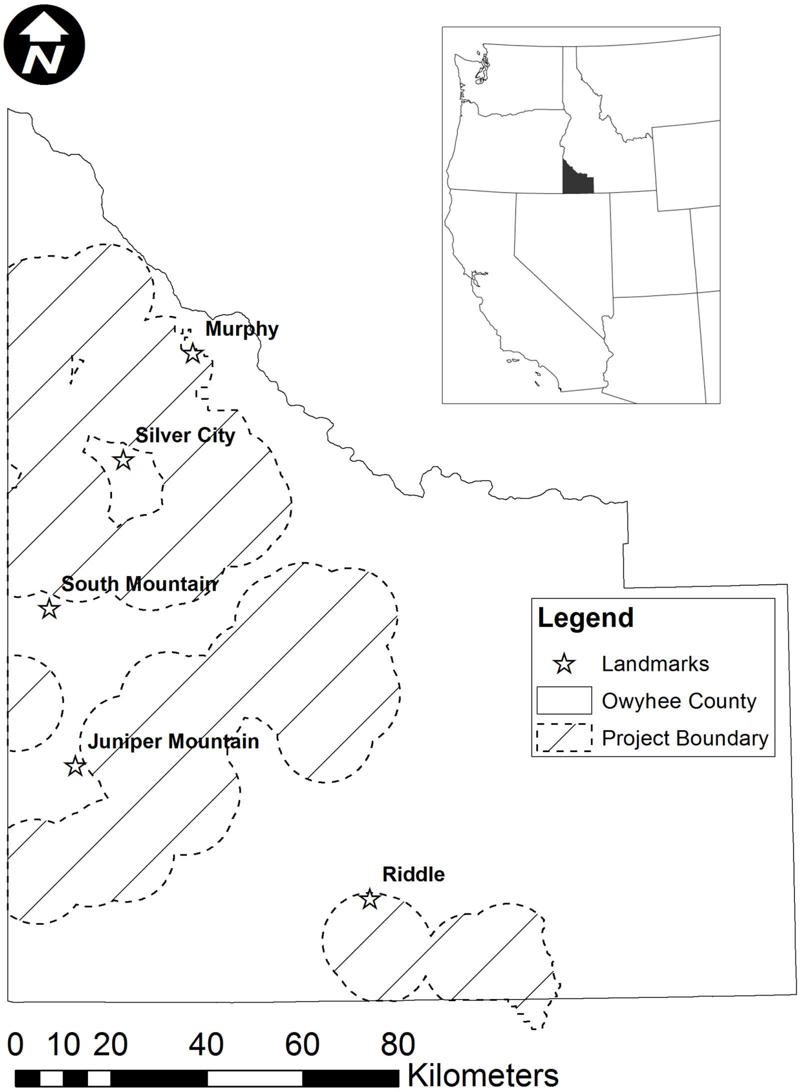


Figure 4.1. Inset map shows the western USA with Owyhee County, Idaho, in dark grey. Map of Owyhee County shows the proposed project boundary and five landmarks for the Bruneau-Owyhee Sage-Grouse Habitat (BOSH) project.

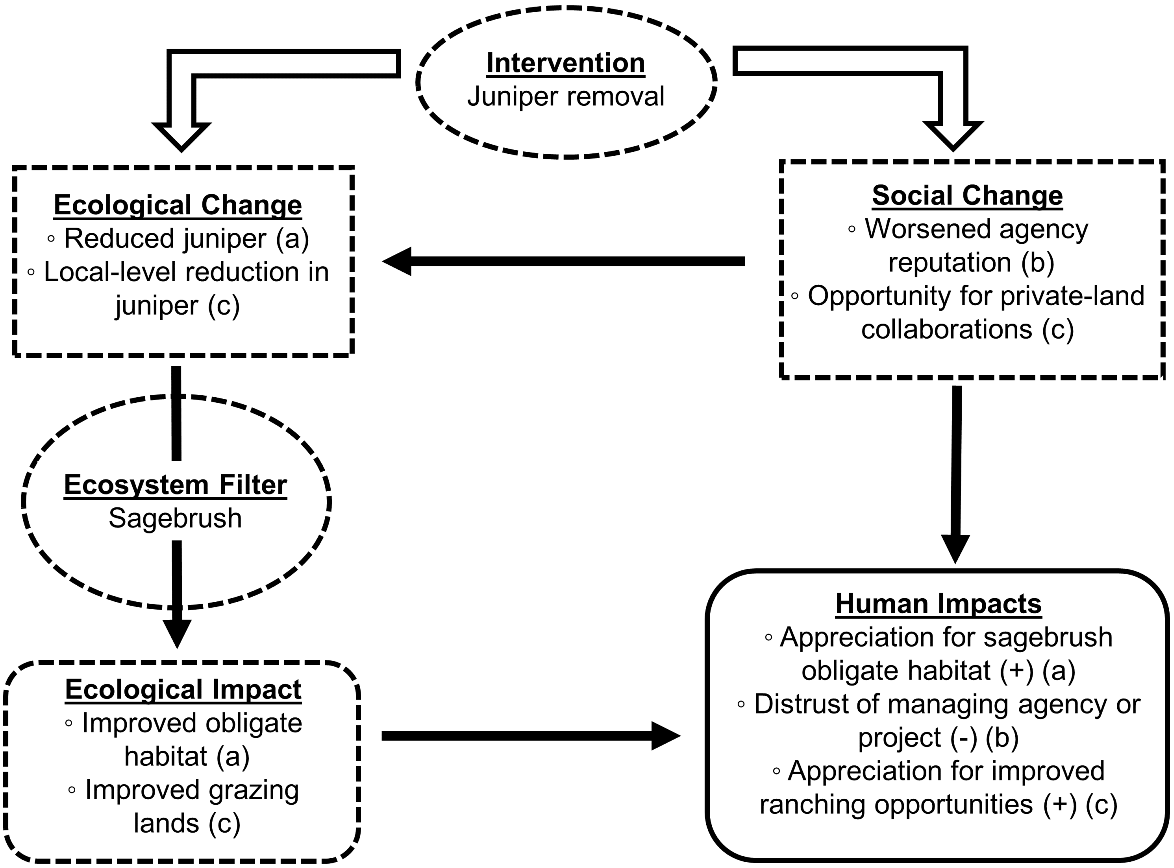


Figure 4.2. Flow diagram of the social-ecological impact assessment (SEIA) framework (modified from Slootweg et al. 2001). The diagram begins with an intervention (e.g., juniper removal), which ultimately generates social or ecological change through three pathways. (a) First, an ecological change might be a reduction in juniper. This change is filtered through an ecosystem (e.g., sagebrush) and results in an ecological impact such as improved habitat for sagebrush-obligate species. This ecological impact could then result in a positive (i.e., +) human impact in terms of appreciation of habitat for sagebrush obligates. (b) Second, an intervention might generate social change that degrades an agency's reputation, which directly generates a negative (i.e., -) human impact in terms of public distrust of the management agency. (c) Lastly, an intervention could produce social change in terms of generating opportunity for private-land collaborations. This collaboration could results in additional local-level juniper removal. This change is then filtered through the ecosystem and generates an ecological impact of improved grazing lands. The human impact via this last pathway is positive (i.e., +) in that it generated an appreciation for improved ranching opportunities. Human impacts are in solid lines and all other components are in dotted lines. All arrows represent pathways to human impacts.

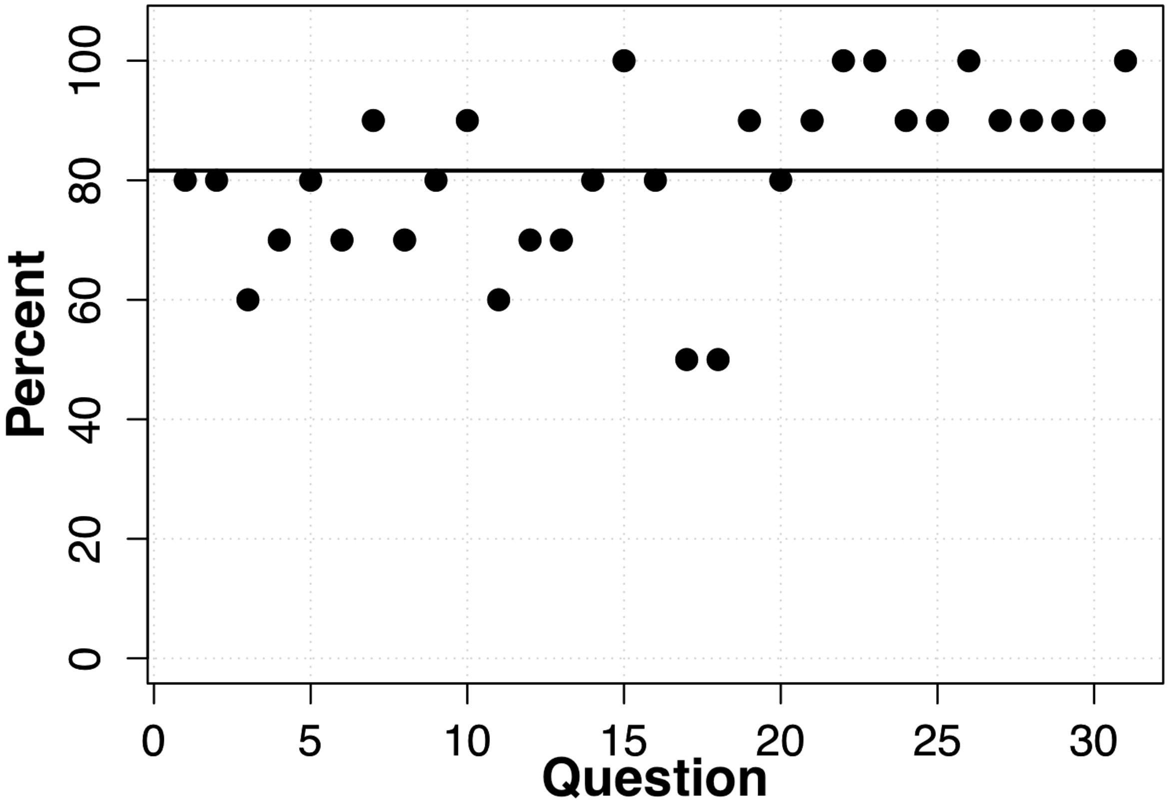


Figure 4.3. Percent of the total range observed for responses for each question. For example, for question 1 we observed a minimum score of one and a maximum score of eight, which translates to 80% range observed. Horizontal line is the average range observed across all questions.

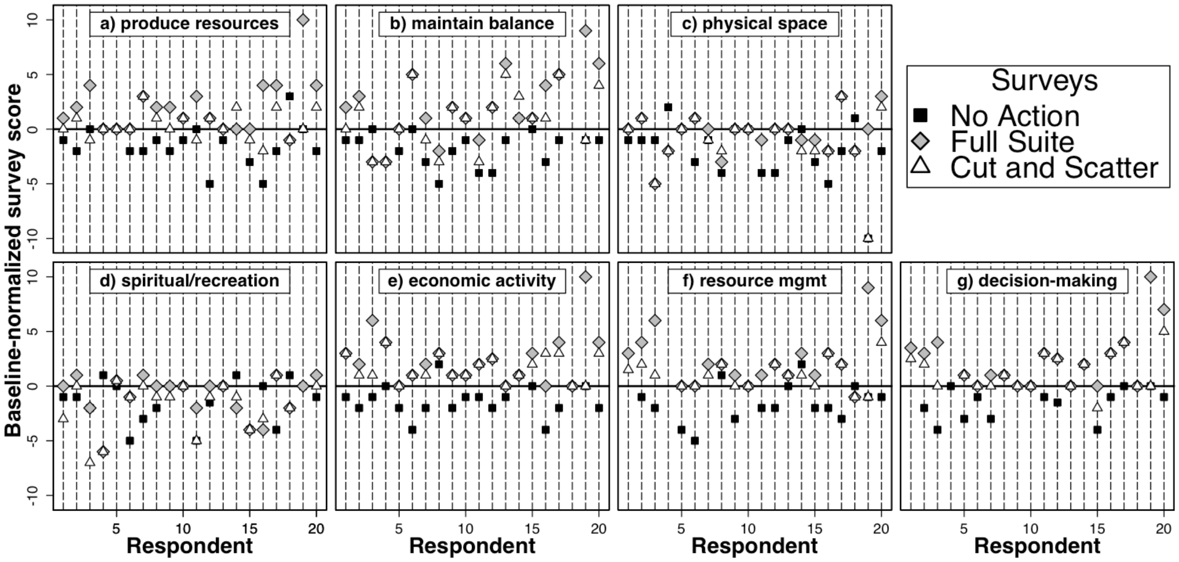


Figure 4.4. Participant responses to seven questions concerning the current state of Owyhee County (i.e., baseline) and the Bruneau-Owyhee Sage-Grouse Habitat (BOSH) project alternatives: no action, full suite, and cut and scatter. Displayed scored as baseline-normalized by subtracting the participant baseline score form his/her alternative score. Responses about alternatives were normalized to baseline scores (e.g. participant 1 baseline score is 7, full suite score is 8, and the baseline-normalized score is 1).

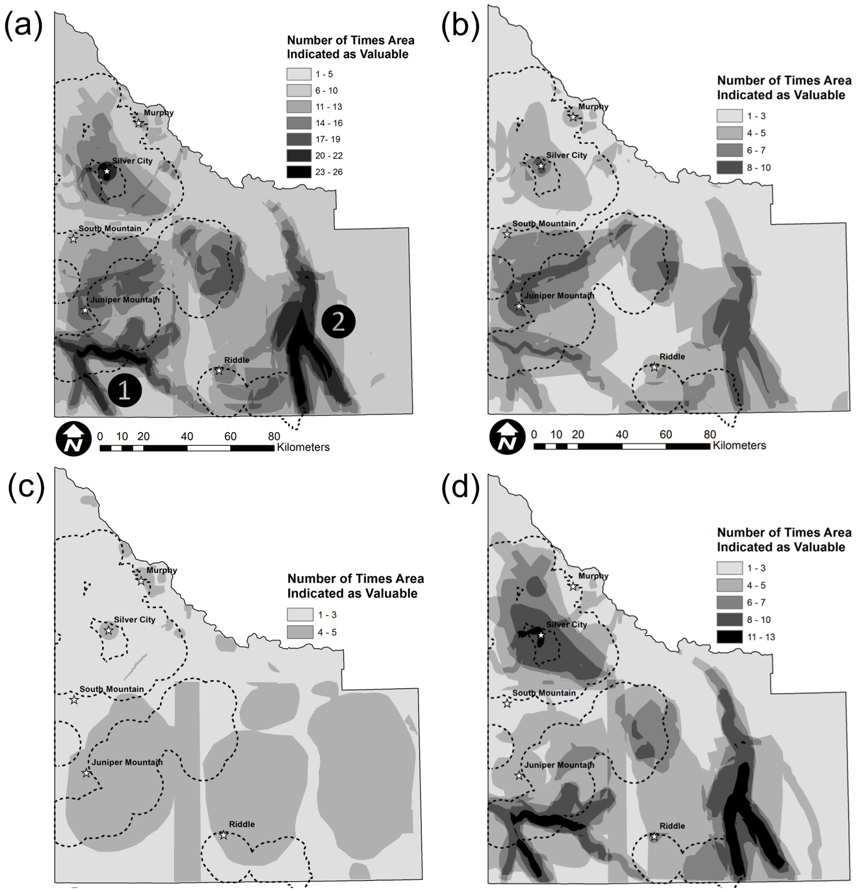


Figure 4.5. Frequency of the polygons derived for all values combined (a), social values (b), economic values (c), and ecological values (d) in Owyhee County, Idaho, USA. The proposed project boundary for the Bruneau-Owyhee Sage-Grouse Habitat (BOSH) project is indicated by the dotted lines. Point 1 and 2 in panel (a) indicate the Owyhee and Bruneau-Jarbidge watersheds and associated wilderness areas.

Dissertation Conclusion

The challenges that face semi-arid ecosystems in the western U.S. require managers to have both sufficient hydrologic knowledge and effective social-ecological impact assessments. The research to complete this dissertation helped develop knowledge in both of these arenas. The hydrologic research revealed that western juniper intercept a large portion of precipitation and that snow dynamics in western juniper produce tree wells that increase the amount of snow that is deposited at the base of trees compared to the interspace. This research also revealed that while increases in temperature shift surface water input to earlier in the spring, changes in land cover from sagebrush species to western juniper potentially has a greater impact on the amount of surface water input. The below ground hydrologic research revealed that juniper preferentially increase infiltration at their base. This research also revealed that western juniper can extract moisture at layers ass deep as 12 m below the surface – well into the saprolite and portions of the weathered bedrock. This information has implications for ecological dynamics in semi-arid systems as well as hydrologic impacts on changes in land cover from expansion or removal of western juniper.

The social science study developed a novel integrated social-ecological impact assessment. Not only that, but this assessment was implemented for a 1.75 million acre sage-grouse habitat project that primarily focused on western juniper removal near sage-grouse leks. This study revealed that both dialogue-based workshop coupled with a public participatory GIS workshop produces social and spatially complex information required to adequately assess how a land management action can impact people across a diverse society.

Several unanswered questions persist for hydrologic work related to semi-arid systems. First, the research in chapter 1 only included one storm and although chapter 2 spanned two water years of data, it only measured snow dynamics below juniper and in the interspace. Future work could compare snowpack dynamics between juniper and sagebrush across one or multiple water years and with different types of storms (e.g. low wind vs. high wind). Second, there is still a need to understand how increasing temperatures could alter interception and throughfall dynamics and specifically if shifts from snow to rain alter interception loss. Although average throughfall was greater in snow than in rain (Fig 2.1), this does not mean interception loss was lower in snow than in rain since snow redistribution confounded the ability to measure interception loss in snow. If it is in fact true that snow interception loss is greater than rain, this contradicts many current model assumptions that interception is greater in snow than in rain. Furthermore, while our simulations only included increases in temperature, future simulations could include both changes in temperature and changes in precipitation amount and intensity under future climate change.

The research on the impact of juniper on below-ground hydrologic processes was revealing, although several questions remain unanswered. First, while the research revealed that moisture is transpired by juniper from layers as deep as 12 m (Fig. 3.12, Fig. 3.13), this was only through a wet and dry season electrical resistivity tomography survey in a year with average precipitation and below average snowpack. Future studies could elucidate if juniper transpire moisture from these depth in years with wetter or drier conditions. Future work could also use moisture probes at deeper depths to understand temporal moisture dynamics at deeper layers and approximate what percentage of total plant water use is from moisture at deep layers. Furthermore, a process-based study that traces tree water use could ascertain to what extent infiltration funneled deeper in the soil profile by the juniper roots ends up as deep as 10 m and if that water is then used by the juniper. This process based research could also ascertain if sagebrush, which similar to juniper have deep tap roots, also increases deep infiltration through preferential flowpaths. This could be done with a similar paired study design that includes a probe directly below a sagebrush and in the interspace.

Although this research helps elucidate how hydrologic processes play out at the patch scale, which is important for ecological and wildlife processes, it will be essential to understand how theses process scale up and ultimately impact streamflow dynamics across a catchment. Chapters 1, 2, and 3 reveal that juniper “funnel” more water to their base through snow deposition and preferential flow. However, questions remain as to how these impacts play out at a larger scale. Specifically, does this impact result in appreciable increases (decreases) from juniper removal (encroachment) in sagebrush steppe? Previous work revealed that removal of semi-arid tree species in the southwest and Texas did not result in appreciable gains in streamflow. The implication is that changes in semi-arid tree cover does not impact the hydrologic scale at a larger scale. But these chapters reveal that in the northern Great basin where, contrary to the southwestern U.S. and Texas precipitation occurs primarily in the cold season, semi-arid trees alter the system’s hydrology at the patch scale. Research is required at a larger scale to elucidate if this impact persists at a watershed scale. Currently the Northwest Watershed Research Center has four instrumented juniper-dominated catchments approximately 60 miles south of Reynolds Creek Experimental Watershed that are aimed at answering just such these questions. One catchment has already undergone juniper cutting and prescribed fire in 2015 and plans exist to do the same treatment in another catchment in 2016. Results from this and other juniper studies in the northern Great Basin can reveal if hydrologic impacts of juniper cover change persist at a larger scale.

Finally, continued research is required to continue to improve integrated social-ecological impact assessments to greater fulfill the spirit of the National Environmental Policy Act. This could be accomplished in several ways. First, by developing a truly integrated social-ecological assessment. Our assessment integrated ecological aspects into our assessment, but an iterative processes that first assessed what aspects of a system are important to stakeholders, then assessed how those ecological aspects are changing, and finally presented this ecological assessment to stakeholder and assess how their well-being is impacted by these ecological changes. This could be an iterative process where the social sphere (stakeholders) informs the ecological assessment, and the ecological assessment informs how people perceive impacts of the land management action. This is a potentially cumbersome and difficult process, making it all the more important for further development of integrated social-ecological assessment that are both rigorous and easy to use by non-experts. Future research could conduct a more robust comparison of if social learning occurred with our impact assessment. Our research did not conduct before and after surveys, thereby assessing what social learning occurred. Furthermore, future analysis could compare how a dialogue-based social impact assessment such as ours compares to the quality and quantity of impact data acquired either from submitted responses to the scoping document or technical, quantitative analysis based on technical models.

Appendix A - Questionnaire used to solicit responses from the social-ecological impact assessment (Chapter 4)

Table A1. Deliberative workshop questionnaire, including seven questions related to ecosystem services and social processes. Participants completed the same questionnaire four times while considering the present state and potential future states of the Owyhees under the three project alternatives.

1. …the ability of the Owyhees to produce useful resources for people will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

2. …the ability of the Owyhees to maintain or restore its balance through physical, biological and chemical processes and interactions will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

3. …the availability of physical space and environmental conditions that are suitable for human activities will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

4. …the ability of the Owyhees to provide opportunities for spiritual enrichment, aesthetic enjoyment, contemplation, meditation and recreation will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

5. …the economic activity in the Owyhees – including the ways people make a living – will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

6. …the efficiency and effectiveness of organization(s) in and around the Owyhees that are responsible for the management or supply of the natural resources upon which stakeholders depend will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

7. …the ability of stakeholders to contribute to decision-making that affects their lives will be:

As bad as can be 1 2 3 4 5 6 7 8 9 10 As good as can be

Why?

8. Implementing this alternative in Wilderness areas within the project area boundary is (please circle one):

Extremely Unacceptable	Somewhat Unacceptable	Neutral	Somewhat Acceptable	Extremely Acceptable
Why?				

Appendix B - Summary of all responses and example quotations from the social-ecological impact assessment (Chapter 4)

Table B1. Response to the no action alternative, including potential changes to social processes and ecosystem services with related direction of impact and quote from deliberative workshop dialogue.

Social-ecological system characteristic	Direction of Impact	Potential Change	Example Quote
Economic Processes	Negative	Local economy – less opportunity	“[Local people might be] counting on the logging jobs.”
Economic Processes	No Change	Local economy – same opportunity	“[The BOSH proposal] does not deal with economic issues driving the Owyhees.”
Economic Processes	Negative	Tension on livestock operators	“The only thing for me that I perceive changing with a no action alternative would be the future economic activity in the Owyhees, including the way people make a living. With the potential listing of sage grouse, if sage grouse are listed, that puts an added tension on especially livestock operators, which is the major economic activity in the county.”
Institutional and legal processes	Negative	Disheartening to land managers	“So if you’re not going to do anything, it’s really disheartening to everybody that worked all those years, and biologists, and it’s in every plan, the Owyhee [Initiative], the Governor’s task force, the state plan. It would be a big discouragement to everybody.”
Institutional and legal processes	Negative	Endangered listing – Greater sage grouse	“But I think there’s, what I like to say is that, the impact to the people I think may not be as much related to, okay we’re going to have more juniper out there, but it may simply be how a (sage grouse) listing decision affects the community out there.”
Empowerment processes	Negative	Stakeholder collaboration – less opportunity	“There is a lot of agreement that some action is needed and if nothing happens, folks may feel disenfranchised.”
Empowerment processes	No Change	Stakeholder collaboration – same opportunity	“Collaboration efforts exist but litigation will always be a challenge.”
Provisioning	Positive	Impact to ecosystem	“More trees – cooler streams, let nature take its course.”
Provisioning	Negative	Decline of historic plant communities	“The resources itself – historic plant communities, those types of things, they’re going to decline.”

Processing	Negative	Ability to balance or restore landscape / ecological processes – more difficult	"…the ecological site condition will continue to deviate from the historical condition affecting watershed, range & grazing, wildlife."
Processing	Negative	Reduction of watershed functionality	"When juniper encroaches on springs and streams, it reduces their functionality. There's at least plenty of anecdotal evidence of juniper leading to springs drying up, reducing water output."
Supporting	Negative	Loss of biodiversity & habitat	"The area will lose diversity as juniper monocultures develop."
Supporting	Negative	Loss of sage grouse habitat	"Are we able to actually effectively manage the habitat for sage grouse to offset these big losses we're going to have?"
Cultural	Positive	Availability of areas without treatment for study	"And as far as not taking trees out, I think that would be great. I realize that it's actually maybe it gives you an area that you can actually do some studies to figure out what's going on because you haven't messed with this, you can have this area that hasn't had a treatment on it, maybe somebody can get in there and figure out what was really going on."
Cultural	Positive	General enjoyment of the Owyhees – improved	"Because there won't be this specific manipulation in wilderness."
Cultural	No Change	General enjoyment of the Owyhees – no change	"Action or no action will have minor effect if any"
Cultural	Negative	Loss of open space	"There would be loss of open space…you would lose the sagebrush views."
Cultural	Negative	Limits on recreation	"[Big impact to Owyhee County] on recreation…everything from motorized, which a lot of people use down there…no hunting season for the sage grouse."
Cultural	Negative	Less aesthetic enjoyment	"Aesthetic enjoyment would decrease for me [due to] loss of sagebrush/sage-steppe."
Cultural	Negative	Hunting – diminished	"Areas will have reduced value for human activity as juniper continues to expand = decreased recreation, hunting, decreased quality areas for wildlife."
Cultural	Negative	Spiritual experience - diminished	"I think the [spiritual] opportunities available now are a result of the landscape available if it changes these may cease to exist,"

Cultural	No Change	Spiritual experience – no change	“You know for me with the exception of the spirituality portion because I think you can find the spirituality of it whether they’re sagebrush, sage grouse, junipers – there’s a beauty in whatever aspect of it.”

Table B2. Response to the full suite alternative, including potential changes to social processes and ecosystem services with related direction of impact and quote from deliberative workshop dialogue.

Social-ecological system characteristic	**Direction of Impact**	**Potential Change**	**Quote**
Economic Processes	Positive	Local economy – more opportunity	“Grazing will be improved and juniper control could hopefully prevent ESA listing thereby preventing regulation and control of producers.”
Economic Processes	Positive	Ability to make a living - improved	“More jobs for loggers.”
Institutional and legal processes	No Change	Ability to make a living – no change	“I don’t see much in that change…the ability for people to actually make a living out there. If we’re focusing on just these Phase I, Phase II [juniper stands], visually, as I go out there, I’m not going to see that much of a difference. I’m not going to experience that much change because we’re talking about small scale.”
Institutional and legal processes	Positive	Management – improved	“Management would be better through active work on the ground.”
Institutional and legal processes	Negative	Management – worse	“And we have enough problems as it is and when we do stuff like that it makes us look even worse, especially this thing here…You know we have our plan it sounds great on paper, but when we don’t get the money from Congress or whatever to follow through, then we end up dealing with this next thing that happens.”
Institutional and legal processes	No Change	Management – no change	“The future of the efficiency – of the effectiveness of the management of our supply of natural resources aren’t going to change by us simply removing the junipers…at some point in time once the juniper are gone and we’ve created this habitat for sage grouse, let’s go back to doing something that’s not going to bring the juniper back again.”
Institutional and legal processes	Negative	Worsened agency reputation	“I work for the BLM, that’s my job. I’m not here representing the BLM, but I actually work for the BLM. And we have enough problems as it is and when we do stuff like that it makes us look even worse.”
Empowerment processes	Positive	Stakeholder collaboration – more opportunity	“People will see the fruits of the labor and will want to keep collaborating if their contributions are influencing positive change.”

Provisioning	Positive	Range and grazing - improved	“I think if it’s implemented, we’re trying to get this juniper removed, that will improve range conditions, and it will improve grazing. It will improve ranching operations. And I think if we’re able to use equipment and masticators and stuff, then we can have a bigger impact on juniper encroachment and reduce it at a bigger scale than what we’re limited to hand crews and stuff.”
Processing	Positive	Increased watershed functionality	“Increased watershed and overall ecological health.”
Processing	Negative	Increased fire danger	“But when it gets down to actually implementing it I’ll bet you we end up with a bunch of dead trees out there that look like crap that maybe you’re going to end up catching or actually causing the fire because now you’ve got all this dead wood that you’ve left lying around.”
Supporting	Positive	Increased biodiversity	“Taking action in areas where we will see the most positive + cost effective benefits = more habitat for wildlife, lands for hunting/recreation; hopeful treatment/action to improve sage-grouse habitat – keeping it from being listed, and more diversity.”
Supporting	Positive	Wildlife habitat – improved	“I think it’s agreed that sage grouse is kind of a keystone species that if the habitat is improved for them, deer and elk and a vast majority of other species kind of are also positively benefitted,”
Supporting	Negative	Wildlife habitat – degraded	“A lot of blue birds, chickadees other birds that are cavity nesters, they need junipers to nest in. So they would definitely be affected…” “One of the issues, if you do have a lot of mechanical treatment, you do have to worry about noxious weeds. And hopefully the outcome is good. And you do have to worry about soil disturbance. And also disruption of wildlife and if it’s a sensitive nesting time or things like that.”
Supporting	Positive	Sage grouse habitat - maintained/improved	“I think it’s agreed that sage grouse is kind of a keystone species that if the habitat is improved for them, deer and elk and a vast majority of other species kind of are also positively benefitted.”
Cultural	Positive	General enjoyment of the Owyhees – improved	“Increased diversity of animals and habitat will create better experiences for more people with

			diverse interests,"
Cultural	No Change	Solitude – no change	"I'm trying to keep in mind the scale of what we're talking about as far as Phase I, really early Phase II juniper. Yes, it'll be a success for us if we're actually able to do something out there, but as far as any other changes that are occurring, I guess personally I don't see much in that change… as far as… people's feeling of solitude."
Cultural	Positive	Hunting – improved	"Taking action in areas where we will see the most positive + cost effective benefits = more habitat for wildlife, lands for hunting/recreation; hopeful treatment/action to improve sage-grouse habitat – keeping it from being listed, and more diversity."
Cultural	Negative	Recreation – disrupted	"The treatment activities will be disruptive to recreationists for a period of time."
Cultural	No change	Recreation – no change	"For instance, well it hasn't changed the future physical space that's suitable for human activities. I guess it depends on what human activity you want. If the junipers are there, there's a human activity that can still be used whether it's watching birds or it's hunting whatever the case. You remove those junipers, to some degree, those human activities are still available – may not be the *exact* same."
Cultural	Positive	Viewshed – improved	"…for me personally, it would improve because I'd be able to go out to that lek and not see that juniper stand there anymore. So for me personally, I'm going to get to go out and be like, "Wow, this is awesome." I feel like we accomplished exactly what we set out to do. I can stand and look at those birds and not see the juniper in the background."
Cultural	Negative	Viewshed – degraded	"I know when I was at a Wildlife Refuge eight years ago, BLM came in around that area and cut down all the juniper trees, and they just laid there for years. And eventually they went and they started burning them up, but that was such a black eye for the BLM. The locals around there, they're all like, "Freaking waste." All these trees lay and it looked like crap."
Cultural	No Change	Viewshed – no change	"…the average Joe is still going to drive into Mud Flat Road and see exactly what they've always seen. They're not going to realize that on

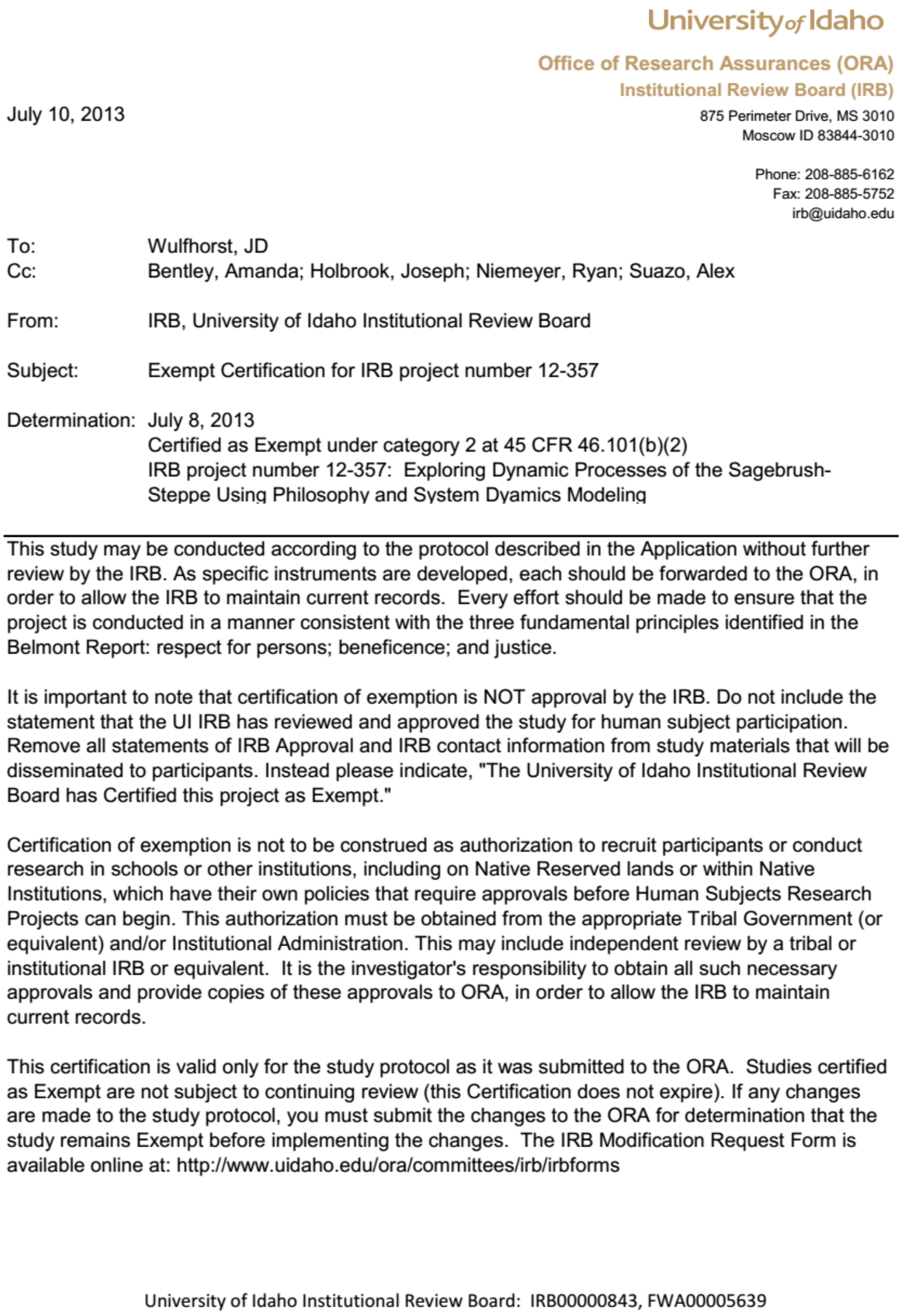
			the ground, there have been people that have been removing junipers out there to improve sage grouse, or for whatever. Most people aren't going to notice that."
Cultural	Positive	Spiritual experience - improved	"But for the scope of this project, it will improve my personal spirituality or whatever, if you will, because I can actually now visually see this – no more trees within this area, this lek, these encroaching junipers are gone,"
Cultural	No Change	Spiritual experience – no change	"Again I go back to the fact that I can find beauty in a butterfly on a juniper as easily as I can find beauty in a butterfly on a sagebrush. So that aspect of my spiritual portion of it doesn't change by the fact that we do or do nothing to it."
Cultural	Positive	Culture tied to cowboy & sage grouse - maintained	"It's not just the cowboy aspect. I love sage grouse, you know. And I think having all the tools available, having all the resources available is from the get-go probably the best option."

Table B3. Response to the cut and scatter alternative, including potential changes to social processes and ecosystem services with related direction of impact and quote from deliberative workshop dialogue.

Social-ecological system characteristic	**Direction of Impact**	**Potential Change**	**Quote**
Economic processes	Positive	Local economy – more opportunity	“More jobs.”
Economic processes	Negative	Weakening of local livelihoods	“BLM regulations would probably still be a limiting factor in ranching operations.”
Economic processes	Negative	Range and grazing – reduced	“Ranchers/cowboys would not do well grazing would be reduced / riding the range reduced.”
Institutional and legal processes	Negative	Management effectiveness – diminished	“The efficiency of management would be reduced since mastication and jackpot burns are useful tools for juniper encroachment,” and “So if those tools aren’t available, you may not treat the acres you’d like or as effective as you’d like.”
Empowerment processes	No Change	Stakeholder decision-making – no change	“A change is not possible – unless litigation process is changed.”
Provisioning	Positive	Ecosystem health and characteristics - improved	“In 5-15 years there would be some improvement in soil and water resources. Grasses would improve also.”
Provisioning	Positive	Increased water availability	“…getting that functioning ecosystem we can pretty much all agree on…without water, nothing functions…water is the sustaining thing of life, period.”
Processing	Positive	Watershed functionality - improved	“slowed on fields and hills” and when “you get snow blowing up against the back end or on the north face, then you’ve got extra protections.”
Processing	Negative	Increased fire danger	“…increased fire danger, fuel after it dries out, which would have a big negative impact,” and “I think leaving all the wood down is a fire hazard and probably has other environmental consequences.”
Supporting	Positive	Wildlife habitat – improved	“…at least we’re getting trees cut and slashed, and that’s great. That’s a lot better than doing nothing. A whole lot better, in my book, than doing nothing,” and “We’re talking about mostly Phase 1. We’re talking small trees – those can get dropped pretty darn low to the ground, and there won’t be a lot of fuel buildup in those areas. So there are going to be a lot of positives, even if

			that's what we were to do for the sage grouse."
Supporting	Negative	Sage grouse habitat - degraded	"…if it's [juniper branches] left lying there, the sage grouse are not going to walk through that probably either."
Supporting	Negative	Increased cover for sage grouse predators	"…it's cut and scatter, so that'll take some of the cover away. It'll leave more of the just the bowl, and the branches will be scattered out. But there's the potential it could create more cover."
Cultural	Negative	Viewshed - degraded	"Negative visual impact to the public. A pile of dead trees laying on the ground… it just doesn't look natural," and "I will see those trees still lying down in some areas that will not necessarily improve sage grouse habitat."
Cultural	No Change	General enjoyment of the Owyhees – no change	"Landscape features would be about the same as cut trees would take a long time to decay. If trunks are used for fire wood or other purpose this would help in this area."

Appendix C - Institutional Review Board Approval from the University of Idaho for implementing the social-ecological assessment (Chapter 4)



University of Idaho

Office of Research Assurances (ORA)
Institutional Review Board (IRB)
875 Perimeter Drive, MS 3010
Moscow ID 83844-3010

Phone: 208-885-6162
Fax: 208-885-5752
irb@uidaho.edu

July 10, 2013

To: Wulfhorst, JD
Cc: Bentley, Amanda; Holbrook, Joseph; Niemeyer, Ryan; Suazo, Alex

From: IRB, University of Idaho Institutional Review Board

Subject: Exempt Certification for IRB project number 12-357

Determination: July 8, 2013
Certified as Exempt under category 2 at 45 CFR 46.101(b)(2)
IRB project number 12-357: Exploring Dynamic Processes of the Sagebrush-Steppe Using Philosophy and System Dyamics Modeling

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This study may be conducted according to the protocol described in the Application without further review by the IRB. As specific instruments are developed, each should be forwarded to the ORA, in order to allow the IRB to maintain current records. Every effort should be made to ensure that the project is conducted in a manner consistent with the three fundamental principles identified in the Belmont Report: respect for persons; beneficence; and justice.

It is important to note that certification of exemption is NOT approval by the IRB. Do not include the statement that the UI IRB has reviewed and approved the study for human subject participation. Remove all statements of IRB Approval and IRB contact information from study materials that will be disseminated to participants. Instead please indicate, "The University of Idaho Institutional Review Board has Certified this project as Exempt."

Certification of exemption is not to be construed as authorization to recruit participants or conduct research in schools or other institutions, including on Native Reserved lands or within Native Institutions, which have their own policies that require approvals before Human Subjects Research Projects can begin. This authorization must be obtained from the appropriate Tribal Government (or equivalent) and/or Institutional Administration. This may include independent review by a tribal or institutional IRB or equivalent. It is the investigator's responsibility to obtain all such necessary approvals and provide copies of these approvals to ORA, in order to allow the IRB to maintain current records.

This certification is valid only for the study protocol as it was submitted to the ORA. Studies certified as Exempt are not subject to continuing review (this Certification does not expire). If any changes are made to the study protocol, you must submit the changes to the ORA for determination that the study remains Exempt before implementing the changes. The IRB Modification Request Form is available online at: http://www.uidaho.edu/ora/committees/irb/irbforms

University of Idaho Institutional Review Board: IRB00000843, FWA00005639