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Ecosystem Water Availability in Juniper versus Sagebrush Snow-Dominated Rangelands☆

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ABSTRACT

Western Juniper (*Juniperus occidentalis* Hook.) has greatly expanded in the past 150+ years and now dominates over 3.6 million ha of rangeland in the Intermountain Western United States. The impacts of juniper encroachment on critical ecohydrological relationships among snow distribution, water budgets, plant community transitions, and habitat requirements for wildlife, such as the greater sage grouse (*Centrocercus urophasianus*), remain poorly understood. The goal of this study is to better understand how juniper encroachment affects water availability for ecohydrologic processes and associated wildlife habitat in snow-dominated sagebrush (*Artemisia* spp.) steppe ecosystems. A 6-yr combined measurement and modeling study is conducted to explore differences in snow distribution, water availability, and annual water balances between juniper-dominated and sagebrush-dominated catchments. Although there is large interannual variability in both measured weather data and modeled hydrologic fluxes during the study, results indicate that juniper-dominated catchments have greater peak accumulations of snow water equivalent, earlier snow melt, and less streamflow relative to sagebrush-dominated catchments. Water delivery is delayed by an average of 9 days in the sagebrush-dominated scenario compared with the juniper-dominated scenario as a result of increased water storage in snow drifts. The delayed water input to sagebrush-dominated ecosystems in typical water years has wide-ranging implications for available surface water, soil water, and vegetation dynamics associated with wildlife habitat for sagebrush obligates such as sage grouse. Results from this study imply that the retention of high-elevation, sagebrush-dominated landscapes may become crucial for sage grouse habitat management if mid- and low-elevation precipitation continues to transition from snow to rain dominated.

Introduction

Western Juniper (*Juniperus occidentalis* Hook.) now dominates over 3.6 million ha of rangeland in the Intermountain Western United States (Miller and Tausch, 2001), much of which represents expansion from presettlement habitat (Tausch et al., 1981; Johnson and Miller, 2006; Miller et al., 2008). Juniper (*Juniperus* spp.) expansion into sagebrush (*Artemisia* spp.) ecosystems can influence the vegetation community (Bates et al., 2000; Miller and Tausch, 2001; Miller et al., 2005) and the hydrology and soil resources of an area (Pierson et al., 2007, 2010), which all affect wildlife habitat. Disentangling the ecological ramifications of the transition from sagebrush-dominated systems to juniper-dominated systems requires a holistic understanding of key interacting ecohydrologic feedbacks (Romme et al., 2009; Williams et al., 2016). These ecohydrologic transformations reduce habitat of key sagebrush indicator species, such as the greater sage grouse (*Centrocercus urophasianus*) (Connelly et al., 2011; Knick and Connelly, 2011). The effects of the transition from sagebrush-dominated to woodland-dominated landscapes on wildlife habitat have been well established in the literature (Connelly et al., 2011), and critical ecological relationships between vegetation and hydrologic processes have emerged (Petersen et al., 2009; Pierson et al., 2010, 2013; Williams et al., 2014, 2016). However, a coherent understanding of feedback among vegetation, hydrology, and habitat remains tenuous (Blomberg et al., 2012; Guttery et al., 2013; Donnelly et al., 2016).

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Sage grouse require a mosaic of mature shrubs and tall grasses for cover and a balanced composition of herbaceous species and sagebrush to provide forage during their annual life cycle stages (Connelly et al., 2000, 2011). Plant community composition, structure, and productivity are all strongly coupled with the timing and amount of ecosystem water availability (Flerchinger et al., 1998, 2010; Rodriguez-Iturbe, 2000; Ryel et al., 2010; Chauvin et al., 2011; Roundy et al., 2014b). Sagebrush and herbaceous productivity is strongly tied to soil water recharge deep in the soil profile (Cline et al., 1977; Sturges, 1977; Richards and Caldwell, 1987; Caldwell and Richards, 1989; Ryel et al., 2004; Schlaepfer et al., 2012). Sage grouse also require seasonal high-elevation wet meadows, riparian areas, springs, and the associated forbs for late brood rearing in late summer/early autumn seasons (Connelly et al., 2011; Hammersmark et al., 2008; Loheide et al., 2009; Loheide and Gorelick, 2007). The sustainability of wet meadows, riparian areas, and springs is also intimately linked to the timing and magnitude of water delivery to the landscape (Whiting and Godsey, 2016).

Juniper impacts sage-grouse directly by changing the vegetation structure and creating overhead perches for predators (Casazza et al., 2011) but might also have indirect effects via altering the hydrologic behavior of an area (Blomberg et al., 2012; Guttery et al., 2013; Donnelly et al., 2016). There is a common perception that juniper encroachment can lead to a loss of surface water, but there is little science to quantify these changes. The ecohydrologic impacts of tree encroachment on soil water dynamics have been described and quantified (Miller et al., 2005; Mollnau et al., 2014; Roundy et al., 2014b). Junipers have competitive advantages over intercanopy herbaceous species in terms of soil water extraction, including extensive root systems capable of soil water redistribution (Breshears et al., 1997, 1998; Miller et al., 2000, 2005; Newman et al., 2010). Most of the woodland encroachment research dealing with impacts on soil water dynamics have focused on changes following juniper removal (Bates et al., 2000; Young et al., 2013; Mollnau et al., 2014; Roundy et al., 2014b), which may be influenced by the short-term flush in herbaceous vegetation immediately following tree removal (Miller et al., 2014; Roundy et al., 2014a).

The links between ecosystem water availability and the redistribution of snowfall are critical but understudied components in the literature regarding ecohydrologic impacts of juniper encroachment. Plant community transitions from sagebrush to juniper woodlands in the Intermountain West commonly occur on sites with snow-dominated precipitation regimes. Wind and topography in these uplands interact to redistribute falling snow, while vegetation reduces wind velocities (Burke, 1989; Marks and Winstral, 2001; Marks et al., 2001, 2002; Winstral and Marks, 2002). The reduction of wind speeds caused by trees both promotes the deposition of snow and decreases turbulent fluxes that melt snow.

Vegetation-snow feedbacks produce consistent ecosystem characteristics such as growing season length, soil temperatures, species composition, and primary production (Hiemstra et al., 2006). Deeper snow accumulation commonly benefits plant productivity by providing greater insulation for, and prolonged water delivery to, the soil profile (Sturm et al., 2001; Liston et al., 2002).

For snow-dominated semiarid uplands, knowing how and where snow accumulates and melts is crucial in the understanding the distribution of catchment water inputs, available soil water, and the timing and amount of streamflow (Flerchinger et al., 1998; Flerchinger and Cooley, 2000; Seyfried et al., 2009; Williams et al., 2009). The distribution of snow on the landscape may also be the best predictor of spatial and temporal patterns in soil moisture in semiarid snow-dominated sagebrush catchments (Williams et al., 2009). Both the vegetation-affected distribution of snow and the snowmelt-driven water delivery control catchment streamflow initiation, volume, and recession (Flerchinger and Cooley, 2000; Luce et al., 1998; Luce and Tarboton, 2004; Seyfried et al., 2009; Williams et al., 2009). Snow distribution differences between sagebrush- and woodland-dominated landscapes are therefore key links for understanding differences in water availability for plant communities and wildlife.

The goal of this study is to better understand how juniper encroachment affects water availability for ecohydrologic processes and associated wildlife habitat in snow-dominated sagebrush steppe systems. Our specific research questions are: 1) What are the differences in snow distribution and water delivery to the landscape between juniper-dominated and sagebrush-dominated catchments, 2) What is the effect of those differences on the catchment water balance and streamflow, and 3) What are the implications of tree-induced changes on water availability and those effects on sagebrush steppe ecosystem dynamics? To address these research questions we performed a combined measurement and modeling study to quantify snow distribution, water delivery to the landscape, and streamflow for four rangeland watersheds currently in the late stages of juniper encroachment (juniper-dominated) and for the same watersheds with a mosaic of sagebrush and herbaceous vegetation (sagebrush-dominated).

Study Site and Measured Data

The study area consists of four catchments referred to herein as the South Mountain Experimental Catchments. The catchments are located (−116.90°W, 42.67°N) on South Mountain in the Owyhee Mountains just east of the Idaho-Oregon border (Fig. 1). Precipitation at the study area is snow dominated (Fig. 2). The study spans 6 water yrs (WY) (1 October to 30 September) from WY2008 to WY2013, which provide a range of weather conditions typical for this region. The 6-yr water year average precipitation is 620 mm, with WY2011 being the wettest year with 867 mm and WY2012 being the driest year with 445 mm (Table 1). Average annual air temperature for the study area is 7.0°C (Table 2). The prevailing wind direction during precipitation is from the west (274°). The drainage areas and relief for the four catchments range from 20 to 70 ha and 1665 to 1898 m, respectively (Table 3). Mean hillslope gradients across the four catchments range from 18% to 23%. The study area spans multiple ecological sites, each with sagebrush as the dominated shrub component for the reference community. Currently, vegetation in each of the catchments is primarily juniper-dominated, with significant canopy closure. Soils are classified mostly as well-drained gravelly loams, which is supported by observations (NRCS, 2016).

Four drop box v-notch weirs (Bonta and Pierson, 2003) and six weather stations were installed at the South Mountain Experimental Catchments from 2006 to 2008 with the purpose of studying the ecohydrologic response of juniper-dominated sagebrush steppe systems to juniper removal. Each weather station records precipitation mass, wind speed and direction, air temperature, relative humidity, and incoming solar radiation at an hourly interval. Snow depth is also recorded every 15 minutes at each station using ultrasonic sensors. Manual measurements of snow water equivalent (SWE) were made two to three times each year at snow courses near the six weather stations. In addition, mean densities from four intensive snow surveys were used with automated snow depth values to obtain additional SWE model validation values.

A Lidar dataset acquired in November 2007 before snowfall provides an accurate 1 m^2 snapshot of bare earth elevation and vegetation structure for each of the study catchments (Sankey et al., 2013). The Lidar point density was 7 points per square meter resulting in a vertical accuracy of approximately 3 cm. All Lidar processing was done using tools developed by the Boise Center Aerospace Laboratory (BCAL, 2016). In addition to Lidar-derived vegetation heights, a manual vegetation survey at three randomly located 30 × 30 m plots in each of the four study catchments was conducted in August 2008. Heights of all junipers >1 m within each plot were measured, and the heights of all shrubs and junipers <1 m were recorded along five transects within the plots (Fig. 3).

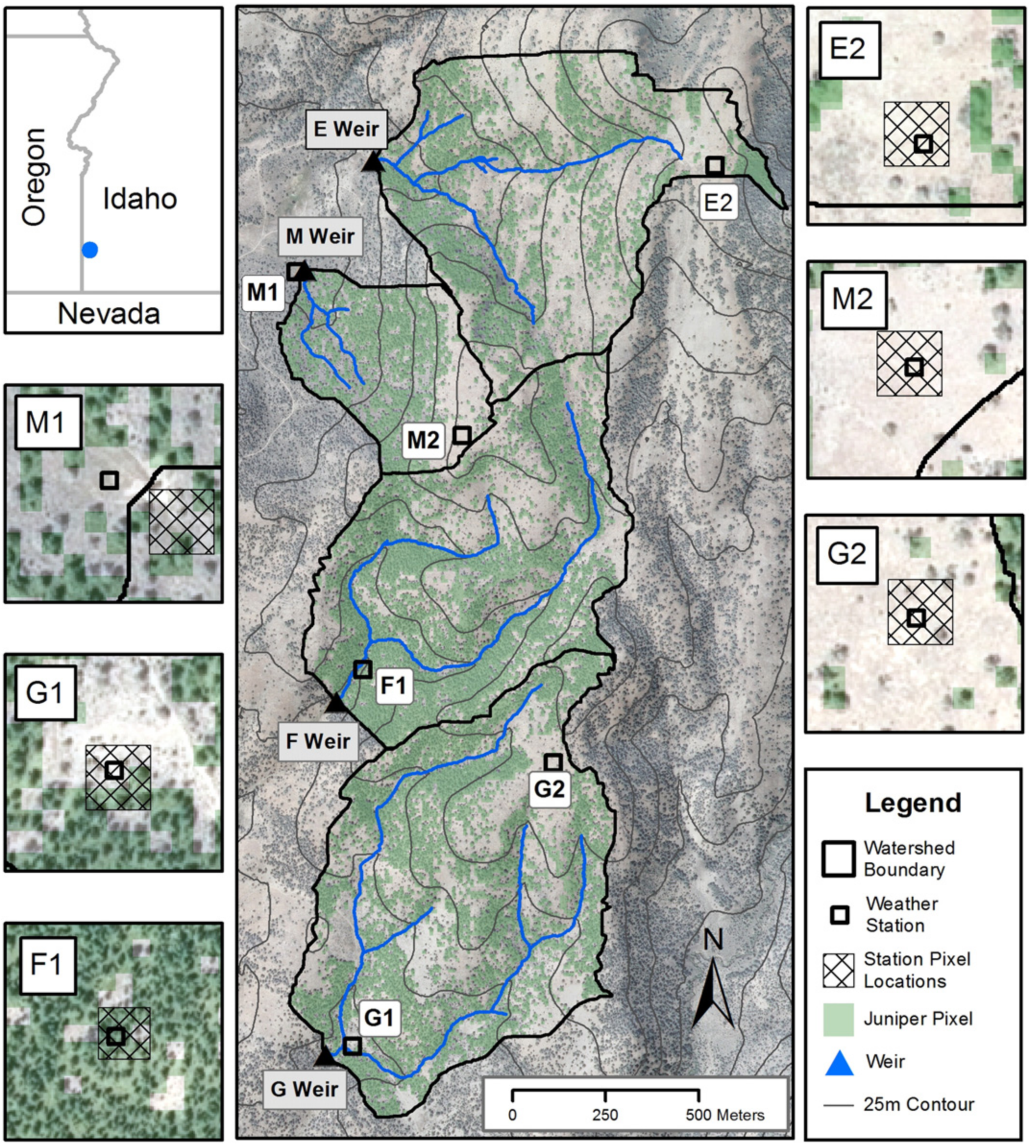

Figure 1. Location map of the South Mountain Experimental Watersheds showing the location of the four weirs that define catchments E, F, G, and M and the six weather stations (E2, F1, G1, G2, M1, and M2). Close views of each weather station include model pixels classified as juniper dominated and the location from which model results were extracted to compare to measurements.

Methods

Distributed snowpack accumulation and melt are modeled for the South Mountain Experimental Catchments with the present late-succession juniper conditions (juniper-dominated scenario) and for conditions with a mosaic of sagebrush vegetation (sagebrush-dominated scenario). Water availability for each study catchment under both conditions is assessed by a combination of time series modeling (water delivery to the soil surface) and the derivation of annual water budgets through a water balance approach.

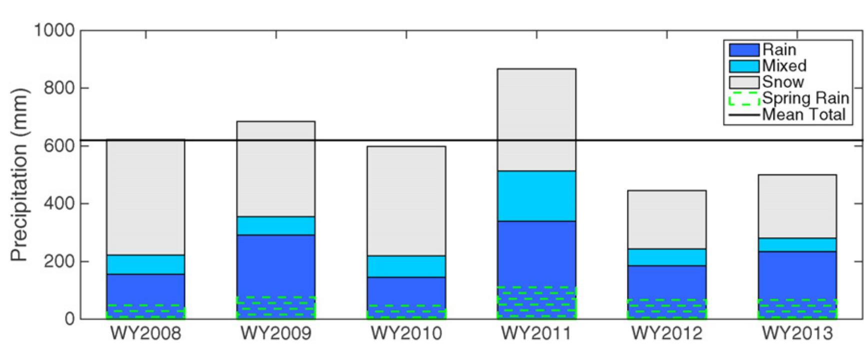

Figure 2. Water year precipitation measured at the six weather stations showing the proportion of rain, snow, and mixed events. The dashed area of the rain bar depicts the amount of spring rains (1 March to 30 May) received that year. The mean water year precipitation total for the 6 years of this study was 620mm.

Table 1
Measured (meas) and modeled (mod) water year water precipitation (precip) and water balance terms (snow water input [SWI], streamflow [Q], evapotranspiration [ET]) for the South Mountain Experimental Catchments (SM). The weighted *P* value (p-val) from paired *t*-tests is included as a performance measure of the ET modeling (Flerchinger et al. in press), indicating that none of the simulations were significantly different from measured values at the $\alpha = 0.05$ level. Precipitation is also shown for Upper Sheep Creek (USC) subcatchment of the nearby Reynolds Creek Experimental Watershed. Juniper-dominated ET is calculated as the residual (resid) of the water balance.

	Measured precipitation		Juniper-dominated scenario				Sagebrush-dominated scenario			
Water	Precip SM	Precip USC	Precip	SWI	Q	ET	Precip	SWI	Q	ET (p-val)
Year	(meas, mm)	(meas, mm)	(mod, mm)	(mod, mm)	(meas, mm)	(resid,mm)	(mod, mm)	(mod, mm)	(resid, mm)	(mod, mm)
2008	623	523	675	652	144	508	562	546	258	288 (0.61)
2009	685	589	705	688	110	578	619	607	240	367 (0.37)
2010	622	615	658	634	144	490	543	524	101	423 (0.65)
2011	867	745	927	908	222	686	825	806	357	450 (0.13)
2012	445	432	490	479	48	431	430	422	191	231 (0.07)
2013	474	463	529	516	23	492	465	455	124	331 (0.73)
All years	620	561	664	646	115	531	574	560	212	348 (0.43)

Snow Modeling

The *iSnobal* model (Marks et al., 1999a,b) uses the catchment topography and distributed meteorological forcings to estimate the snow accumulation and melt. *iSnobal* is a physically based mass and energy model that has been extensively applied to investigate snow physics, processes, and the distributed melt patterns in similar areas in the Owyhee Mountains (Marks and Winstral, 2001; Marks et al., 2001, 2002; Winstral and Marks, 2002, 2014; Seyfried et al., 2009; Nayak et al., 2011; Kumar et al., 2013; Reba et al., 2014; Rasouli et al., 2015) and forested areas (Marks et al., 1998; Link and Marks, 1999; Garen and Marks, 2005). The model produces estimates of SWE, snow melt, and surface water input (SWI), which is the combined liquid water drainage leaving the bottom of the snow pack and rain on the ground surface. Input data required by the model include precipitation and available energy. The use of a complex, physically based snow model is necessary to be able to sufficiently parameterize vegetation differences between juniper- and sagebrush-dominated catchments. The energy balance of the snowpack at each model pixel is expressed as:

$$\Delta\mathcal{H} = (R_{net} + H + L_vE + G + M)\Delta t \quad (1)$$

where $\Delta\mathcal{H}$ is change in snowpack energy; and R_{net}, H, L_vE, G, and M are net radiative, sensible, latent, conductive, and advective (from precipitation) energy fluxes, respectively (Marks et al., 1992); and Δt is the time step. The model requires spatially distributed net solar, incoming thermal, air temperature, vapor pressure, wind speed, soil temperature, and precipitation. *iSnobal* represents the snowpack as a two-layer system, with a fixed-thickness surface layer, and a variable thickness lower layer representing the remainder of the snow cover. The model computes outgoing thermal radiation to get R_{net} and solves for the rest of the energy balance. If $\Delta\mathcal{H}$ is negative, the snow will cool, increasing its cold content, or the amount of energy required to bring the snow to 0°C. If $\Delta\mathcal{H}$ is positive, the snow will warm, reducing its cold content. Once the snow is at 0°C, the cold content is zero and any addition of energy will result in melt. If the addition of liquid water to the snow by either melt, or rain exceeds 1% (Davis et al., 1985), the excess is released to the soil as SWI. If the ground is not snow covered, the model passes precipitation that falls as rain to the soil as SWI.

We apply *iSnobal* at an hourly time step on a 10-m DEM created by resampling the 1-m Lidar-derived bare earth elevation model. This resolution optimizes our ability to capture vegetation and topographic differences while maintaining sufficient computational efficiency. Mean daily SWE and SWI are derived from respective model outputs for the four study catchments and compiled in a time series dataset. The total SWI for the WY is used in conjunction with measured data to develop annual water balance estimates as described in the water balance subsection.

Juniper effects on snow accumulation and melt are accounted for in *iSnobal* by classifying model pixels as being juniper-dominated, juniper-sheltered, forest opening, or open. The lidar-derived 1 m^2 mean vegetation height map was classified as juniper or no juniper using a 1.5-m threshold based on the manual vegetation height surveys (*see* Fig. 3) (Sankey et al., 2013). This threshold was chosen to minimize the classification of any other vegetation as juniper. Model pixels (10×10 m, a 100 m^2 area) were classified as juniper dominated if at least one-third (33) of the 1-m^2 Lidar cells were classified as junipers. This conservative threshold is chosen on the basis of a comparison between collocated NAIP imagery and the 10-m pixel classification. Higher thresholds excluded many pixels with large junipers, while lower thresholds overestimated the juniper coverage of the basin. Maximum canopy height is calculated as the mean of the 1-m Lidar-derived maximum vegetation heights classified as juniper. Model pixels are classified as forest openings if at least five of the eight surrounding pixels are classified as juniper-dominated (Winstral and Marks, 2002). Juniper-sheltered pixels are defined for each of the cardinal wind directions and are on the lee side of a pixel classified as juniper dominated.

Several variables used to run the snow model are affected by junipers, including snow accumulation, surface wind speeds, net solar radiation, and incoming thermal radiation. These effects and the parameterization of model-forcing data to account for them are described later in the associated subsections.

Table 2
Water year precipitation-weighted wind speed and direction and water year average air temperature.

Water year	Wind speed	Wind direction	Air temperature
	($m\ s^{-1}$)	(deg)	(°C)
2008	2.06	280	6.4
2009	2.03	271	7.2
2010	1.91	272	6.0
2011	1.88	274	6.7
2012	2.12	267	8.0
2013	2.13	280	7.4
All years	2.00	274	7.0

Table 3
Watershed areas, the percent of the pixels classified as juniper-dominated, elevation ranges, and mean slopes. Mean catchment elevations are in parentheses.

Watershed	Area	Juniper cover	Elevation range	Mean slope
	(ha)	(%)	(m)	(%)
E	56.7	42	1704-1898 (1793)	23
F	56.6	61	1687-1815 (1748)	23
G	70.2	53	1693-1814 (1758)	21
M	21.0	54	1665-1791 (1723)	18

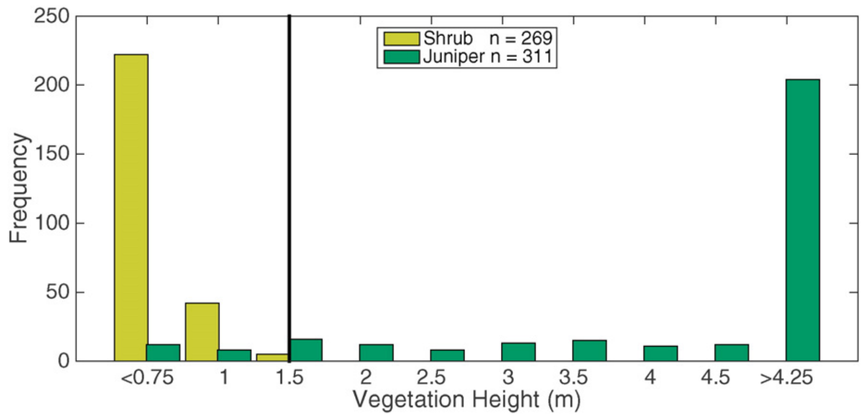

Figure 3. Histogram of measured vegetation heights of junipers and shrubs. The vertical black line shows the 1.5 m cutoff used in this study to classify junipers.

Solar Radiation

Clear sky incoming solar radiation and snow albedo are calculated using the Image Processing Workbench (IPW) software package utility *stoporad* (Frew, 1990; Marks et al., 1999b). *Stoporad* accounts for the interaction of measured topography, calculated sun angle, and empirically derived snow grain size based on the time from last snowfall (Dozier, 1980; Dozier and Frew, 1981; Dubayah, 1994. Incoming solar radiation and albedo are split into visible ($0.28 - 0.70\ \mu$m) and near infrared ($0.70 - 2.8\ \mu$m) wavelengths to better model the effects of albedo differences in those wavelengths (Marshall and Warren, 1987). Both visible and near infrared incoming solar radiation are further split into beam and diffuse portions to better account for vegetation shading affects. Incoming solar radiation is corrected for cloud cover using the clear sky fraction, or the ratio of measured incoming solar radiation and modeled clear sky radiation at weather stations E2, G2, and M2 (see Fig. 1). Surrounding vegetation affects incoming solar measurements at the other weather stations. Cloud-corrected incoming solar radiation is used for the sagebrush-dominated scenario. Juniper canopy effects are then accounted for in pixels classified as juniperdominated using the maximum vegetation height for each model pixel, an optical transmissivity of 0.16 and an extinction coefficient of 0.074 m^{-1} equivalent to dense conifer (Link and Marks, 1999). In addition, late-season albedo values are decreased to account for juniper litter accumulation on the snow surface (Marks and Winstral, 2001; Winstral and Marks, 2002; Kormos et al., 2014).

Thermal Radiation

Incoming clear sky thermal radiation is calculated using elevation and humidity data and corrected for surrounding topography (Marks and Dozier, 1979). Those values are corrected for cloud cover using a measured relationship between the clear sky fraction from the nearby Reynolds Mountain East subcatchment, 45.5 km from the study site within the Reynolds Creek Experimental Watershed (RCEW). This relationship is then applied to the South Mountain Experimental Catchments using the locally calculated clear sky fraction (Reba et al., 2011). Cloud corrected incoming thermal radiation is used for the sagebrush-dominated scenario. Juniper canopy effects are represented by assigning a canopy transmissivity of 1 to open areas, 0.16 to pixels classified as juniper, and 0.75 to forest openings (Link and Marks, 1999; Winstral and Marks, 2002). Incoming thermal radiation from the canopy is calculated using the Stefan Boltzman equation with a canopy emissivity of 0.96 assuming that the measured air temperature was equivalent to the canopy temperature.

Precipitation

Measured hourly precipitation at the six weather stations is distributed by detrended kriging if it is classified as rain or mixed phase precipitation events based on dew point temperature (Garen et al., 1994; Garen, 1995; Marks et al., 2013). The distribution of snow events account for wind redistribution as a function of wind speed, wind direction, topography, and vegetation (Winstral et al., 2013).

The degree of topographic or canopy sheltering or exposure, with subsequent scour or deposition and drifting, was achieved using methods developed by Winstral and Marks (2002) that have been successfully applied across many mountain environments in North America (Winstral et al., 2009, 2013; Winstral and Marks, 2014). As discussed in the cited papers, the wind field is derived from the maximum upwind slope parameter. The wind flow separation, or the wind behavior that promotes drifting to occur, is described by the slope break parameter. These parameters are calculated from the 10-m digital elevation model using the procedures described by Winstral and Marks (2002). Accumulation ratios are calculated as a function of the exposure of each model pixel to define drift and scour zones (Winstral et al., 2013). Accumulation ratios for pixels located in areas defined as drift zones are calculated as a function of measured wind speed (Winstral and Marks, 2014). A minimum accumulation ratio of 1.1 and a maximum of 4.2 is imposed on pixels within drift zones. Accumulation ratios in model pixels outside the drift zones vary between 0.0 and 1.0.

Juniper effects on precipitation distribution are accounted for by modifying the accumulation ratios in pixels defined as juniper dominated or juniper sheltered. Juniper-dominated and juniper-sheltered pixels are assigned an accumulation ratio of 1.0 (Winstral and Marks, 2002). Pixels in drift zones are assigned the drift accumulation ratio regardless of vegetation classification. The precipitation distribution is then obtained by multiplying the distributed accumulation ratio by wind-corrected, measured precipitation at station E2. We chose E2 on the basis of the fact that vegetation influences are minimal and it measured the most precipitation most often (23% of the time).

Wind

Measured wind speeds are distributed across South Mountain for each time step as a function of measured wind direction and vegetation and topographic sheltering or exposure to get the juniper model wind field (Winstral et al., 2009, 2013). Wind distributions for the sagebrush-dominated scenario are obtained by increasing measured wind speeds using a relationship between wind speeds measured at a semivegetation sheltered site and from a fully wind-exposed ridge site at the nearby RCEW (Fig. 4). The RCEW semisheltered site is similar to weather stations E2, M2, and G2 in that it is on a ridge with a few large trees close to it. We expect this increase in wind speed as a result of a reduction of the near surface roughness for a modeling domain without junipers. The increased wind speeds are then distributed across South Mountain for each hour as a function of topographic sheltering and exposure.

Water Balance

We used a simple annual water balance to demonstrate the differences in water delivery to juniper- and sagebrush-dominated catchments:

$$SWI = ET + Q \quad (2)$$

where SWI is the modeled surface water input, which includes snowmelt, rain draining through the snow, and rain on snow-free surfaces. *ET* is evapotranspiration, and *Q* is stream discharge. SWI values account for evaporation from the snow surface.

ET is estimated for juniper-dominated scenarios as the difference between modeled SWI and measured Q. A range of ET values for the sagebrush model scenario is obtained from a well-validated measurement (eddy covariance and soil moisture) and modeling exercise from low sagebrush (*A. arbuscula* Nutt. subsp. *arbuscula*) and mountain big sagebrush (*A. tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle) vegetation communities in the Upper Sheep Creek subwatershed (USC) of RCEW (Flerchinger, 2016). These ET values are available for the same water years and similar elevation (1837 − 2023 m), weather, and precipitation conditions as in this study (see Table 1). Simulated weekly ET from mountain big sagebrush was not significantly different from eddy covariance system measurements for any of the six WYs (mean P value 0.546, $\alpha = 0.05$). Simulated weekly ET from low sagebrush was not significantly different from soil moisture mass balance calculations of ET for 4 of the 6 WYs, with WY2010 and WY2011 showing significant differences (mean P value 0.396). For simplicity, we present the results of the mass balance portion of this study assuming a vegetation distribution of 20% mountain big sagebrush and 80% low sagebrush. This distribution is based on 1) mountain big sagebrush occurs where drifts occur; 2) 10% of the catchment is classified as drift zones using a wind direction of 274°, the mean direction during storms; and 3) increases in water inputs from that 10% drift area may support an additional 10% of the catchment to develop mountain big sagebrush. The other 80% of the catchment is assigned ET values of low sagebrush communities that require less water. This exercise is supported by observations of vegetation structure and drift locations at USC (Flerchinger and Cooley, 2000).

Q for the juniper-dominated scenario is measured at the four weirs. Q for the sagebrush-dominated scenario is calculated as the difference between sagebrush-dominated modeled SWI and ET values from USC with the assumed vegetation distribution. Runoff ratios are calculated as the ratio of measured or calculated Q to modeled total basin SWI from juniper-dominated and the sagebrush-dominated scenarios.

Fortuitously, interception-induced losses to evaporation in this region are not a large component of the annual water balance and are not considered for this exercise. Losses from the interception of rain are assumed negligible due to the timing difference between high evaporative demand in the summer and high precipitation in the winter. Though both trees and shrubs intercept snow, the combination of moderate temperatures and generally sunny and/or windy conditions following storms leads to intercepted snow sloughing off and becoming either melt water drip, or accumulations of wet snow at the base of the canopy. Additional discussion and an evaluation of the implications of this assumption are addressed in the discussion section.

The melt-out date of the four catchments is the first day of the WY that the modeled basin averaged SWE is zero after peak accumulation. The timing of water delivery to the four study catchments is evaluated using the WY day when 75% of the modeled SWI enters the catchments. We chose 75% to highlight late-season differences in water availability related to snow distribution. Higher percentages (later differences) are more spring rain dependent, which have identical distributions for the juniper- and sagebrush-dominated scenarios. The difference between this metric for juniper- and sagebrush-dominated scenarios provides a measure of how much longer water is available for a sagebrush-dominated catchment than a juniper-dominated catchment.

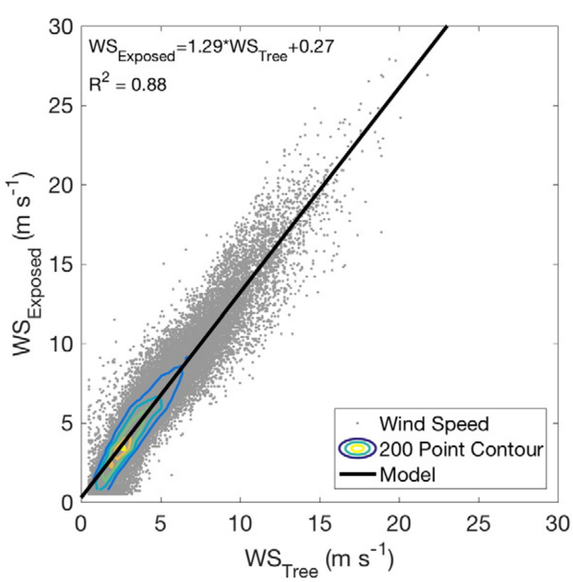

Figure 4. Relationship between two wind speed (WS) measurement sites at Reynolds Creek Experimental Watershed used to account for increased wind speeds in the sagebrush-dominated scenario. $WS_{Exposed}$ is a wind measurement site on an exposed ridge with no surrounding vegetation. WS_{Tree} is a wind measurement site on a ridge and partially sheltered by trees. Contour lines depict point density based on a 0.5 ms^{-1} square grid.

Results

Snow Accumulation and Melt Patterns

The modeled accumulation and melt of snow for the juniper-dominated scenario reasonably matches SWE measurements near the six weather stations (see Figs. 1 and 5). The snow model over predicts SWE near weather station F1, which has the most juniper cover from WY2008 to WY2011 (see Figs. 1 and 5, Table 3). These years are characterized by normal or above normal precipitation (see Fig. 2, Table 1). Modeled SWE near weather stations E2 and M2, which have sparser juniper cover, are underestimated for all years. Although the data available to assess model performance are limited, results indicate that the snow system is represented well, and that they can help us to better understand how juniper encroachment affects snow deposition and water availability in these systems.

Basin average SWE from the juniper-dominated scenario has a greater accumulation and melts out an average of 18 days earlier than the sagebrush-dominated scenario (Fig. 6). The greater SWE accumulation for the juniper-dominated scenario is a result of modeled differences in precipitation distributions (see Table 1), where pixels classified as juniper dominated or juniper sheltered trap more snow than pixels that are not juniper dominated. The shortest melt-out timing difference across catchments was WY2011, which had a mean of 1.75 days. Catchment F had the lowest difference in melt-out timing across all years with an average of 11 days.

Earlier melt-out and greater accumulation from the juniper-dominated scenario are reflected in the modeled cumulative basin SWI time series (Fig. 7). The WY day that 75% of the total SWI has

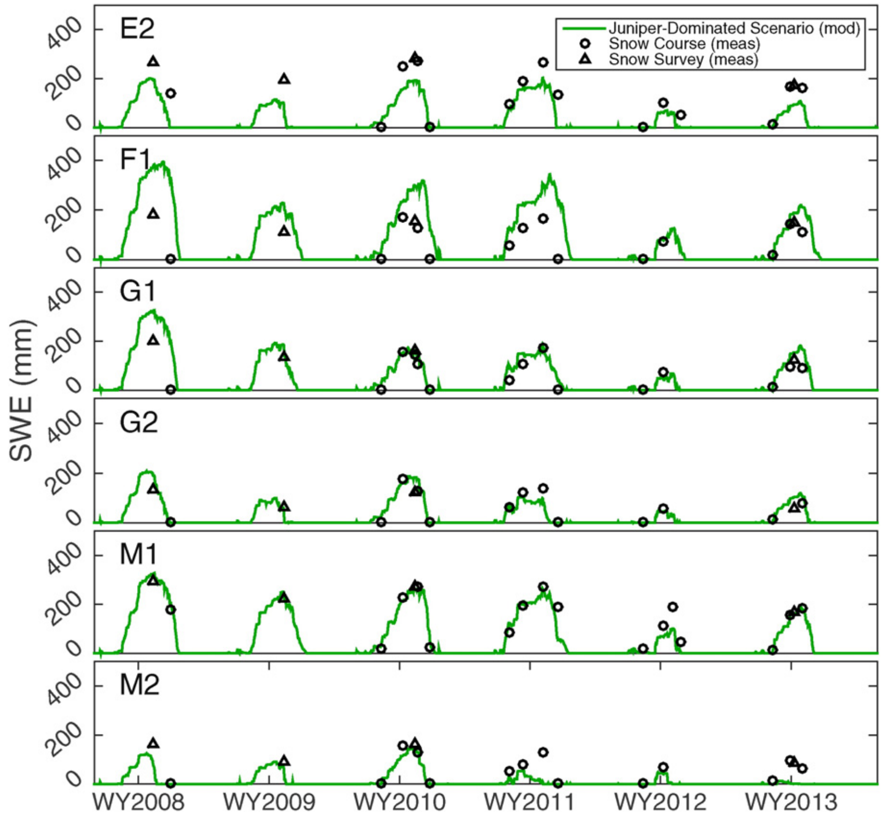

Figure 5. Measured (meas) snow water equivalent (SWE) points (black circles and triangles) and modeled (mod) SWE (green lines) near the six weather stations in the South Mountain Experimental Catchments.

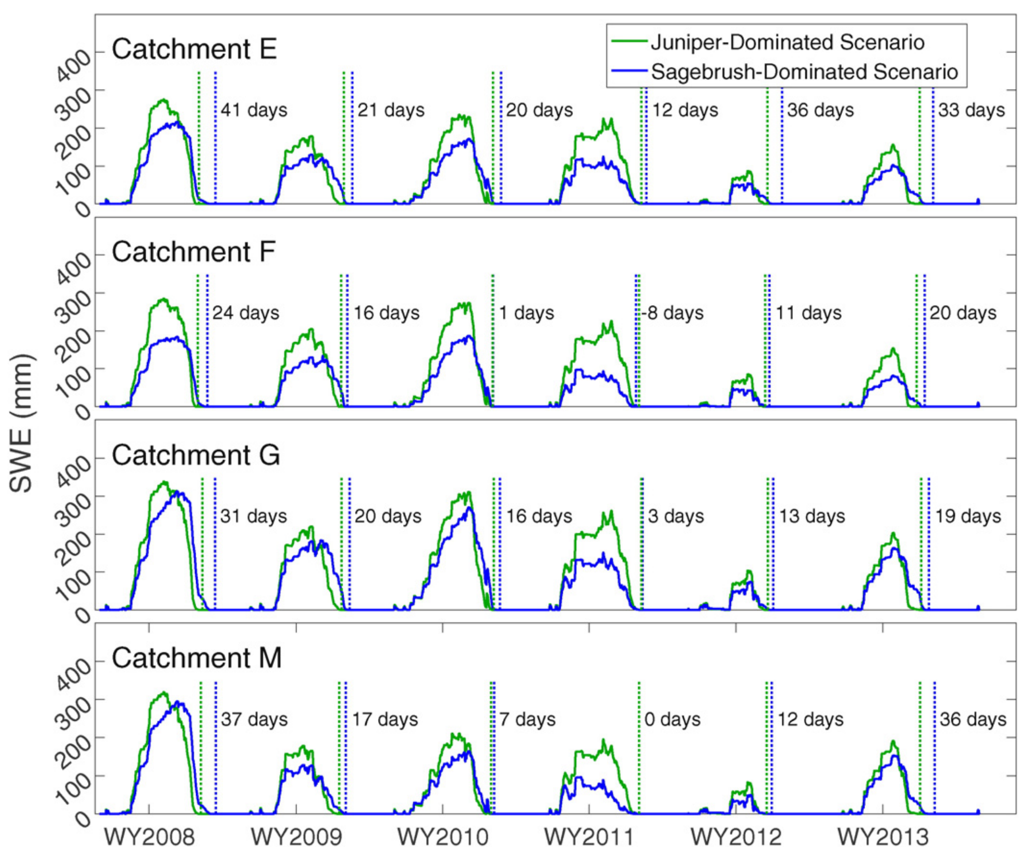

Figure 6. Modeled mean basin snow water equivalent (SWE) for juniper- and sagebrush-dominated scenarios showing higher peak accumulation and earlier melt out for juniper-dominated scenario in number of days.

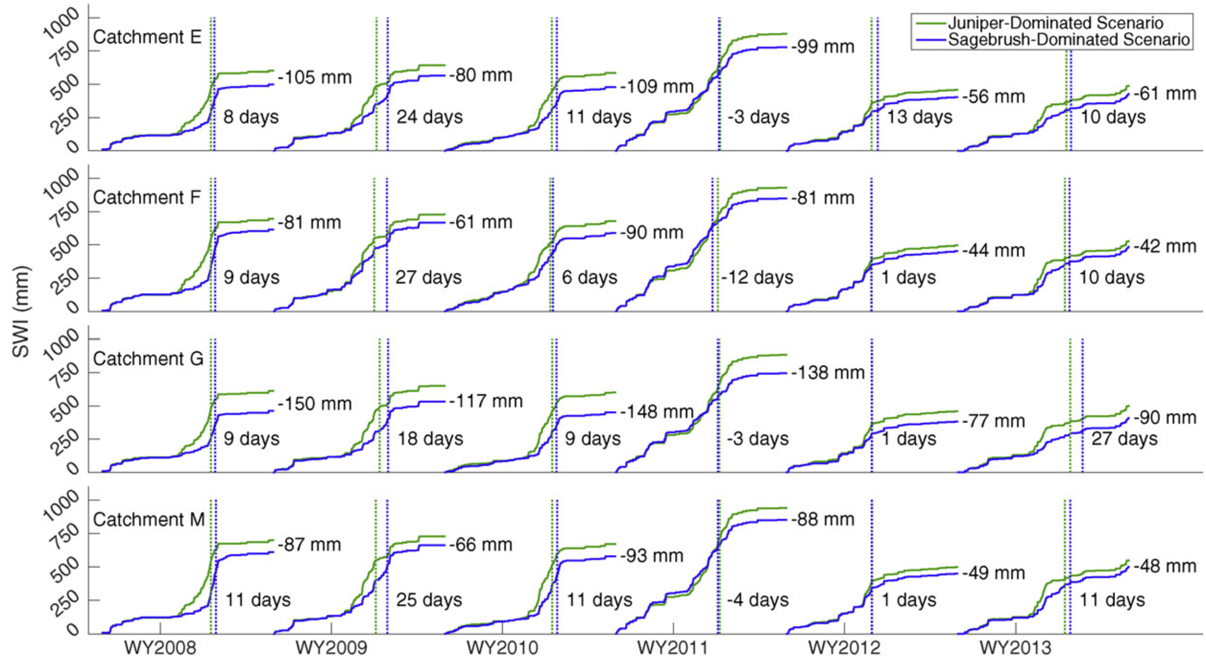

Figure 7. Modeled total basin cumulative surface water input (SWI) from each of the catchments showing the time of delay of water inputs (days) in sagebrush-dominated scenario and the higher magnitude of total SWI (mm) in juniper-dominated scenario.

entered a catchment occurs on average 7 May for the juniper-dominated scenario and May 16th on sagebrush-dominated scenario, a difference of 9 days. This time varies from −12 to +27 days. Total SWI values are an average of 86 mm more for the juniper-dominated simulations and range from 42 to 150 mm.

The SWE distributions on 1 April illustrate how juniper cover plays an important role in the distribution of snow cover (Fig. 8). The difference in snow cover for the juniper- versus sagebrush-dominated scenario varies markedly across years. Catchments for the juniper-dominated scenario produce a more uniform snow distribution (as indicated by SWE, Fig. 8A) while the absence of trees produces a more heterogeneous snow distribution (Fig. 8B). Drifts tend to occur in the same places in all years regardless of vegetation cover but are larger in sagebrush-dominated model scenarios.

Water Balance

The four catchments behave similarly in terms of snow dynamics, even though there is large interannual variability in precipitation and weather conditions. This is demonstrated by the small range in SWI within years but the large variability between years (see Figs. 7 and 9). Average estimated ET from all years is 531 mm and 348 mm for the juniper- and sagebrush-dominated scenario, respectively (see Figs. 9 and 10, see Table 1). Mean annual measured Q for the existing

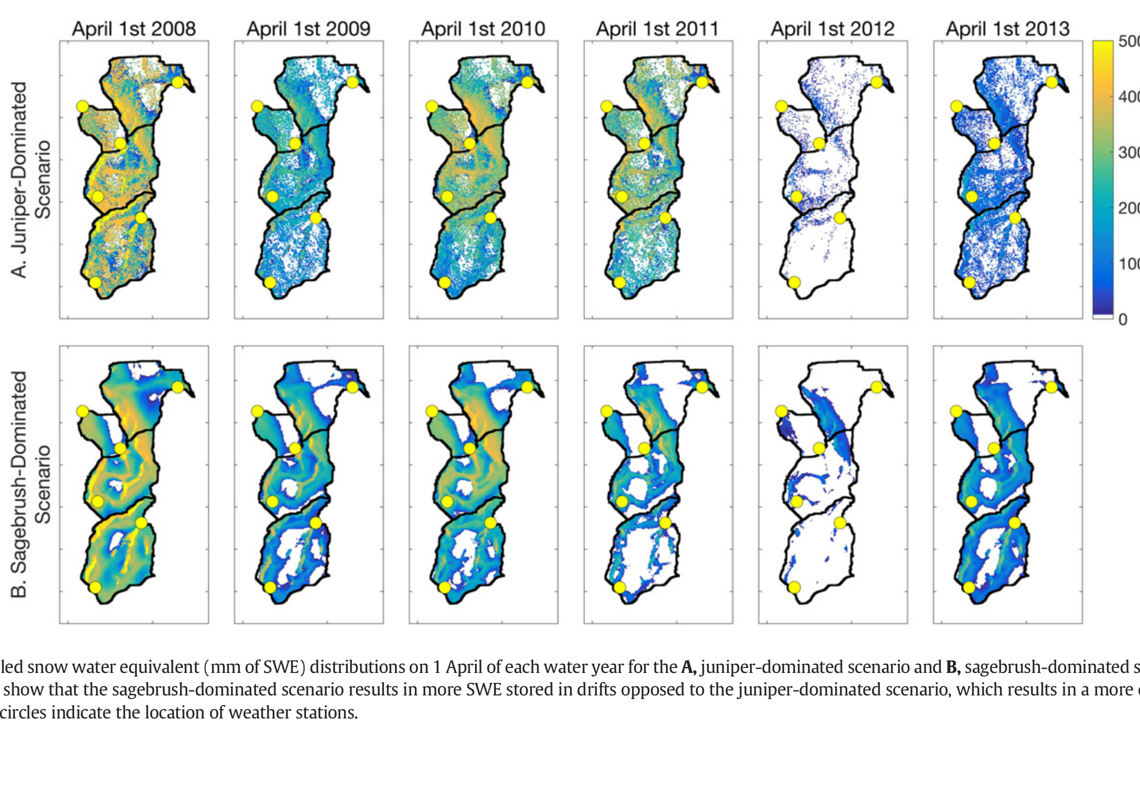

Figure 8. Modeled snow water equivalent (mm of SWE) distributions on 1 April of each water year for the **A,** juniper-dominated scenario and **B,** sagebrush-dominated scenario. Late season differences show that the sagebrush-dominated scenario results in more SWE stored in drifts opposed to the juniper-dominated scenario, which results in a more even snow distribution. Yellow circles indicate the location of weather stations.

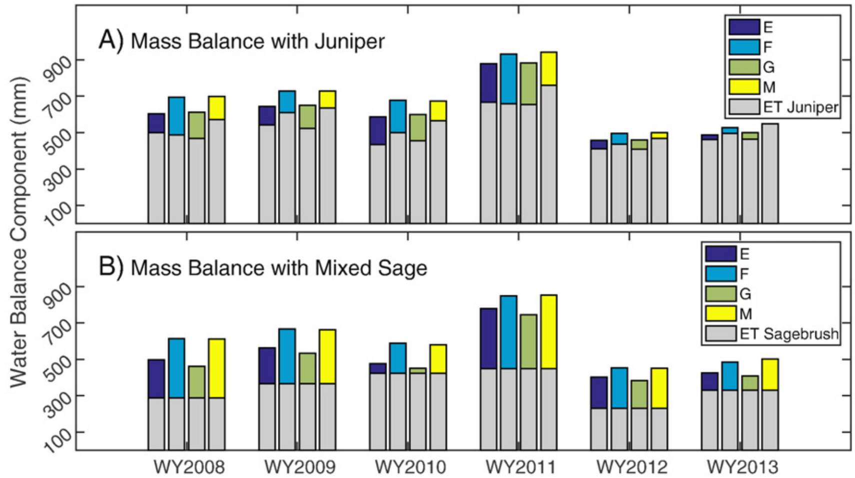

Figure 9. Water year mass balance for the South Mountain Experimental Catchments showing total modeled surface water input (SWI) for each catchment as total bar height. That total input is divided into evapotranspiration (ET) depicted as the gray bar height, and stream discharge depicted as the colored bar height. ET for the sagebrush-dominated scenario is estimated as a weighted average with 20% mountain big sagebrush and 80% low sagebrush, which is the assumed vegetation distribution.

juniper vegetation community is 115 mm. Estimated mean annual streamflow for the sagebrush-dominated scenario is 212 mm (see Fig. 9, Table 1). The estimated mean runoff ratio from the sagebrush-dominated scenario is 0.38, compared with the juniper-dominated scenario value of 0.16 (Fig. 11).

Discussion

The results of this study suggest that the conversion of grassland and shrub-steppe communities to juniper woodlands within the Intermountain Western United States can significantly alter local water balances by altering both patterns of snow deposition and the timing and magnitude of melt and the delivery of water to the soil.

Spatiotemporal Differences in Snow Distribution and Water Availability

Model results indicate that mean catchment peak SWE accumulations are greater for all years for all catchments in the juniper-dominated scenario (see Fig. 6). The differences in peak snow accumulation result from a balance between widespread vegetation sheltering in the juniper-dominated scenario and higher wind speeds forming larger drifts in the sagebrush-dominated scenario (see Fig. 8). Both processes result in increased snow accumulation, but widespread vegetation sheltering results in a more homogenous increase in snow accumulation compared with increased snow storage in drifts induced by higher wind speeds. The lower peak basin accumulations in the sagebrush-dominated scenario occur because of increased snow scour in the absence of trees (Hiemstra et al., 2002). The snow distribution under the sagebrush-dominated scenario is concentrated in topographically sheltered snow drifts. The 1 April snow distributions from WY2012 and WY2013, which were the lowest snow years of this study, illustrate these marked differences (see Fig. 8). Similar sheltering effects on snow distribution are observed from 21 detailed snow surveys over 11 years in RCEW (Winstral and Marks, 2014), in arctic tundra (Essery et al., 1999), and in alpine and boreal forests (Pomeroy et al., 1999).

Model results also indicate that the snow melts out earlier in the juniper-dominated scenario (see Figs. 6 and 7). The earlier snow melt-out times are a result of a balance between the previously discussed accumulation differences. The lower WY2011 melt-out timing difference results from low winds during storms for this year (see Table 2) leading to smaller drift enhancement. Smaller differences in melt-out timing from Catchment F result from high juniper cover leading larger tree-sheltering enhancement of snow compared with drift enhancement (see Table 3). Increased late-season melt dynamics also affect melt-out timing. Net all-wave radiation increases quickly in the presence of junipers as a result of increased incoming solar radiation, decreased albedo from litter accumulation, and warming trees emitting more thermal radiation to the snowpack (Koivusalo and Kokkonen, 2002). The snow albedo in drifts decays more slowly in the sagebrush-dominated scenario due to the lack of tree litter accumulation (Link and Marks, 1999; Cristea et al., 2014). This allows isolated snow drifts to persist later into the growing season than the more evenly distributed snow cover that results from the juniper-dominated scenario.

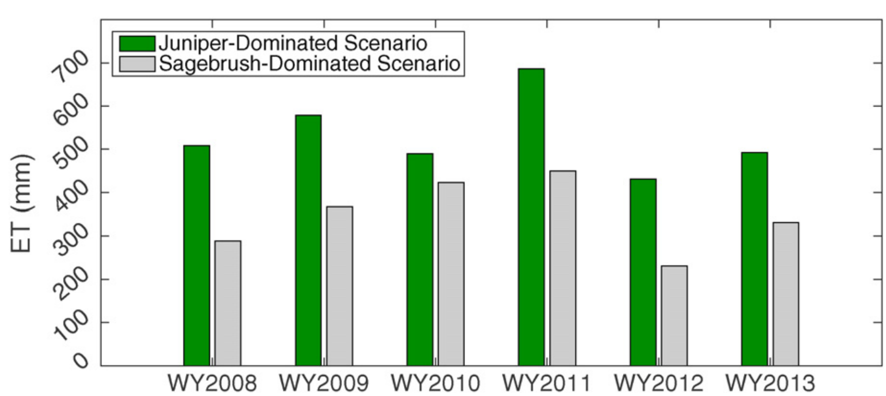

Figure 10. Estimated evapotranspiration (ET) differences between juniper- and sagebrush-dominated scenarios.

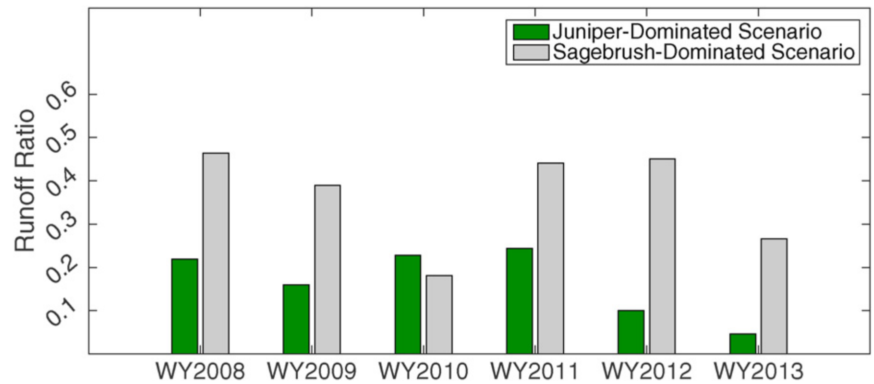

Figure 11. Runoff ratios (Q/SWI) showing the difference between the juniper-dominated and sagebrush-dominated scenarios for the 6 water years of this study.

Catchment Water Balances and Streamflow Estimates

Catchment estimated ET is similar from year to year in the juniper-dominated scenario. The exception is WY2011, in which ET is 155 mm higher than the 6-yr average (see Fig. 10, Table 1). This year is characterized by a large magnitude of total precipitation but also a large proportion of spring rainfall, when ET demands increase (see Fig. 2). For this reason it is the year that we have the least confidence that loss due to canopy interception is not an important term in the water balance and, in turn, the least confidence in the sagebrush-dominated Q and juniper-dominated ET estimates. This result may skew streamflow estimates and runoff ratios from juniper-dominated scenarios slightly higher, but this does not affect the overall implications of the study.

Annual total catchment SWI magnitudes are higher for the juniper-dominated scenario than for the sagebrush-dominated scenario as depicted by the total bar height in Figure 9. However, due to greater estimated ET from junipers, mean annual streamflow is often larger in the sagebrush-dominated scenarios, as indicated by the height of the colored bars in Figure 9. These modeled estimates suggest that sagebrush-dominated catchments produce substantially more streamflow than juniper-dominated catchments, about 100 mm in this study (see Figs. 9 and 11, Table 1). This result is dependent on the assumed amounts of mountain big sagebrush and low sagebrush (20% and 80%) in the catchment, as well as precipitation and weather conditions. The anomaly in this pattern is WY2010, which has slightly below average measured precipitation and generates less streamflow for the sagebrush-dominated scenario (see Table 1). The lower stream discharge is likely the result of USC modeled ET from WY2010 being too high of an estimate to be used for the South Mountain Experimental Catchments based on precipitation-ET relationships for the other 5 WYs.

Over large areas, (>500 km^2) where drift and scour zones essentially average out, total snow deposition and SWI magnitudes for any given year would be expected to be similar between juniper- and sagebrush-dominated catchments. However, these catchments are relatively small compared with the dominant scale of precipitation patterns. There is also a large area to the east of these watersheds that is less vegetation-sheltered, which we expect to act as a snow source area. Winstral et al. (2009, 2013) observed that, in areas designated as topographic scour zones, snow accumulates to about 80% of the surrounding vegetation height (Walker et al., 2001; Essery and Pomeroy, 2004). Additional deposition is simply scoured away. Low vegetation and shrubs (i.e., sagebrush) are filled and then become sources of snow for downwind deposition sites. In general junipers are taller and unlikely to be filled to within 80% of height and therefore able to capture snow throughout the season. For these reasons, we believe that the differences in annual snow deposition and SWI values between the juniper- and sagebrush-dominated scenarios are reasonable.

Snowy, sagebrush-dominated catchments are more efficient at translating precipitation and snow melt to streamflow as is indicated by considerably higher mean runoff ratios (see Fig. 11). The difference in runoff ratios is a result of the sagebrush-dominated scenario having lower total catchment SWI values and higher mean annual discharge values, a function of estimated ET (see Table 1). Differences between runoff ratios in the juniper- and sagebrush-dominated scenarios are greater for windy years, when the snow distribution differences are dominated by drift zones (see Figs. 8 and 11, Table 2).

Model Performance and Evaluation of Assumptions

Modeled SWE values near weather stations reasonably match measured values from snow courses and snow surveys, especially considering the shallow and ephemeral nature of the snowpack in this environment. The current best-practice methods employed in this study limit errors in the precipitation distribution by 1) maintaining a realistic mass balance between measured and modeled precipitation totals (see Table 3), 2) accounting for vegetative sheltering of blowing snow, 3) accounting for topographic induced drifting, and 4) accounting for topographic-induced decreases in accumulation. Deviations between measured and modeled SWE highlight the difficulty in parameterizing a precipitation distribution in catchments with complex vegetation and topography. Modeling errors in the parameterization of juniper effects on precipitation distribution (i.e., increased accumulation from vegetation sheltering) would have systematic effects on our mass balance results, given the extent of juniper cover in the catchments (see Fig. 1, Table 3). It is important to note that any overestimation in juniper-dominated precipitation will result in an overestimate of the same magnitude in ET from the juniper-dominated scenario (see Table 1, Eq. (2)). For this reason, the juniper-dominated ET estimates presented in Table 1 are an upper bound estimate. This would also translate into a lower bound estimate of the presented runoff ratios for the juniper-dominated scenario (see Fig. 11) and a decrease in the discrepancies between the juniper- and sagebrush-dominated scenario peak SWE accumulations (see Fig. 6) and total basin SWI (see Fig. 7).

Interception-induced losses are assumed to be negligible in this environment across both the juniper- and sagebrush-dominated scenarios. We acknowledge that in colder environments where intercepted snow remains in the canopy longer (Musselman et al., 2008; Bradford et al., 2014), or evaporative demand is higher following storms (Owens et al., 2006), direct sublimation losses can be important. In this environment, losses due to the interception of rain are minimized by the offset between high precipitation and high evaporative demand. Minimal loss due to snow interception is supported by a careful lysimeter measurement study from a maritime site in Oregon, which showed 1) snow intercepted by a forest canopy rapidly sluffed from the trees,

2) subsequent sublimation losses were generally close to zero, and 3) sublimation was approximately 5% of winter precipitation (Stork et al., 2002). That site was wetter (average winter precipitation of 2000 mm), lower (1200 m), and more densely forested (30- to 50-m canopy heights, 65%—80% canopy closure). Their meticulous measurement effort found that up to 60% of snow was intercepted by the mature forest canopy. However, their lysimeter data show the primary interception removal mechanism was melt water drip and mass release to the ground below the canopy.

The South Mountain Experimental Catchments are located in the interior Western United States, which is generally cooler, drier, and more open in terms of canopy compared with the Oregon study site (Stork et al., 2002). Lower vegetation generally becomes covered with snow early in the winter. Although we assume negligible loss of mass to sublimation of intercepted snow, we carefully calculate wind-driven turbulence, vapor gradient, and sublimation/condensation from or to snow on the ground. Over the six snow seasons of this study, sublimation losses averaged −3.5% of precipitation, with condensation gains of +0.5%, for a mean flux of −3%. Furthermore, if direct loss from intercepted snow was significant, we would expect a systematic overestimate of measured snow within the juniper-dominated South Mountain. However, our model results indicate that measured and simulated snow over the six snow seasons of this study are well matched, and that, while the match is not perfect, there is not a systematic bias (see Fig. 5).

On the basis of those results, we believe that negligible interception in this climate and environment is a valid assumption. However, the lack of measured site-specific interception data and a common perception that this component of the water balance may be large warrants more consideration. Interception and subsequent sublimation from a juniper-dominated catchment in any climate is expected to be larger than interception from a sagebrush-dominated catchment because turbulence in the upper regions of a 4- to 5-m juniper canopy will be greater than in a submeter shrub canopy. A systematic reduction in the precipitation or SWI magnitudes in the juniper-dominated scenario compared with the sagebrush-dominated scenario would 1) decrease the difference in annual catchment precipitation/SWI totals, 2) enhance the melt-out times that 75% of the SWI enters the juniper-dominated catchments (see Fig. 7), 3) decrease the difference between ET magnitudes (see Fig. 10), and 4) decrease the difference between runoff ratios (see Fig. 11). The implications of increased interception from junipers could reduce the difference in total peak SWE and SWI between model scenarios but would result in an earlier meltout within juniper-dominated catchments, thereby enhancing the extended delivery of water input into the summer for sagebrush-dominated catchments.

Effects of Water Availability on Vegetation Dynamics and Habitat

Water from snow drifts is known to provide much needed soil water for vegetation and often sustains streamflow into the late spring/early summer (Luce et al., 1998; Luce and Tarboton, 2004; Kumar et al., 2013; Wang et al., 2013). The combination of delayed water inputs to and increased streamflow from sagebrush-dominated catchments may lead to substantial habitat benefits for sagebrush obligates when compared with the hydrology of juniper-dominated catchments. Delayed water inputs to a catchment, resulting from increased snow drifting, may result in more distributed surface water sources such as springs and wet meadows, which would improve sage grouse habitat conditions. Because the drifts delay the delivery of SWI to the soil until well into the growing season, there is water available for shrubs and forbs that would otherwise be desiccated by a summer generally without precipitation. The extension of water availability from winter precipitation provided by snow drifts is known to be important for sage grouse during late brood-rearing times (Connelly et al., 2011). Following treatment of western juniper by fire or cutting, forbs often increase in cover and production, indicating the importance of increased available water and soil nutrients (Bates et al., 2000; Roundy et al., 2014a,b).

Interacting Effects of Climate on Snow Distribution and Water Availability

The 6 yrs of this study period encompass sufficient interannual variability in weather conditions to discuss the hydrologic implications in a broader climate context. In general, model results indicate that sagebrush-dominated catchments produce more streamflow, later into the summer than juniper-dominated catchments (see Fig. 9 and 11, Table 3). Snow melt-out times are similar between juniper- and sagebrush-dominated scenarios on years with lower wind speeds during storms (WY2010 and WY2011) and in catchments with higher juniper density (catchments F and M). Under these conditions, increases in energy balance components related to the juniper canopy are outweighed by the shear magnitude of the snowpack increases by wind sheltering from trees. This suggests that there are combinations of low winds, high precipitation amounts, and cold air temperature conditions during storms where streamflow from juniper-dominated systems may extend longer into the summer compared with sagebrush-dominated systems.

Regional shifts in precipitation from snow to rain in low- to mid-elevations highlight the importance of maintaining high-elevation summer sage grouse habitat (Knowles et al., 2006; Nayak et al., 2010). Because drift formation is dependent on snowfall, the extended release of meltwater into the late spring or early summer from drifts may be declining for lower to middle elevations. Sage grouse habitat at rain-dominated lower elevations has already been substantially reduced due to extensive cheatgrass (*Bromus tectorum* L.) invasion and an associated increase in annual area burned (Balch et al., 2013; Miller et al., 2011). Blomberg et al. (2012) suggested that sage grouse populations across low- to mid-elevations are strongly influenced by climate-driven variation in resource availability, primarily precipitation and soil water availability for food production. The study further found sage grouse populations were negatively impacted by cheatgrass invasion and suggested that more frequent drought and increased spread of exotic grasses under warming climate conditions would further reduce sage grouse habitat. Guttery et al. (2013) likewise concluded that decreased snowfall with warming climate conditions would reduce late season soil moisture and the quality of habitat for sage grouse brood rearing. The retention of sagebrush steppe vegetation at higher elevations and the associated spatiotemporal patterns of snow accumulation and melt may be critical with respect to maintaining sage grouse summer habitat with changing climate (Blomberg et al., 2012; Guttery et al., 2013). Sage grouse diets depend on forbs during this summer season, and they will travel a long distance, often to higher elevations, to meet this need (Connelly et al., 2011). Although this stage represents a fraction of sage grouse life cycle, the loss of high-elevation sagebrush steppe areas due to woodland encroachment may have disproportionately adverse effects on sage grouse as precipitation continues to shift toward a rain-dominated regime (Guttery et al., 2013).

Conclusions and Ecological Implications

Vegetation and topography impart distinct signatures on the distribution of snow and surface water availability that, in turn, strongly influence the diversity of ecosystem properties including habitat for sagebrush obligates like the greater sage grouse. Results from this study generally indicate that snow water equivalent peaks higher, snow melts out earlier, and more water is lost to evapotranspiration in catchments dominated by juniper as compared with sagebrush steppe vegetation. Our results also indicate that snow drifts are larger and persist longer (due to higher wind speeds) in sagebrush-dominated catchments. The prolonged snow retention in drifts generates greater annual and prolonged summer-season streamflow with respect to juniper-dominated catchments. Our results suggest that catchments in snow-dominated climates with sagebrush vegetation effectively capture, store, and deliver water that may be used for sustaining vegetation diversity associated with critical sage grouse habitat. In contrast, juniper-dominated systems in similar climates likely generate greater overall water input, but the timing of water availability is less beneficial to late season shrub and herbaceous productivity and habitat recruitment. We did not specifically assess the succession point at which juniper encroachment imparts the previously noted impacts, but our results clearly demonstrate ecohydrologic benefits associated with retention of sagebrush mosaics on snow-dominated rangelands. Our results imply that retention of high-elevation sagebrush vegetation in snow-dominated uplands may be particularly important in sustaining sage grouse habitat under warming climate conditions. Decreased snowfall associated with warming winter temperatures at lower elevations is likely to reduce late summer water availability critical for sustaining sage grouse habitat, which is already diminished due to invasive annual grasses and increasing wildfire activity.

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