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Impacts of climate change on groundwater recharge in Wyoming big sagebrush ecosystems are contingent on elevation

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ABSTRACT.—Water is the most limiting and important natural resource in drylands, where low precipitation, high evaporative demand, and drought events are common. Groundwater is the critical resource for human livelihoods to persist through the intra-annual dry periods in dryland ecosystems. Overexploitation of groundwater resources and the externalities associated with depleted aquifers make understanding the ecohydrology of drylands an essential issue. We focus on the water balance and climatic drivers of big sagebrush ecosystems, an important dryland ecosystem type in Wyoming that covers a large spatial extent. The goal of this project was to understand how groundwater recharge (GWR) may change in magnitude and seasonality across multiple sites in Wyoming in the future. We used a combination of fieldwork and simulation modeling to explore key climatic and ecohydrological drivers of GWR. We simulated soil water balance using SOILWAT2, a process-based ecosystem-scale soil water model, and future climate data to estimate change in GWR through 2100. We found that mean annual temperature and precipitation explained 65% of the variation in future change in GWR. High-elevation (>2200 m) wet sites had larger increases in GWR in the future compared to low-elevation dry sites. The among-site variability in GWR was also higher for sites >2200 m, which indicates that mean annual precipitation and perhaps snowpack are important explanatory variables for GWR. Our research suggests that GWR for high-elevation big sagebrush sites may increase in magnitude from current values and may occur earlier in the year, with important implications for the timing and availability of water resources.

RESUMEN.—El agua es el recurso natural más importante y limitante en las tierras áridas, donde la precipitación es escasa, existen altos índices de evaporación y los eventos de sequía son habituales. El agua subterránea es un recurso fundamental, que hace posible la persistencia de los asentamientos humanos, durante los períodos secos intra-anuales de los ecosistemas de tierras áridas. La sobreexplotación de los recursos de agua subterránea y los factores externos asociados al agotamiento de los acuíferos hace que la comprensión de la ecohidrología de las tierras áridas se vuelva un tema esencial. Nos enfocamos en el balance hídrico y en los factores determinantes del clima de los grandes ecosistemas de artemisas, un importante tipo de ecosistema de tierras secas en Wyoming, que cubre una gran extensión espacial. El objetivo de este proyecto fue comprender cómo la recarga artificial de acuíferos (GWR, por sus siglas en inglés) puede cambiar en el futuro, tanto en magnitud como en estacionalidad en distintos sitios de Wyoming. Combinamos el trabajo de campo con modelos de simulación para explorar los factores claves determinantes del clima y ecohidrológicos de la GWR. Simulamos el balance hídrico del suelo utilizando SOILWAT2, un modelo de agua del suelo de escala ambiental, basado en procesos y en datos climáticos futuros para estimar el cambio de la GWR hacia el 2100. Encontramos que la temperatura y la precipitación media anual explicaron el 65% de la variación futura en la GWR. Los sitios húmedos de gran elevación (>2200 m) mostraron mayores aumentos en la GWR futura en comparación con los sitios secos de baja elevación. La variabilidad entre sitios de la GWR también fue mayor en los sitios >2200 m, indicando que la precipitación media anual y, quizás, la acumulación de nieve son variables explicativas importantes para la GWR. Nuestra investigación sugiere que las GWR en los ecosistemas de artemisas que se encuentran a mayor elevación puede aumentar en magnitud a partir de los valores actuales y tener lugar a principios del año, con importantes implicaciones en el momento y en la disponibilidad de los recursos hídricos.

Dryland ecosystems encompass 40% of the global terrestrial surface and are characterized by low and variable precipitation and frequent dry periods (Millennium Ecosystem Assessment 2005, Schlaepfer et al. 2012b, Huang et al. 2017). Two billion people live in drylands globally, and in the United States 40% of the population growth between 1960 and 2000 occurred in dryland states (Millennium Ecosystem Assessment 2005, Liu et al. 2011).

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Globally, groundwater represents 50% of the domestic water supply, 40% of all industrial water, and 20% of irrigation water supply (Döll 2009). In the western United States, more than one-third of water used for irrigation is groundwater, and as groundwater extraction persists, imbalances between groundwater recharge (GWR) and extraction result in overall groundwater depletion (Döll 2009, Döll et al. 2014).

In water-limited regions, understanding how changing climatic conditions will influence regional water balance is essential for water management and for the prevention of extended periods of water scarcity (Green et al. 2011). Some evidence suggests GWR will increase in the future primarily due to warming and a greater fraction of precipitation falling as rain. Kundzewicz and Döll (2009) used WaterGAP (Water Global Assessment and Prognosis), a global hydrology model, to project global GWR rates, which suggested the western United States may have increases in GWR of approximately 30%. Jyrkama and Sykes (2007) used the hydrologic model HELP3 (Hydrologic Evaluation of Landfill Performance) to assess the Grand River Watershed over a 40-year period. Their results suggested increases in GWR by approximately 100 mm/year due to a greater fraction of precipitation received as rain than as snow and increasing temperatures that will reduce ground frost and increase recharge (Jyrkama and Sykes 2007). Palmquist et al. (2016a, 2016b) used SOILWAT2, a soil-water balance model, to project mean increases of 30% in GWR and shifts in peak GWR to earlier in the year by mid- and end-of-century for 898 randomly selected big sagebrush ecosystems in the western United States.

Our study focused on temperate dryland ecosystems typified by higher evaporative demand than precipitation, with total precipitation and snowmelt as the major controls on soil-water recharge and GWR (Schlaepfer et al. 2012a). In the western United States and Wyoming, big sagebrush (*Artemisia tridentata*) ecosystems are an extensive dryland vegetation type (West and Young 1989, Knight et al. 2014) and are the focus of our work. Within Wyoming, these ecosystems cover about 33% of the terrestrial surface (Knight et al. 2014) and provide important habitat for many plant and animal species of conservation concern (Wisdom et al. 2005).

Our objective was to assess groundwater recharge across 51 sites representing drylands dominated by big sagebrush in Wyoming. These sites spanned the range of big sagebrush plant community types, as well as their climatic and elevational gradients within Wyoming. We assessed GWR using a process-based, daily time-step soil water simulation model (SOILWAT2) under current and projected climate using 13 global circulation models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for representative concentration pathway 8.5 (RCP8.5). Specifically, we asked 3 questions: (1) What are the predicted future changes in average annual and seasonal GWR rates in big sagebrush ecosystems in Wyoming? (2) How do the predicted changes in average annual and seasonal GWR vary between high- and low-elevation sites? And (3) to which climate variables are changes in recharge rates most sensitive? Based on a combination of information from fieldwork and simulation modeling, we had 4 expectations: (1) high GWR variability across sites given the strong relationships between the type and timing of precipitation influence on GWR in drylands, (2) a positive relationship between elevation and GWR as high-elevation areas receive larger quantities of precipitation and subsequent GWR, (3) a precipitation regime of high-elevation sites dominated by snow, and (4) high-elevation sites with greater snowpack, which will contribute to increased magnitudes of GWR. Our focus on groundwater stemmed from the integral role groundwater recharge plays within the water balance of drylands. In addition, quantifying how climate change will affect groundwater is critical for future water management efforts and prevention of unsustainable extraction of subsurface water in drylands (Green et al. 2011).

METHODS

Study Area, Site Selection, and Field Sampling

Our 51 sites spanned the environmental gradients within Wyoming big sagebrush plant communities from hot, dry sites at low elevations (<2200 m) to cold, wet sites at higher elevations (>2200 m). We divided sites into elevational bins with 2200 m as the boundary between low- and high-elevation sites to distinguish between sites dominated by *Artemisia*

TABLE 1. Elevation, mean annual climate, and mean annual ecohydrological variables for sites in each Wyoming basin. Change in climatic and ecohydrological variables represent the difference in mean annual values from current to the end-of-century (2070–2100). For more information on basins, see Supplementary Material 1.

Climatic or geospatial variable	Bighorn	Great Divide	Green River	Hanna	Laramie	Saratoga	Shirley	Thunder	Washakie	Wind River
Elevation	1502	2210	2201	2152	2534	2474	1946	1432	2170	1886
MAP (mm)	249	255	323	306	580	528	324	369	222	268
Change in MAP (mm)	36	41	48	37	83	74	43	36	16	47
MAT (°C)	6.58	4.35	2.86	5.57	2.90	2.27	5.48	7.74	5.26	5.74
Change in MAT (°C)	5.34	5.58	5.75	5.48	5.37	5.52	5.51	5.31	5.60	5.54
Cold-season precipitation (mm)	73	92	139	129	219	237	131	97	74	81
Change in cold-season precipitation (mm)	19	27	28	28	101	88	45	22	20	15
Cold-season precipitation/total precipitation ratio	0.28	0.36	0.41	0.42	0.38	0.45	0.41	0.26	0.33	0.30
Change in cold-season precipitation/total precipitation ratio	0.05	0.07	0.05	0.04	0.11	0.10	0.06	0.03	0.06	0.03
Snow/precipitation ratio	0.15	0.29	0.35	0.34	0.42	0.48	0.30	0.17	0.23	0.20
Change in snow/precipitation ratio	−0.06	−0.07	−0.13	−0.18	−0.09	−0.16	−0.12	−0.08	−0.10	−0.10

tridentata ssp. *wyomingensis* and sites dominated by *Artemisia tridentata* ssp. *vaseyana* (West and Young 1989, Knight et al. 2014). These 2 subspecies occur at different elevations: *Artemisia tridentata* ssp. *vaseyana* occupies higher-elevation sites (typically over 2200 m) than *Artemisia tridentata* ssp. *wyomingensis* (typically below 2200 m). The boundary we set between low- and high-elevation sites was also compelling because our sites >2200 m receive 73% more mean annual precipitation (MAP) than our sites <2200 m. Thus, we made the choice to differentiate on elevation based upon dominance of different *Artemisia tridentata* subspecies and differences in the magnitude of MAP. Mean elevation among our sites was 1993 m, with a minimum of 1310 m (in the Thunder Basin) and a maximum of 2652 m (in the Saratoga Basin) (Tables 1, 2). Mean annual temperature (MAT) was 4.8 °C (range −0.01 °C to 8 °C), MAP was 312 mm (range 184 to 580 mm), and the mean snow ratio, which is the proportion of annual precipitation received as snow, was 0.30 (range 0.12 to 0.53) (Tables 1, 2).

Sites were chosen to not only capture the relevant environmental gradients, but also to span Wyoming's basins that were dominated by *Artemisia tridentata* (Table 1; Knight et al. 2014). Additional site selection criteria included minimal disturbance from invasive species (e.g., *Bromus tectorum*), natural resource extraction, heavy grazing, and presence of a big sagebrush overstory with an understory of native perennial grasses and forbs.

At each site, we collected soil samples within a 1000-m^2 Carolina Vegetation Survey plot (Peet et al. 1998). A 7-cm-diameter auger was used to obtain soil samples at depths of 0–10 cm, 10–20 cm, and 20–30 cm in four of the ten 100-m^2 subplots for all 51 sites. Soil samples were analyzed for percent gravel (particles >2 mm), sand, silt, and clay using a hydrometer method modified from Bouyoucos (1951).

Soil Water Simulation Modeling

We calculated changes in diffuse groundwater recharge for each of our 51 sites using SOILWAT2, a daily time-step, multiple soil layer, process-based soil water balance simulation model (Lauenroth and Bradford 2006, Schlaepfer et al. 2012a, 2012b, Bradford et al. 2014a). SOILWAT2 has been successfully applied to multiple dryland ecosystems, such

Table 2. Elevation, annual climate, and annual ecohydrological vaiables for all 51 sites. Variables are shown as averages for all sites, standard deviations (SD) for all sites, and mean values for sites <2200 m and >2200 m elevation. Changes in climatic and ecohydrological variables represent the differences in mean annual values from current to the end-of-century (2070–2100).

Climatic or geospatial variable	Site average	SD	(>2200 m)	(<2200 m)
Elevation	1993	345	2352	1844
MAP (mm)	312	101	379	278
Change in MAP (mm)	46	18	63	39
MAT (°C)	4.80	2.00	2.45	5.77
Change in MAT (°C)	5.52	−0.07	5.57	5.49
Cold-season precipitation (mm)	12	59	168	91
Change in cold-season precipitation (mm)	34	24	58	24
Cold-season precipitation/total precipitation ratio	0.4	0.08	0.41	0.33
Change in cold-season precipitation/total precipitation ratio	0.04	0.09	0.06	0.03
Snow/precipitation ratio	0.3	0.11	0.39	0.22
Change in snow/precipitation ratio	−0.1	−0.03	−0.13	−0.10
Groundwater recharge (mm)	25	38	53	15
Change in groundwater recharge (mm)	6	12	17	2

as grasslands (Lauenroth and Bradford 2006), big sagebrush ecosystems (Schlaepfer et al. 2012a, 2012b, Palmquist et al. 2016a, 2016b), lodgepole pine–sagebrush ecotones (Bradford et al. 2014b), and other drylands globally (Schlaepfer et al. 2017). The version for big sagebrush ecosystems incorporates a validated snow module, hydraulic redistribution, and site-specific vegetation parameters (Schlaepfer et al. 2012b). SOILWAT2 uses daily precipitation and temperature data, monthly climate conditions (relative humidity, wind speed, cloud cover), monthly vegetation parameters (total aboveground biomass, litter, living aboveground biomass, active root depth profile), and properties from various layers of the soil profile to model all components of daily water balance (Schlaepfer et al. 2012a, 2012b). Included in the components of the daily water balance are interception by vegetation and litter, evaporation of intercepted water, bare-soil evaporation, infiltration, transpiration from each soil layer, and groundwater recharge. Of the output generated by SOILWAT2, we focus on daily and annual groundwater recharge.

Model Parameters and Input Data

For each of our 51 sites, we extracted daily temperature and precipitation data for current conditions from ⅛-degree gridded weather data for 1980–2010 (Maurer et al. 2002). Monthly estimates of relative humidity, wind speed, and cloud cover were obtained from the Climate Maps of the United States (http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl). Future temperature and precipitation data for each of 13 Global Circulation Models (GCMs) were extracted from the “Downscaled CMIP3 and CMIP5 Climate and Hydrology Projects” archive (Maurer et al. 2007). We used a hybrid-delta downscaling method, which utilizes historic daily weather data with monthly future predictions to calculate future daily data (Hamlet et al. 2010, Dickerson-Lange and Mitchell 2014). To run our model, we first statistically downscaled the data from each of the 13 GCMs for each of our 51 sites. We parameterized site-specific soil properties for each soil layer using percent sand, silt, clay, and gravel calculated from soil samples collected in the field. We obtained soil depth for each site from the SSURGO database (Soil Survey Staff 2017a) when available and from STATSGO otherwise (Soil Survey Staff 2017b). We generated site-specific vegetation parameters based on both current and future climatic conditions. The relative abundance of plant functional types for current and future conditions were estimated using empirically observed relationships derived by Paruelo and Lauenroth (1996) and described and applied in Bradford et al. (2014a). Current and future plant functional type composition and the associated vegetation parameters (monthly aboveground biomass, monthly live biomass, and monthly litter) were estimated based on MAP, ratio of winter precipitation (December–February) to MAP, ratio of summer precipitation (June–August) to MAP, and MAT (see Appendix S2 *in* Bradford et al. 2014a). We then ran

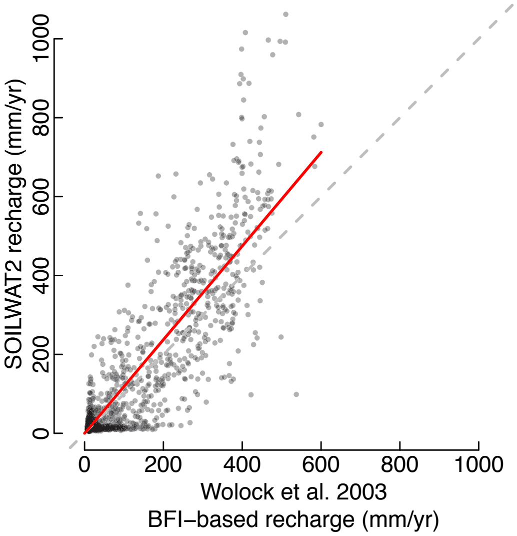

Fig. 1. Model comparison of the BaseFlow Index (BFI) to SOILWAT2 estimated groundwater recharge for 1951–1980 for all sites from Wolock et al. (2003) in Wyoming. The gray dotted line represents the 1:1 line. The red line is the best-fit line ($y = 1.19x + 0$). The RMSE is 78 mm per year.

SOILWAT2 using site-specific inputs for each site/GCM combination.

Data Analysis

Answering our research questions required us to quantify changes in future precipitation and temperature regimes and GWR across each of the 13 GCMs, as defined by RCP8.5. We summarized the magnitude, type, and seasonality of precipitation, including snowpack (SWE, mm), cold-season precipitation (mm), cold-season precipitation/total precipitation ratio, and snow/precipitation ratio, along with MAT (°C) and daily and annual GWR (mm) (Table 1). The annual mean value for each variable was calculated by averaging output for each site/GCM combination for the current, midcentury, and end-of-century time periods. We calculated the daily mean for each variable across each day of the year for all 51 sites and all 13 GCMs for each time period. In addition to quantifying mean values, we also present variability in GWR and snowpack in response to forcing by climate from the 13 different GCMs. To summarize variability in GWR and snowpack on a daily basis, we calculated the daily mean across our 51 sites for each of the 13 GCMs. We present the minimum and maximum of those 13 values for each day of the year (DOY). These results provide perspective on the uncertainty of future GWR and snowpack.

We assessed relationships between GWR and climate variables using multiple linear regression. We then used additive variance partitioning to quantify the variance in GWR explained by each variable individually, along with the shared variance explained by multiple variables (Legendre and Legendre 2012). In addition, we summarized each variable for the 2 elevation bins, >2200 m and <2200 m (Table 2), to understand how changes in GWR differed between lower- and higher-elevation sites. We compared estimated GWR from SOILWAT2 for 1951–1980 in Wyoming to the Baseflow Index (BFI) data from Wolock et al. (2003) to assess the degree of confidence we should have in the performance of SOILWAT2 in Wyoming. BFI is a commonly used metric for estimating potential recharge (Wolock 2003, Niraula et al. 2017).

Results

Comparing SOILWAT2 Recharge with BFI-based Recharge

We extracted BFI recharge data for Wyoming from 1951 to 1980 to make a comparison between estimates of groundwater recharge from SOILWAT2 and estimates from BFI (Fig. 1). The regression of SOILWAT2 on BFI had an intercept of zero and a coefficient of 1.19, indicating that the SOILWAT2 estimate of GWR was on average 19% higher than BFI. The Pearson correlation coefficient was 0.89.

Predicted Future Changes in Annual and Seasonal Groundwater Recharge Rates

Compared to current conditions, our results indicated that GWR will increase in magnitude in the future (Fig. 2). Our simulations suggested mean annual increases of 4 mm (16%) and 6 mm (24%) in GWR across all sites by midcentury (2030–2060) and end-of-century (2070–2100), respectively (Table 2). GWR was projected to occur earlier in the year, with a longer duration of sustained recharge by both midcentury and end-of-century, especially for high-elevation sites (Fig. 3b). For current conditions, the maximum GWR occurred at the

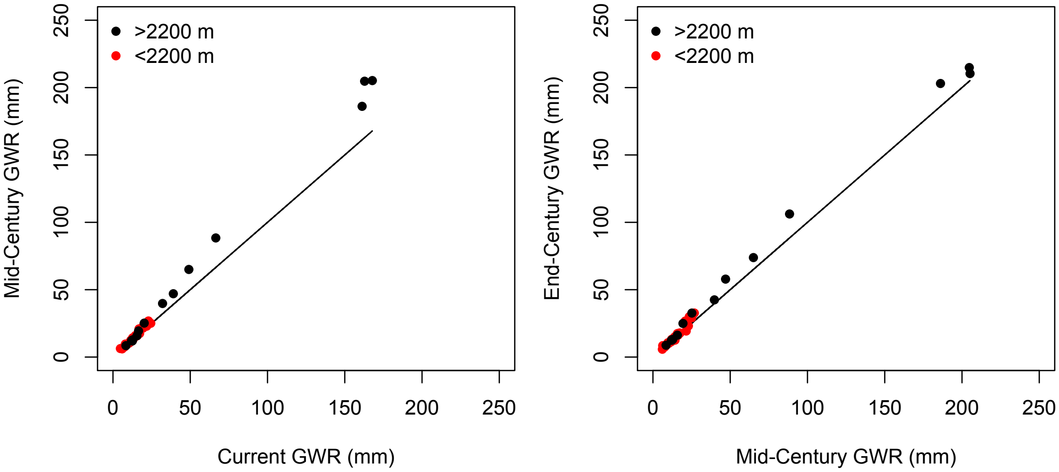

Fig. 2. Current mean annual groundwater recharge (GWR) versus midcentury GWR (left) and mean annual midcentury GWR versus end-of-century GWR (right). The black lines represent the 1:1 relationship. Sites are highlighted by elevational bin (<2200 m [red], >2200 m [black]).

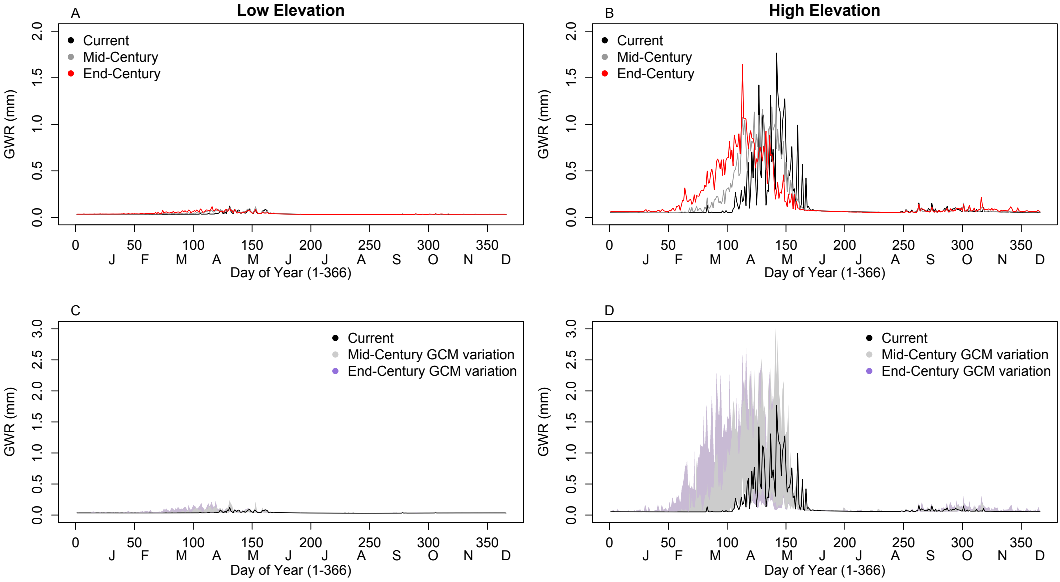

Fig. 3. Daily groundwater recharge (GWR) for sites <2200 m and >2200 m through the century. Daily GWR magnitudes represent mean values across all 13 GCMs for each day of the year for low-elevation sites (**A**) and high-elevation sites (**B**). The min-max variation in daily absolute GWR values for each of the 13 GCMs averaged across the 51 sites for each day of the year for low-elevation sites (**C**) and high-elevation sites (**D**). Each line corresponds to a different time period: current (1980–2010), midcentury (2030–2060), end-of-century (2070–2100).

end of May. By midcentury, that peak occurred 15 d earlier, and by the end-of-century, the maximum GWR shifted 30 d earlier to late March. GWR was projected to start 49 d earlier by the end-of-century with a magnitude that was on average 0.10 mm per day greater than current conditions (Fig. 3a, b). For both low- and high-elevation sites, as well as estimates for the mid- and end-of-century, the variability in estimates introduced by differences among GCMs was substantially larger than the means (Fig. 3d).

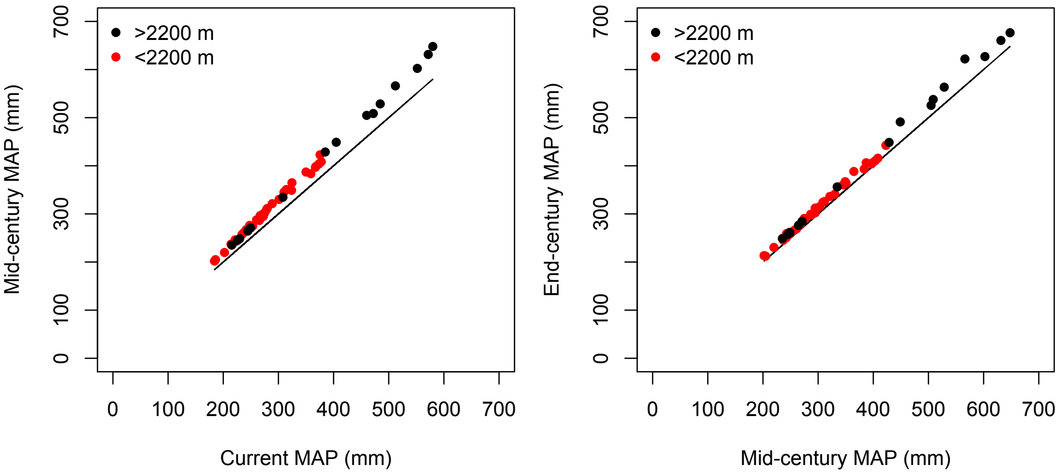

Fig. 4. Current mean annual precipitation (MAP) versus midcentury MAP (left) and midcentury MAP versus end-of-century MAP (right). The black lines represent the 1:1 relationship. Sites are highlighted by elevational bin (<2200 m [red], >2200 m [black]).

Variation in Annual and Seasonal GWR between Low- and High-elevation Sites

We found a positive relationship between elevation and GWR (current: $r = 0.46$; midcentury: $r = 0.47$; end-of-century: $r = 0.49$) which was related to differences in MAP across low- and high-elevation sites (Supplementary Material 2). Under current conditions, sites >2200 m had 101 mm more precipitation on average than sites <2200 m (Table 2). MAP was projected to increase the most at the highest-elevation sites (Fig. 4). Our simulation results suggested increases in MAP of 27 mm (<2200 m) and 38 mm (>2200 m) by midcentury, and 39 mm (<2200 m) and 63 mm (>2200 m) by end-of-century for low- and high-elevation sites, respectively (Table 2). Sites >2200 m also had the largest average annual increases in GWR in the future (Fig. 2, Table 2). The 3 sites with the largest magnitude and change in GWR were at elevations >2200 m (Supplementary Material 2). Two of these were in the Saratoga Basin and one was in the Laramie Basin.

GWR Sensitivity to Mean Annual Precipitation and Mean Annual Temperature

Future MAT and MAP explained 65% of the variation in future GWR. Variance partitioning indicated that MAP explained more variation in future GWR ($R^2 = 0.37$) than MAT ($R^2 = 0.03$). The shared variance explained by both MAP and MAT was 0.25. Net increases in GWR were associated with higher future MAP (Supplementary Material 2). The magnitude of the GWR increase decreased by the end of the century, indicating that the largest increases in GWR and MAP occurred by midcentury (Table 2, Fig. 2).

Both MAT and MAP influenced GWR through their effect on the mean snow precipitation ratio. Under both current and future conditions, GWR was strongly positively correlated to the snow precipitation ratio (current: $r = 0.80$; midcentury: $r = 0.82$; end-of-century: $r = 0.83$). However, by the end of the century our results suggested an 11% decrease in precipitation received as snow, indicating a shift to rain becoming more dominant in the precipitation regime for these sites, while snow remained the dominant variable contributing to GWR (Table 2). In addition, our simulations projected snowpack peak volume occurring 44 d earlier by the end of the century with a 75% decrease in snow-water equivalent (Fig. 5). At the end of the century, snowpack was projected to disappear 26 d earlier and the projected duration of zero snowpack increased by 52 d (Fig. 5). Our results suggest declines in the snow/precipitation ratio for all sites for each of the 13 GCMs, except for one site where one of the 13 GCMs used in our simulations suggests an increase in

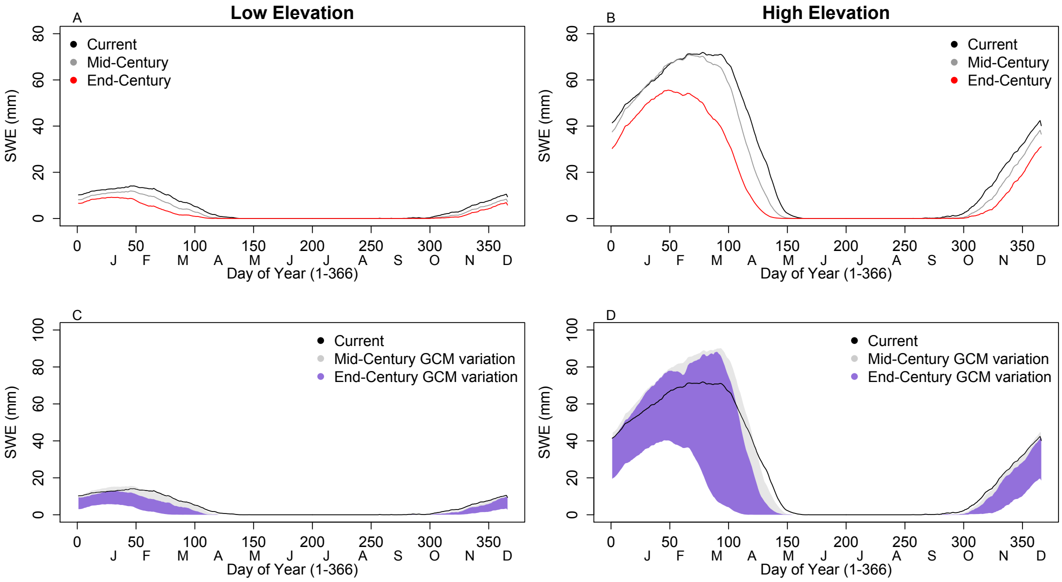

Fig. 5. Daily snowpack for sites >2200 m and <2200 m through 2100. Snow-water equivalence (SWE) refers to the volume of water present within the snowpack. Daily SWE magnitudes represent the mean SWE value across all 13 GCMs for each day of the year for low-elevation sites (**A**) and high-elevation sites (**B**). The min-max variation in daily absolute SWE values for each of the 13 GCMs are averaged across the 51 sites for each day of the year for low-elevation sites (**C**) and high-elevation sites (**D**). Each line corresponds to a different time period: current (1980–2010), midcentury (2030–2060), and end-of-century (2070–2100).

snow/precipitation ratio by the end of the century. We attribute these future declines in snow/precipitation ratio and snowpack to increased temperatures.

DISCUSSION

Our results indicated that, on average across our 51 big sagebrush sites, GWR will likely increase in the future. Those increases were considerably larger for high-elevation sites (>2200 m) relative to low-elevation sites (<2200 m). Larger magnitudes of GWR for sites >2200 m arose primarily because those sites currently receive larger amounts of precipitation and will continue to receive larger amounts in the future. MAP and MAT collectively explained 65% of the variation in GWR at the end of the century.

Relationship Between Elevation, MAT, MAP, and GWR

Our results indicated that the most sensitive macroclimatic variables that influence GWR are MAT and MAP, the magnitude, type, and seasonality of which are essential for replenishing both soil water in the deepest soil layers and groundwater. The rate and magnitude of GWR is dependent on losses from evapotranspiration, snowpack characteristics, land use, and the amount, intensity, and timing of precipitation (Klove et al. 2014). In Wyoming, groundwater recharge for drylands dominated by big sagebrush is controlled by total precipitation, precipitation in the cold season, and snowmelt, which allow for the establishment of hydraulic connectivity and eventual recharge (Schlaepfer et al. 2012a). In big sagebrush ecosystems, annual evaporative demand is greater than annual precipitation, which results in a dependence on cool season precipitation for recharge of deep soil layers during the spring and early summer months (Schlaepfer et al. 2012a). Therefore, the most relevant processes influencing GWR occur during periods of relatively low temperature and low evaporative demand, while water storage at depth in the soil profile contributes to water availability during dry months (Lauenroth et al. 2014). Future increases in precipitation and GWR closely follow an elevational gradient, with the largest expected magnitudes at the highest elevations.

Implications of Climate Change

Our simulation results indicated that climate change will likely affect the water balance of big sagebrush ecosystems in Wyoming through increasing total precipitation and temperature and shifting precipitation type and seasonality, similar to other dryland studies (Jyrkama et al. 2007, Ajami et al. 2012, Schlaepfer et al. 2012a, 2012b, Klove et al. 2014, Palmquist et al. 2016a). Similar to our work, several studies have reported shifts in the mean seasonal and annual groundwater levels (Schlaepfer et al. 2012b, Lauenroth et al. 2014, Palmquist et al. 2016a, 2016b), which were correlated with the amount of precipitation and snowmelt (Schlaepfer et al. 2012a, Klove et al. 2014). Our work builds on these previous studies (i.e., Palmquist et al. 2016a, 2016b) through the exploration of climatic variables most relevant to GWR and the identification of distinctive patterns in future GWR that are closely related to differences in elevation (i.e., >2200 m or <2200 m) for sites spanning the climatic and elevational gradients characteristic of big sagebrush ecosystems in Wyoming.

Changing precipitation regimes, changing soil water dynamics, and increasing temperatures can have important implications for the distribution and abundance of plant functional types (Sala et al. 1997). Warmer temperatures increase potential evapotranspiration and can alter the competitive advantage of different plant species and the length of the growing season (Ajami et al. 2012, Lauenroth et al. 2014). Furthermore, with warmer temperatures, C_4 species may have a competitive advantage (Paruelo and Lauenroth 1996), resulting in potential shifts in plant functional type composition in big sagebrush plant communities. However, Lauenroth et al. (2014) suggested that the changes in precipitation regimes and temperature variability would have to be extreme for any large-scale shifts in dominance to occur in big sagebrush ecosystems.

SOILWAT2 Model Performance in Wyoming

Comparison of SOILWAT2 estimates of GWR in Wyoming with the Baseflow Index (BFI) (Wolock et al. 2003) revealed a close relationship (Fig. 1). An average overestimation of 19% by SOILWAT2 is very likely attributable to the fact that SOILWAT2 does not estimate runoff separately, which results in the inclusion of water that would otherwise be lost to overland flow in estimates of recharge. A recent comparison of 3 widely used land surface models (Noah, Mosaic, and VIC) with BFI (Niraula et al. 2017) found that Noah estimates of GWR were most highly correlated with BFI (r = 0.86), which is similar to the relationship we document between SOILWAT2 and BFI GWR estimates (data from the western United States: r = 0.88; data from Wyoming: r = 0.89). Noah underestimated BFI by 19%, Mosaic underestimated BFI by 30%, while VIC overestimated BFI by 32% (Niraula et al. 2017). Thus, our SOILWAT2 estimates of GWR are similar to estimates from both BFI and other models that predict GWR.

Future Climatic Uncertainty

Any analysis that uses future climate information is subject to the uncertainty associated with both the RCPs (representative concentration pathways) and the individual GCMs (Baker et al. 2017). Utilization of models incorporating GCM data as input will also have uncertainty associated with assumptions of initial conditions, downscaling techniques, and empirical model deficiencies for the parameterization of recharge and potential evapotranspiration (Ajami et al. 2012). Studies have suggested that to understand the full range of potential climate change outcomes on the ecohydrology of a region, it is necessary to utilize multiple GCMs. Palmquist et al. (2016a) exemplified the significance of assessing the range of GCM outcomes: input data from 9 of 10 GCMs resulted in increases in GWR, while the data from one GCM projected a decrease. Our study summarized climatic and ecohydrological variables across 13 GCMs by presenting mean values, similar to an ensemble approach, but it also summarized variability in GWR forced by 13 different GCMs to gain a more thorough understanding of the effect climate change may have on variables influencing GWR, as well as characterizing the uncertainty across GCMs. Although there is high variability in future GWR forced by the 13 GCMs, particularly for the wet sites, most GCMs agree on the direction of change of the mean values we report (see Supplementary Material 3).

Implications for Water Management

From 1960 to 2000, 40% of the population growth experienced by the United States took place in arid and semiarid regions (Liu et al. 2011). Ensuring sustainable access to water in these areas will require accurate estimates of diffuse GWR under varying climate conditions (Green et al. 2011). This work and other studies have shown that higher temperatures in the winter season, compared to historical trends, will likely have important implications for sustainable management of water resources in dryland basins where the timing and magnitude of recharge is projected to change (Ajami et al. 2012).

Our results suggested a 75% reduction in snowpack by the year 2100, which could have serious implications for the water budgets of Wyoming and downstream areas (Jyrkama and Sykes 2007, Harpold et al. 2017). Decreasing snowpack will directly influence overland flow, which is regionally important for irrigation and domestic uses, and will have additional implications for flood management (Harpold et al. 2017). Even though precipitation is projected to increase slightly in the future for our sites, the timing and form of precipitation will influence the duration and severity of periods of water scarcity in Wyoming and likely in other states with similar topography and climate. The potential for snowpack reductions due to climate and vegetation changes following hypsometric gradients between elevation and increasing precipitation, is a well-established trend suggesting that snowpack variability poses a barrier to comprehensive water resources management in the western United States (Harpold et al. 2017, Tennant et al. 2017). Lack of winter precipitation as snow, increasing variability and seasonality in the dominant precipitation regimes characteristic of high elevations, decreasing duration of snow cover, and increasing rates of ablation are all factors associated with predicted regional warming trends in the western United States. These trends require further attention and development of metrics that will help inform scientists and water managers on the vulnerabilities of drylands to increased drought periodicity (Pierce et al. 2013, Tennant et al. 2017, Harpold et al. 2017).

Garnering a better understanding of underlying ecohydrological processes influencing GWR is critical for comprehensive water management strategies for dryland ecosystems and will be important for mitigating future conflicts over water scarcity (Wang et al. 2012). As regions have experienced an increase in the frequency and severity of drought, discussions of regional and transboundary water issues have continued to develop in complexity with a concomitant change in methods for assessing the water balance of these regions (Green et al. 2011).

SUPPLEMENTARY MATERIAL

Three online-only supplementary files accompany this article (scholarsarchive.byu.edu/wnan/vol79/iss1/4).

SUPPLEMENTARY MATERIAL 1. Surface map of Wyoming showing the location of 51 sites representing a dryland ecosystem dominated by big sagebrush. Prominent mountain ranges and basins of interest are also shown.

SUPPLEMENTARY MATERIAL 2. Current groundwater recharge (GWR) and absolute change of GWR versus current mean annual precipitation (MAP) and end-of-century MAP.

SUPPLEMENTARY MATERIAL 3. Mean change in groundwater recharge (GWR) by end-of-century for each site (change in GWR) and the number of global circulation models (GCMs) that agree on the direction of the mean change in GWR for each site (GCM agreement, out of 13 possible GCMs).

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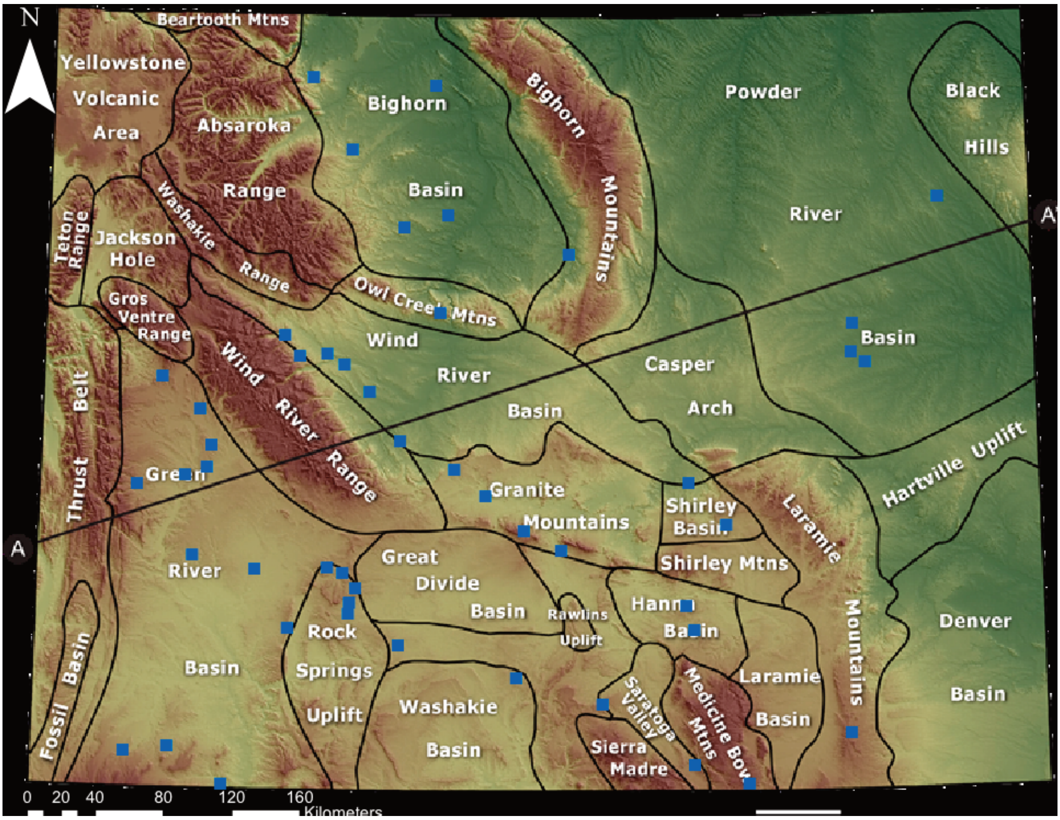
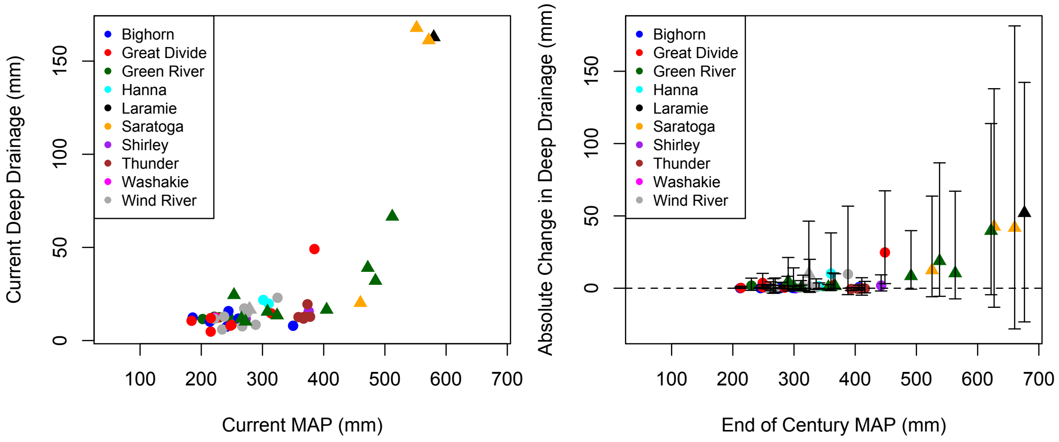


SUPPLEMENTARY MATERIAL 1. Surface map of Wyoming where blue squares represent the geographical location of each of the 51 sites representing a dryland ecosystem dominated by sagebrush. Prominent mountain ranges and basins of interest are outlined in black.



Supplementary Material 2. Current groundwater recharge (GWR) and absolute change of GWR versus current mean annual precipitation (MAP) and end-of-century MAP. All 51 sites are highlighted by basin. Triangles represent sites >2200 m elevation, while circles represent sites <2200 m. Whiskers correspond to the minimum and maximum GCM values for the absolute change in GWR for each of the 51 sites.

SUPPLEMENTARY MATERIAL 3. Mean change in groundwater recharge (GWR) by end-of-century for each site (change in GWR) and the number of global circulation models (GCMs) that agree on the direction of the mean change in GWR for each site (GCM agreement, out of 13 possible GCMs). Sites are sorted according to elevation and elevational bin (low or high).

Site	Elevation (m)	Elevational bin	Change in GWR	GCM agreement
21	1310	Low	−0.5	11
17	1345	Low	0.05	6
13	1424	Low	0.1	4
22	1428	Low	−0.4	10
18	1446	Low	−0.4	10
12	1473	Low	0.7	11
16	1481	Low	0.4	9
19	1488	Low	−0.1	8
20	1490	Low	−0.2	9
14	1631	Low	0.2	7
37	1660	Low	1.3	5
15	1662	Low	−0.1	11
9	1717	Low	−0.1	9
27	1735	Low	0.4	10
30	1787	Low	−0.03	10
28	1822	Low	−0.1	10
29	1847	Low	−0.1	9
26	1892	Low	0.7	9
23	1892	Low	9.7	10
36	1947	Low	2.6	12
24	2006	Low	0.9	8
1	2019	Low	1.8	10
2	2065	Low	0.7	13
34	2067	Low	1.9	12
38	2083	Low	9.9	11
41	2099	Low	1.5	11
11	2111	Low	1.3	12
40	2119	Low	1.3	8
25	2140	Low	0.5	8
4	2157	Low	3.7	13
47	2158	Low	0.4	10
7	2171	Low	0.6	11
10	2175	Low	1.8	7
39	2177	Low	4.7	10
31	2180	Low	0.2	8
8	2193	Low	10.1	9
3	2203	High	−0.1	10
32	2209	High	0.4	10
50	2217	High	39.7	11
6	2242	High	0.4	10
5	2279	High	0.4	11
49	2284	High	8.4	12
48	2300	High	0.7	12
42	2302	High	18.8	10
43	2365	High	42.6	12
33	2379	High	0.7	13
46	2406	High	12.4	8
51	2438	High	10.4	8
35	2465	High	24.7	13
44	2535	High	52.0	12
45	2652	High	41.8	9