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Consequences of declining snow accumulation for water balance of mid-latitude dry regions

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Abstract

Widespread documentation of positive winter temperature anomalies, declining snowpack and earlier snow melt in the Northern Hemisphere have raised concerns about the consequences for regional water resources as well as wildfire. A topic that has not been addressed with respect to declining snowpack is effects on ecosystem water balance. Changes in water balance dynamics will be particularly pronounced at low elevations of mid-latitude dry regions because these areas will be the first to be affected by declining snow as a result of rising temperatures. As a model system, we used simulation experiments to investigate big sagebrush ecosystems that dominate a large fraction of the semiarid western United States. Our results suggest that effects on future ecosystem water balance will increase along a climatic gradient from dry, warm and snow-poor to wet, cold and snow-rich. Beyond a threshold within this climatic gradient, predicted consequences for vegetation switched from no change to increasing transpiration. Responses were sensitive to uncertainties in climatic prediction; particularly, a shift of precipitation to the colder season could reduce impacts of a warmer and snow-poorer future, depending on the degree to which ecosystem phenology tracks precipitation changes. Our results suggest that big sagebrush and other similar semiarid ecosystems could decrease in viability or disappear in dry to medium areas and likely increase only in the snow-richest areas, i.e. higher elevations and higher latitudes. Unlike cold locations at high elevations or in the arctic, ecosystems at low elevations respond in a different and complex way to future conditions because of opposing effects of increasing water-limitation and a longer snow-free season. Outcomes of such nonlinear interactions for future ecosystems will likely include changes in plant composition and productivity, dynamics of water balance, and availability of water resources.

Keywords: big sagebrush, climate change, nonlinear response, precipitation form, precipitation seasonality, semiarid regions, water availability

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Introduction

Decreases in snow accumulation (Mote *et al.*, 2005; Pederson *et al.*, 2011a,b) and earlier snow melt (Stewart, 2009; Pederson *et al.*, 2011a,b) over the second half of the 20th century in the United States and across the Northern Hemisphere have been linked to increasing winter and spring temperatures and an increasing fraction of precipitation falling as rain instead of as snow (Knowles *et al.*, 2006; McCabe & Wolock, 2010). Earlier and decreased snow melt will reduce stream flow during the growing season when demand is largest, thus intensifying water scarcity in dry areas (Barnett *et al.*, 2005; Cayan *et al.*, 2010; Seager & Vecchi, 2010). Earlier spring snow melt is also associated with a higher wildfire frequency and an increased duration of wildfires at mid-elevations of western North American forests (Westerling *et al.*, 2006). In addition, a positive feedback loop in which rising aridity increases dust load, decreases snow albedo and speeds peak snow melt, could lead to intensified dryness (Painter *et al.*, 2010; Seager & Vecchi, 2010). Observed snow reductions are most pronounced at temperatures near freezing, i.e. those that tend to occur more often at lower elevations and in fall or spring (Knowles *et al.*, 2006; IPCC, 2007), whereas colder areas are less sensitive or may experience increased snowfall due to higher moisture availability (Adam *et al.*, 2009; Stewart, 2009; Rasmussen *et al.*, 2011). Consequently, changes in water cycling and availability will be particularly pronounced at low elevations of mid-latitude dry regions that will be the first to be affected by the effects of rising temperatures on declining snow (Mote *et al.*, 2005; Knowles *et al.*, 2006; IPCC, 2007; Rasmussen *et al.*, 2011).

For dry mid-latitude regions worldwide, snowpack is a major component of water storage and source of runoff; for instance, snow melt in western North America

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contributes up to 50–80% of annual stream flow (Stewart *et al.*, 2004). Snow and snow melt control spatial and temporal patterns of soil water at ecosystem scales, particularly in arid and semiarid catchments (Williams *et al.*, 2009). Lateral water movement including runoff is limited due to insufficient moisture throughout most of the year in dry regions except for short periods during snow melt after hydraulic connectivity is established (McNamara *et al.*, 2005). In dry regions where evaporative demand is larger than precipitation, winter precipitation and snow melt control recharge of deep soil layers and establishment of hydraulic connectivity (Loik *et al.*, 2004; Williams *et al.*, 2009) and hence exert important influence in systems where water balance is storage-dominated.

In addition to hydrologic consequences, altered snowpack and seasonal snow melt have important ecological impacts. In dry ecosystems, which cover c. 30% of global land area (Peel *et al.*, 2007), above ground net primary production and vegetation composition are controlled by spatial and temporal patterns of available water (Noy-Meir, 1973). Deep-rooted woody plants dominate areas with winter precipitation because they can access water stored in deep soil layers (Paruelo & Lauenroth, 1996; Sala *et al.*, 1997) – water that is replenished by cool-season precipitation, often snow. To improve forecasts of plant responses to future climatic conditions (Jackson *et al.*, 2009), we must increase our understanding of the consequences of changes in snow accumulation and melt for ecosystem water balance (Adam *et al.*, 2009; Williams *et al.*, 2009).

To address this need, we used a soil water simulation model (Lauenroth & Bradford, 2006; Schlaepfer *et al.*, 2011a), with a daily time step and multiple soil layers, to characterize water balance under future climate scenarios for ecosystems dominated by *Artemisia tridentata* Nutt. (big sagebrush), the most common of several *Artemisia* species in semiarid regions in western North America. This long-lived shrub relies on water stored in deep soil layers during summer dry periods (Schlaepfer *et al.*, 2011a). We examined 120 randomly selected big sagebrush sites stratified along a climatic gradient from dry, warm and snow-poor to wet, cold and snow-rich (Fig. 1). Hydrological and ecological responses along this climatic gradient were assessed using a suite of variables (Table S1) representing snowpack variables (less or more snowpack and duration of snow cover), soil water flow (less or more infiltration, percolation and drainage), soil water quantity (less or more water in the soil), soil water timing (earlier or later seasonal soil water availability) and vegetation activity (less or more transpiration). Our study addressed the core question: How sensitive are ecosystem water balance and vegetation activity to potential

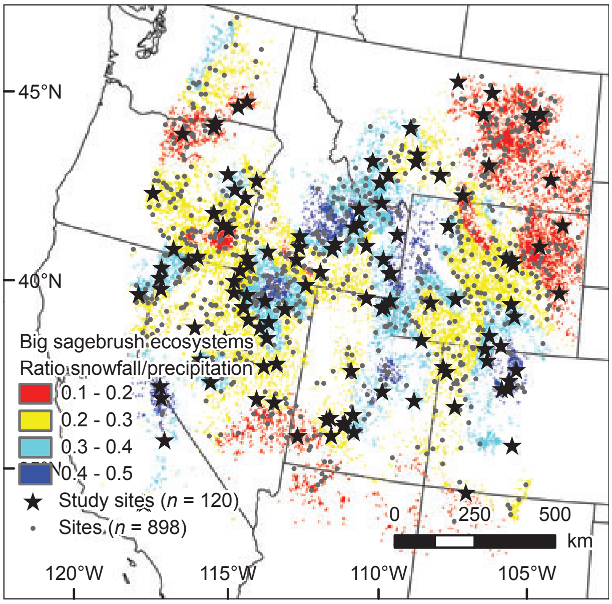

Fig. 1 Geographic distribution of the gradient of snow-precipitation ratio in big sagebrush ecosystems in western United States. Ordinary kriging spatially interpolated values of snow-precipitation ratios of 898 random sagebrush ecosystems sites. From these sites, 120 were selected by stratified random sampling for this study. The map is displayed in Albers equal-area conic projection for the contiguous United States.

changes in snow associated with climate change scenarios, precipitation seasonality, precipitation form (i.e. partitioning into rain and snow), vegetation phenology and snow melt-runoff? Our study also discussed what the consequences of future climate conditions for big sagebrush ecosystems are.

Materials and methods

Study system

Our study area was the 11 western states of the continental United States, a region containing almost all of the big sagebrush ecosystems (Fig. S1, McArthur & Plummer, 1978; West & Young, 2000). We concentrated on ecosystems that are dominated by the shrub *A. tridentata* Nutt. (big sagebrush), the most frequent of several *Artemisia* species in semiarid regions in western United States. The long-lived *A. tridentata* relies on stored water in deep soil layers during summer dry periods (Schlaepfer *et al.*, 2011a), which is accessed with a deep root system (Sturges, 1977; Cleary *et al.*, 2010). The potential distribution of big sagebrush ecosystems was defined using regional GAP cover data (US Geological Survey, 2010) with a spatial resolution of 30 × 30 m^2 for which *A. tridentata* is a substantial component, i.e. 'Inter-Mountain Basins Big Sagebrush Shrubland' (here, SB-Shrubland), 'Inter-Mountain Basins Big Sagebrush Steppe' (SB-Steppe) and 'Inter-Mountain

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Basins Montane Sagebrush Steppe' (SB-Montane) (Schlaepfer *et al.*, 2011a).

We created two hierarchical sets of random sites of big sagebrush ecosystems representing a gradient of the importance of snow as precipitation. First, we randomly sampled 898 GAP grid cells as sites, of which the three GAP big sagebrush ecosystem types were proportionally represented to their spatial extent (Table 1). The random sample was constrained to one site per 1/8th-degree cell of the weather data (Schlaepfer *et al.*, 2011a). Second, a snow-precipitation ratio, calculated as mean percentage of annual snowfall to annual precipitation from 1970 to 1999, categorized the 898 sites into four 'snow-categories', i.e. 10–20%, 20–30%, 30–40%, and 40–50% (Table 1). Snow-precipitation ratios of 0–10% and $\geq 50\%$ represented 1% and 4%, respectively, of total big sagebrush ecosystems and were excluded from this study. We randomly sampled 30 sites per snow-category by sub-sampling 10 sites from three even-spaced sub-intervals of each snow-category (e.g. for the 10–20% category: 10 random sites each from 10–13.3%, 13.3–16.7% and 16.7–20%), for a total of 120 study sites.

Climate scenarios

We used three climate scenarios: current conditions for 1970–1999 and two future conditions for 2070–2099. Current forcing of precipitation and minimum and maximum temperature were derived from daily 1/8th-degree gridded weather data

Table 1 Distribution and mean climatic characteristics of study sites in big sagebrush ecosystems under 1970–1999 and 2070–2099 A2 climates

	Snow-category			
	10–20%	20–30%	30–40%	40–50%
% of big sagebrush ecosystems	32	36	18	9
Elevation (m a.s.l.)	1245	1662	1912	2125
Current climate				
Snow/PPT	0.16	0.25	0.34	0.44
MAT (°C)	8.1	6.9	4.9	3.9
MAP (mm)	320	316	394	480
r (PPT, T_{mean})	0.15	−0.08	−0.08	−0.22
Future A2 climate				
Snow/PPT	0.09	0.13	0.20	0.28
MAT (°C)	12.7	11.5	9.5	8.5
MAP (mm)	332	336	417	514
r (PPT, T_{mean})	0.10	−0.18	−0.17	−0.31

Standard deviations (SD) and data for the 2070–2099 B1 scenarios are in Table S2. Snow/PPT, mean ratio of annual snowfall to annual precipitation; MAT, mean annual temperature; MAP, mean annual precipitation; r, Pearson product-moment correlation coefficient between monthly precipitation and monthly mean temperature measures precipitation seasonality with positive values corresponding to dominantly warm-season precipitation and negative values to cold season precipitation.

(Maurer *et al.*, 2002). The emission scenario families B1 and A2 (Nakicenovic & Swart, 2000), from the special report on emission scenarios (SRES), described future climates scenarios with monthly 1/8th-degree downscaled ensemble median temperature and precipitation predictions of 16 global circulation models (accessed May 2010 from climatewizard.org, Maurer *et al.*, 2007). Future daily forcing consisted of current daily weather conditions with added predicted mean monthly temperature changes, respectively, with multiplied predicted mean monthly precipitation changes (Schlaepfer *et al.*, 2011b). Predicted temperature and precipitation changes were specific to each snow category and represented the mean changes for each month based on the random sample of 30 sites per category. Our future climate scenarios did not include scenarios for changes in climatic variability, wind speed, relative humidity, or cloud cover.

Soil water simulation model

We used SOILWAT, a daily time step, multiple soil layer, process-based, simulation model to predict ecosystem water balance for big sagebrush vegetation for each of the 120 sites. SOILWAT was developed and tested in the semiarid western United States shortgrass steppe (Parton, 1978; Sala *et al.*, 1992). We adapted it for sagebrush ecosystems by (i) incorporating the SWAT2K (Neitsch *et al.*, 2005) snow module, which was calibrated using SNOTEL data for the western United States (Schlaepfer *et al.*, 2011a), (ii) incorporating the process of hydraulic redistribution (Ryel *et al.*, 2002), (iii) utilizing sagebrush ecosystem-specific vegetation parameters and (iv) testing it against field measured data (Schlaepfer *et al.*, 2011a). For the purpose of testing sensitivity to snow melt-runoff, we implemented a non-mechanistic runoff routing that diverts a fixed percentage of daily snow melt to runoff instead of infiltration. For each study site, SOILWAT used daily weather, mean monthly relative humidity, wind speed, and cloud cover data (National Climatic Data Center, 2005), monthly vegetation (live and dead biomass, litter, and active root profile) and site-specific properties of each soil layer [lower layer limits: 5, 10, 20, 30, 40, 60, 80, 100, 150 cm; CONUS-SOIL (Miller & White, 1998)] to simulate the daily ecosystem water balance. Simulated water flows include interception by vegetation and litter, evaporation of intercepted water, snow melt and loss (sublimation and wind redistribution), infiltration into the soil profile, percolation, and hydraulic redistribution for each soil layer, bare-soil evaporation, transpiration from each soil layer, and deep drainage (Lauenroth & Bradford, 2006; Schlaepfer *et al.*, 2011a). Outputs are daily, monthly, and annual values of each water balance component (Parton, 1978).

Simulation of the ecosystem water balance

We ran SOILWAT for 58,320 scenario- and site-combinations each for 31 years including a 1-year spin up. For each of the 120 randomly sampled big sagebrush ecosystem sites, we defined the runs by combinations of climate scenario factors 'climate change precipitation' and 'climate change temperature' and of model factors with artificial levels, 'precipitation form', 'precipitation seasonality', 'vegetation phenology', and 'snow melt-runoff'. Each climate change factor included three levels (current – standard level, B1, and A2). 'Vegetation phenology' included three levels of shifting the monthly biomass trajectory (peak biomass occurring in April, May and June – standard level). The factor 'precipitation form' included two levels ('on', daily precipitation is partitioned into rain and snow – the standard level; 'off', all daily precipitation is treated as rain). 'Precipitation seasonality' included three levels, which were applied on a per-site basis maintaining mean annual precipitation (MAP) (current precipitation seasonality – standard level; 'winter', 30% of mean monthly precipitation of April–September was subtracted and a corresponding amount added to monthly precipitation of October–March; 'summer', 30% of mean monthly precipitation of October–March was subtracted and a corresponding amount added to monthly precipitation of April–September). 'Snow melt-runoff' included three levels describing the percentage of daily snow melt attributed to runoff (0% – standard level, 25% and 50%). Soil parameters of nine soil layers (see above) represented a median sagebrush ecosystem soil of the 'loam' type with 40% sand and 23% clay (Schlaepfer *et al.*, 2011a). Using the median soil texture was sufficient because ecohydrological characteristics of big sagebrush ecosystems showed little sensitivity to soil texture compared to climatic and some biotic variables (Schlaepfer *et al.*, 2011a).

Analysis

All calculations were performed using R version 2.13.0 (R Development Core Team, 2011).

We defined wet and dry periods as days when soil water potential (SWP) for a soil layer is larger or smaller, respectively, than a critical level (SWP_{crit}) chosen as a level of water potential below which transpiration rates decrease substantially. Based on 50% decreases in hydraulic conductivity due to cavitation for different subspecies of big sagebrush (Kolb & Sperry, 1999a,b), we assigned a value of −3.0 MPa to SWP_{crit} for SB-Montane and a value of −3.9 MPa to SWP_{crit} for SB-Steppe and SB-Shrubland (Schlaepfer *et al.*, 2011a). In addition, we included SWP_{crit} = −1.5 MPa which is supported by a decrease in transpiration and leaf area of big sagebrush by 50% when water potential decreased from −1 MPa to −2.5 MPa (Kolb & Sperry, 1999b). Variables dependent on the value of SWP_{crit} were calculated for each of the three values of SWP_{crit} and then averaged.

The nine soil layers used in the simulations were divided into two groups for the purpose of reporting results. The top soil included the soil layer influenced by bare-soil evaporation and transpiration, here to a depth of 30 cm. The bottom soil included the soil layers only influenced by transpiration, here below a depth of 30 cm.

Response variables and summaries of response groups. We defined five groups of response variables describing the main components of the sagebrush ecosystem water balance for a total of 37 response variables (Table S1). The first group 'snowpack variables' included four variables describing the amount of snowpack and duration of snow cover. The second group 'soil water flow' included three variables describing the vertical movement of soil water. The third group 'soil water quantity' included 16 variables describing for top and bottom soil layers the amount of soil water and the duration of wet periods. The fourth group 'soil water timing' included 10 variables describing for top and bottom soil layers the time of peak and minimum soil water and the start of dry periods. The fifth group 'vegetation activity' included four variables describing transpiration rates and actual evapotranspiration.

We then summarized the five response groups by the first principal component for each group by using correlations for the association matrices. We confirmed that the first principal component explained a large proportion of variance, i.e. >50% (Table S7). Thus, we interpreted the first principal components as linear combinations of the original response variables and used them as good approximations of the characteristics of the five response groups (Table S7).

Treatment effects and summaries of study site behavior. We calculated treatment effects as differences between first principal component scores between each treatment combination and current conditions. The standard levels of each factor described current conditions, i.e. partitioning into snow and rain is on, current precipitation seasonality, current precipitation, current temperature, peak vegetation biomass in June and assuming no or negligible snow melt-runoff. Next, we summarized the behavior of the 120 study sites by extracting slope and intercept from standardized major axis regression models between the snow-precipitation ratio and treatment effects for each treatment combination and response group. We used standardized major axis regression because we estimated the lines best describing relationships between the snow-precipitation ratio and responses and did not predict the responses (Warton *et al.*, 2006). We used the R package 'smatr' for standardized major axis regressions (Warton *et al.*, 2011) using the robust estimation method (Taskinen & Warton, 2011). We interpreted a slope as interaction between snow-precipitation ratio and the treatment combination and an intercept as change between current conditions and the treatment combination.

Relative importance of factors. To assess the relative importance of controls on the five response groups, we conducted for each response group two full-factorial analysis of variance (ANOVA) with fixed factors 'precipitation form', 'precipitation seasonality', 'climate change precipitation', 'climate change temperature', 'vegetation phenology' and 'snow melt-runoff' with either slopes or intercepts as response variables. Because SOILWAT contains no true random processes (Parton, 1978), we used the ranking of the mean sum of squares from the ANOVA to estimate relative importance of the factors (Rose *et al.*, 1991) and do not report *F*-statistics and *P*-values, since *F*-statistics assume that the data include an random error term with a non-zero standard deviation (Simpson *et al.*, 1997). Values smaller than the square-root of machine epsilon (here $\sqrt{2^{-52}}$ for 64-bit double) were set to 0. The relative importance of factors for each response group was estimated by the ranking of the median ranks of model mean sum of squares of the standardized major axis regression slope and intercept. The overall relative importance of factors was estimated by the ranking of the median ranks of each response group. We repeated the sensitivity analysis after excluding unrealistic treatment combinations, such as earlier phenology in combination with increases in snowpack.

Responses to specific treatment combinations. We inspected the responses to those factors more closely that were of high relative importance. Because the data showed nonlinear trends for several treatment combinations, we used piecewise linear regression to detect nonlinear responses (Toms & Lesperance, 2003). We estimated piecewise regressions and thresholds with the R package 'SiZer' (Sonderegger, 2011). We combined four approaches to conservatively determine if a threshold exists or if a linear regression explained the data sufficiently. First, a difference in AICc scores of >8 must favor the piecewise linear model (Burnham & Anderson, 2002) calculated with the R package 'AICcmodavg' (Mazerolle, 2011). Second, the slope after the threshold must be significantly different than the first one with a Dunn-Sidak adjusted alpha of 0.05. Third, the bootstrapped confidence intervals at Dunn-Sidak adjusted alpha of 0.05 of the two slopes must not overlap. Fourth, we visually inspected SiZer ('significant zero crossings') plots of the first and second derivative of a locally weighted polynomial regression to confirm the existence of a threshold (Sonderegger, 2011). To represent the relationships visually, we plotted the cloud of 95% of the data as represented by two-dimensional-kernel density estimation from the R package 'MASS' (Venables & Ripley, 2002) along with the regressed lines.

Results

We used the ratio of mean annual snowfall to MAP as a climatic gradient for our analyses because it is negatively correlated with mean annual temperature ($r < -0.74$, $P < 0.001$) and precipitation seasonality ($r < -0.29$, $P < 0.001$), and positively correlated to MAP ($r > 0.65$, $P < 0.001$) and elevation ($r > 0.65$, $P < 0.001$; Tables 1 and S2). Sagebrush ecosystems in the western United States receive on average 26% (95% of the 898 sites were within 11–54%) of precipitation as snow, with those at the highest elevations in the mountain ranges receiving more snow (Fig. 1). Under current conditions, we found strong positive relationships between snow-precipitation ratio and snowpack variables, soil water flow, soil water amount, timing of soil water, or vegetation activity (all $r^2 \in [0.57, 0.82]$, $P < 0.001$; Fig. 2, Table S3).

Sensitivity analysis identified precipitation seasonality and its interaction with vegetation phenology, followed by precipitation form, as the most important influences on model responses of water balance and vegetation activity (Tables 2 and S4). Snow melt-runoff ranked low except for the responses of soil water flow. Climate change factors ranked equally and showed similar importance across response variables. Interactions between climate change temperature scenarios

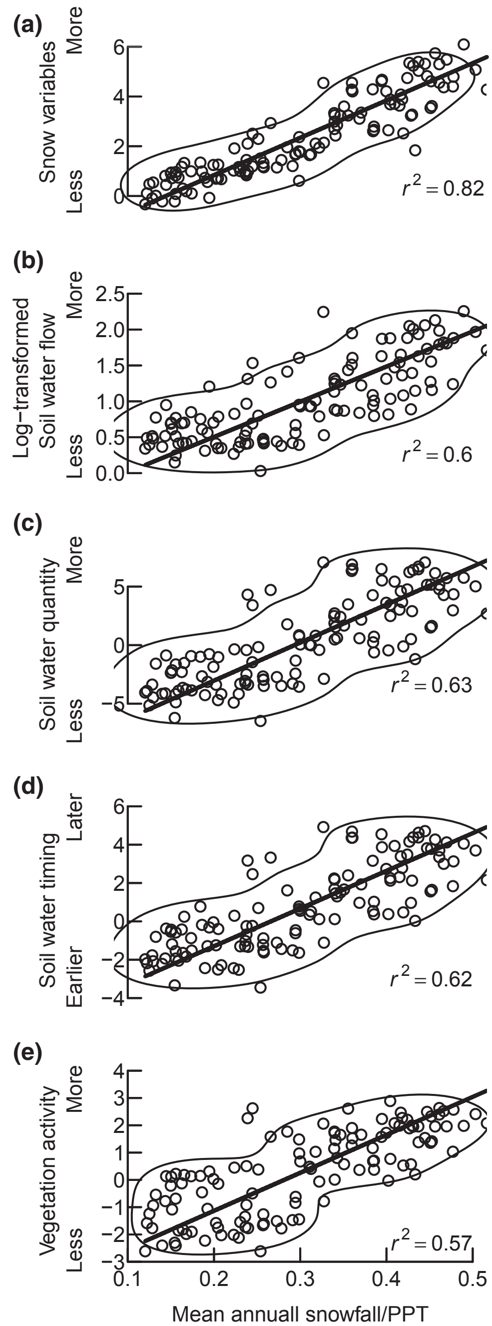

Fig. 2 Relationships between snow-precipitation ratio and five response groups under current conditions. Standardized major axis regressions (lines) with r^2 value for the first principal component scores of the 120 study sites (circles). Contour lines include 95% of the data points. Summary statistics are in Table S3.

Table 2 Relative importance of factors influencing sagebrush ecosystem water balance

		Median ranking of response groups				
	Overall rank	Snow dynamic	Soil water flow	Soil water quantity	Soil water timing	Vegetation activity
Precipitation seasonality	1	5	1	1	1	3.5
Precipitation seasonality × vegetation phenology	2	39.5	28	3.5	4	4
Precipitation-form (partitioning on/off)	3	1	4	19	6	4.5
Climate change temperature	4.5	4.5	5.5	8.5	9	2
Climate change precipitation	4.5	8	5.5	4	3	8.5
Vegetation phenology	8.5	39.5	9	12.5	2	1
Precipitation seasonality × climate change temperature	6	3.5	15	7.5	21	7.5
Precipitation-form × climate change temperature	8.5	4.5	21	9	15	8
Snow melt-runoff	34	39.5	3	25.5	36.5	39

Ranking assessed sensitivity of factors overall. Ranks of individual variables are based on ANOVA mean sum of squares. Terms for each main factor and terms with an overall rank <10 are listed. Overall rank was insensitive to omissions of unrealistic treatment combinations, such as earlier phenology and increases in snowpack. Tied ranks are rounded to one tenth. A ranking of all factor combinations is in Table S4.

and precipitation seasonality and form were also important (Table 2).

Predicted changes in temperature and precipitation influenced all of the categories of response variables we examined. Downscaled ensemble climate projections for the end of the 21st century under the SRES scenario A2 included a mean annual temperature increase of 4.6 °C and 4–7% mean increases in MAP with a seasonality shift toward winter and spring (Table 1). Temperature increases dominated our results although the consequences of rising temperature were opposite of the consequences of precipitation increases (Fig. 3). In response primarily to increased temperature, snowpack variables, i.e. snow pack and duration, decreased relative to current conditions with greater decreases in sites with higher snow-precipitation ratios (Fig. 3a). Responses of soil water flow to precipitation change and temperature increases canceled each other with larger effects for higher snow-precipitation ratios (Fig. 3b). Soil water quantity was increased by precipitation changes for medium snow-precipitation ratios whereas temperature increases decreased the quantity of soil water most strongly for medium snow-precipitation ratios. The net result was a decrease in soil water quantity that was most pronounced in sites with high snow-precipitation ratios (Fig. 3c). The effects of climate change on the timing of soil water were similar to those for soil water quantity with the net result of strong negative responses in sites with high snow-precipitation ratios (Fig. 3d). Vegetation activity responded nonlinearly. Overall climate change did not affect vegetation activity in sites with low snow-precipitation ratios. However, vegetation activity showed a threshold response for sites with snow-precipitation ratios >0.3 (0.2–0.4, corrected 95% confidence interval, Table S5) with increased activity for higher snow-precipitation ratios (Fig. 3e). Patterns were robust across SRES scenarios (Fig. S1 and Table S6).

Precipitation seasonality affected water balance and vegetation activity strongly with precipitation shifts to winter months increasing overall wetness and precipitation shifts to summer months increasing dryness (Fig. S2 and Table S8). Vegetation phenology modulated these responses with earlier biomass peaks increasing wetness. For sites with high snow-precipitation ratios, an earlier phenology was limited by snowpack and hence decreased vegetation activity (Fig. S2). Modeling all precipitation as rain, instead of partitioning into rain and snow, and snow melt-runoff decreased soil water flow for increasing snow-precipitation ratios and decreased the quantity and timing of soil water as well as vegetation activity (Figs S3, S4 and Tables S9–S10).

Discussion

Across the climatic and elevation gradient of sagebrush ecosystems, the effects of climate change on water balance and vegetation activity are often nonlinear. Increasing temperatures will hasten snow melt and increase growing season length. Increasing temperatures and reduced snowpack will cause a drier water balance with less water entering the soil and percolating

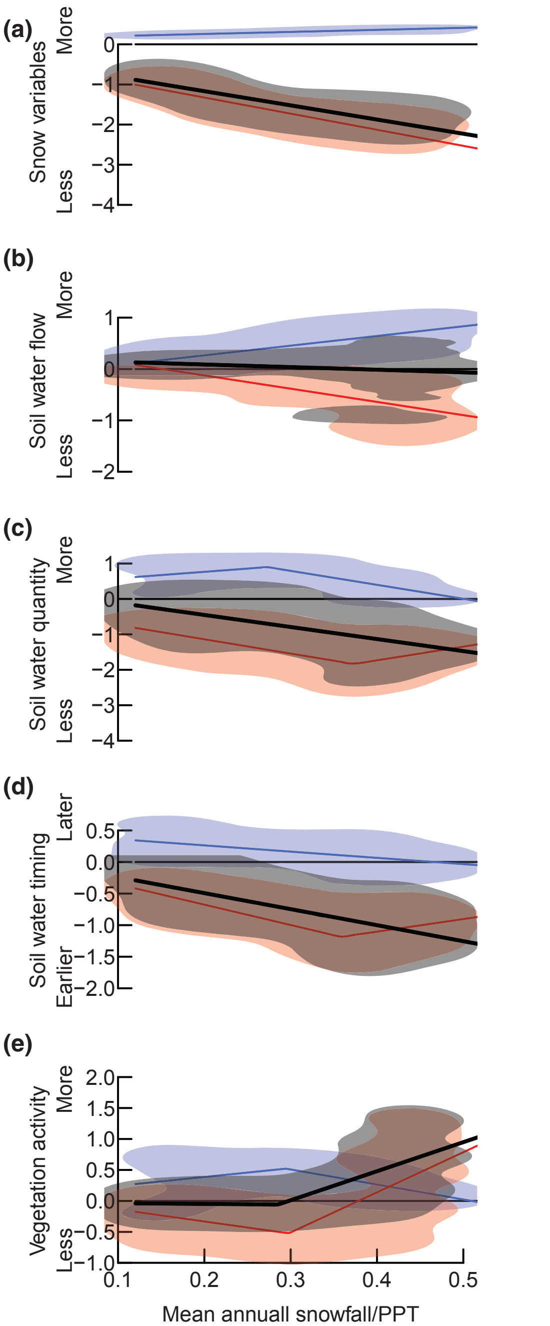

Fig. 3 Effects of 2070–2099 A2 climatic conditions vs. 1970–1999. Piecewise linear or simple linear regressions on the difference between first principal components under current and future conditions against snow-precipitation ratios of the 120 study sites for five response groups. Contour areas include 95% of the data points (a–e). Summary statistics are in Table S5. Effects of temperature scenario (red), precipitation scenario (blue), and combined climate scenario (black) for 2070–2099 under the A2 scenario. Responses to B1 scenario are in Fig. S2.

to deep soil layers and with earlier peaks and minima of soil water. Changing precipitation consisted of small increases and shifts toward winter and spring. Our results were sensitive to both the precipitation amount and pattern as has been shown for mixed grasslands in Wyoming (Chimner *et al.*, 2010). Because precipitation predictions are less certain than those for temperature (IPCC, 2007), studies such as ours need to explore the potential range of possible responses to different precipitation scenarios.

Our results identified the relative importance of factors influencing water balance. However, the sensitivity analysis combined factors with 'restricted' levels, e.g. precipitation form or climate change, with those whose levels were 'arbitrarily' set, e.g. precipitation seasonality. The precise ranking of importance depends on the relative magnitudes of the factor levels. Even though our sensitivity results are thus not on an absolute scale, they provide a sense of relative importance. High importance of climate change and precipitation seasonality for the water balance was expected (Adam *et al.*, 2009; Cayan *et al.*, 2010; Chimner *et al.*, 2010), but low importance of snow melt-runoff and the form of precipitation was surprising. Snow melt-runoff is an important water balance factor for high elevation, snow-rich areas. However, because our sites are at relatively low-elevations in dry regions, deep drainage and runoff are negligible because the soils are unsaturated (Loik *et al.*, 2004; McNamara *et al.*, 2005; Williams *et al.*, 2009). Most instances of snow amounts causing substantial runoff occur at higher elevations (Stewart *et al.*, 2004; Stewart, 2009; Rasmussen *et al.*, 2011) than our sites. Our sensitivity analysis illustrates that mid-latitude dry regions are facing considerably different consequences from changing snow conditions than either high elevation or arctic regions.

Our results indicate that the form of precipitation, snow vs. rain, is of lesser importance for ecosystem water balance than precipitation seasonality. Although turning off the partitioning of precipitation into rain and snow (i.e. simulating winter precipitation as rain only) was necessarily decoupled from climatic controls over precipitation form, it demonstrated the limited importance of whether precipitation falls as rain or snow. Ecosystem water balance was relatively unaffected by whether water is accumulated in a snowpack and subsequently melted or steadily infiltrated into the soil. During the cold season, atmospheric evaporative demand and transpiration are small at mid-latitudes. Consequently, most precipitation that falls during the cold season is stored either in the snowpack or as water in the soil. Regardless of the form of cold season precipitation, increasing evaporative demand during the cold season, caused by increased temperatures, could shift the seasonal hydrology of a system from storage-dominated (with substantial water storage in snowpack or wet winter soils creating a season with reliably wet soils) to pulse dominated (with generally dry soils and periodic brief wet pulses), a change that would have substantial impacts on vegetation composition and processes.

One of the limitations of our approach to snow vs. rain simulation is that warming winter temperatures may not, at least initially, result in uniformly warmer winters. Cold intervals alternating with warm periods may result in incidents of rain falling on frozen soil which is a condition in which surface runoff is almost certain (Iwata *et al.*, 2011). In additon, in cold dry environments, snow redistribution by wind can be an important mechanism. Landscape-scale heterogeneity of suitable conditions for big sagebrush is exacerbated by the interactions of blowing snow and topography (Burke *et al.*, 1989). Such conditions were outside the objectives for our current simulation experiments.

Our simulations also illustrate the important feedbacks vegetation phenology can exert on water balance under changing climatic conditions. Due to the high ecological sensitivity to phenology, consistent with our results, Richardson *et al.* (2012) suggest that improved phenological models should be a priority for better vegetation-climate change models. Longer snow-free growing seasons, particularly for areas of high snow-precipitation ratios in combination with earlier phenology, have the potential for substantial effects on water balance. The sensitivity of evapotranspiration to warming in snow melt-dominated systems has been attributed to a negative feedback due to increased runoff efficiency and by a positive feedback due to reduced surface albedo (Adam *et al.*, 2009). Similar opposing limitations on transpiration between effects of increased temperature and precipitation have been simulated for forested systems in California (Christensen *et al.*, 2008). Our results expand our understanding of the complex nonlinear interplay of water balance drivers in dry regions and suggest a threshold response of vegetation activity to snow precipitation ratios near 0.3. Changes in water balance in response to climate change were small at snow-precipitation ratios <0.3 and increasingly large at ratios >0.3 (Fig. 3). These responses were due to the interaction of the length of the snow-free season and the degree to which water was limiting to vegetation activity.

Implications for big sagebrush ecosystems in the semiarid western United States under declining snow conditions depend on area-specific climatic conditions described by the snow-precipitation ratio. The driest areas of big sagebrush ecosystems are also the ones with the lowest snow-precipitation ratios. Our results suggest no dramatic changes in the water balance of dry to medium areas, because there is not much snow to begin with. However, because of warming, they will likely become even drier and vegetation activity will decrease. Marginal areas near the southern limit of its range may become unsuitable for big sagebrush ecosystems in the future (Schlaepfer *et al.*, 2011b). In addition, if seasonality of precipitation shifts toward the warm season, these areas may undergo a shift in the water balance from storage to pulse dominated with an accompanying vegetation shift. In contrast, our results suggest an increase in vegetation activity for areas with the highest current snow-precipitation ratios. Increases in habitat suitability for big sagebrush ecosystems at high elevations, which correspond to the highest snow-precipitation ratios, are predicted by species distribution models coupled with an ecohydrological model (Schlaepfer *et al.*, 2011b). The species distribution models additionally predicted increases at high latitudes, particularly in the northeast of the study area, where although currently snow-precipitation ratios are small (Fig. 1), decreases of the ratio are predicted to be small and importantly spring as well as MAP is predicted to increase (Maurer *et al.*, 2007). These areas potentially become more suitable for big sagebrush as a result of a longer growing season. Big sagebrush has the potential to respond to favorable growing conditions earlier in the season because it produces two types of leaves, the smaller of which persist throughout the cold season (DePuit & Caldwell, 1973).

These results also provide insight into future changes in mid-latitude dry regions beyond western North America. Even though we simulated big sagebrush ecosystems, similar conditions, e.g. dynamics in shrublands, cold season precipitation patterns, occur in central and northern Asia in Turkmenistan, Afghanistan, Uzbekistan, Tajikistan, Kyrgyzstan, northern China, and southern Mongolia as well as in southern South America in Chile and Argentina (West, 1983). However, the capacity of other vegetation types to phenologically track earlier onsets of growing season depends on the ability of dominant plant species to react to favorable spring conditions or, in case of vegetation shifts, on the characteristics of the new species.

The magnitude and ubiquity of snowpack decline during the past several decades is unmatched over the last millennium, at least for the Rocky Mountains (Pederson *et al.*, 2011b), with major consequences for regional water resources (Barnett *et al.*, 2005; Mote *et al.*, 2005), wildfire (Westerling *et al.*, 2006), and, as we show herein, ecosystem water balance. Responses of ecosystem water balance in low elevation dry regions to altered snowpack are nonlinear, complex, and sensitive to initial and boundary conditions. These consequences are different than those in wetter high elevation alpine or high latitude arctic systems where snow conditions are more widely studied. At low elevations, the water balance consequences of declining snowpack cannot easily be anticipated. The potential of vegetation to track such changes and the details of future climatic regimes will influence composition and productivity of ecosystems, the dynamics of water balance, and the availability of water resources. Our results suggest a need for more detailed understanding of the influence that changing snow conditions will have on the water balance of dry, low-elevation ecosystems that are widespread in mid-latitudes and important for ecosystem services.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Effects of 2070–2099 B1 climatic conditions vs. 1970–1999.
Figure S2. Effects of combinations of precipitation seasonality and vegetation phenology.
Figure S3. Effects of precipitation form.
Figure S4. Effects of snow melt-runoff.
Table S1. Response variable groups, response variables, and predictions.
Table S2. Snow-category distribution in sagebrush ecosystems and their climatic characteristics (mean ± SD) under current (1970–1999) and future (2070–2099) climates.
Table S3. Summary statistics of standardized major axis regressions under current conditions for five response groups.
Table S4. Mean ranking assessed relative importance of factors.
Table S5. Summary statistics of piecewise linear or simple linear regressions under A2 climate change scenario for five response groups.
Table S6. Summary statistics of piecewise linear or simple linear regressions under B1 climate change scenario for five response groups.
Table S7. Principal component (PC) analysis for each of the five response groups.
Table S8. Summary statistics of piecewise linear or simple linear regressions under combinations of precipitation seasonality and vegetation phenology for five response groups.
Table S9. Summary statistics of piecewise linear or simple linear regressions under scenarios described by the factor 'precipitation-form' for five response groups.
Table S10. Summary statistics of piecewise linear or simple linear regressions under scenarios described by different levels of the factor snow melt-runoff for five response groups.

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