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Potential impacts of overlapping land-use and climate in a sensitive dryland: a case study of the Colorado Plateau, USA

Stella M. Copeland,[1,2,]† John B. Bradford,[2] Michael C. Duniway,[3] and Rudy M. Schuster[4]

[1]*Merriam-Powell Center for Environmental Research and Department of Biological Sciences, Northern Arizona University, Flagstaff, Arizona 86001 USA*
[2]*Southwest Biological Science Center, U.S. Geological Survey, Flagstaff, Arizona 86001 USA*
[3]*Southwest Biological Science Center, U.S. Geological Survey, Moab, Utah 84532 USA*
[4]*Fort Collins Science Center, U.S. Geological Survey, Fort Collins, Colorado 80526 USA*

Citation: Copeland, S. M., J. B. Bradford, M. C. Duniway, and R. M. Schuster. 2017. Potential impacts of overlapping land-use and climate in a sensitive dryland: a case study of the Colorado Plateau, USA. Ecosphere 8(5):e01823. 10.1002/ecs2.1823

Abstract. The combination of co-occurring climate change and increasing land-use is likely to affect future environmental and socioeconomic conditions in drylands; these hyper-arid to sub-humid landscapes are limited by water resources and prone to land degradation. We characterized the potential for geographic overlap among land-use practices and between land-use and climate change on the Colorado Plateau—a dryland region experiencing rapid changes in land-use and facing aridification. We characterized spatial patterns and temporal trends in aridification, land-use, and recreation at the county and 10-km^2 grid scales. Increasing trends and overlapping areas of high intensity for use, including oil and gas development and recreation, and climate drying, suggest areas with high potential to experience detrimental effects to the recreation economy, water availability, vegetation and wildlife habitat, and spiritual and cultural resources. Patterns of overlap in high-intensity land-use and climate drying differ from the past, indicating the potential for novel impacts and suggesting that land managers and planners may require new strategies to adapt to changing conditions. This analytical framework for assessing the potential impacts of overlapping land-use and climate change could be applied with other drivers of change or to other regions to create scenarios at various spatial scales in support of natural resource planning efforts.

Key words: agriculture; aridification; climate change; Colorado Plateau; ecosystem services; grazing; landscape attributes; land-use; oil and gas development; population growth; recreation; renewable energy.

Received 20 October 2016; revised 22 March 2017; accepted 10 April 2017. Corresponding Editor: Ginger R. H. Allington.

† **E-mail:** scopeland@usgs.gov

Introduction

Global environmental change includes several different drivers of change that are simultaneously impacting ecosystems and the services that they provide. Foremost among them is climate change, which is predicted to profoundly affect human societies by altering key environmental properties related to human well-being, such as decreasing both freshwater availability and plant productivity (IPCC 2014). In addition to climate change, ecosystems are also being influenced by other drivers of change related to human land-use, including energy extraction, residential development, agricultural practices, and recreational activities. The effects of climate change and land-use are well recognized, and assessing their individual impacts is a major focus of much of modern natural resource science. However, relatively little scientific attention has focused on quantifying how and where multiple, simultaneous drivers of change will have important influences on ecosystems. Because many drivers of change such as climate change and many types of land-use are both pervasive and widespread, understanding these combined effects is essential to accurately forecast loss of ecosystem services, including decreased water resources, soil degradation, and negative impacts on environmental characteristics of high cultural and spiritual value (MEA 2005*a*).

The combined effects of individual land-use pressures and climate trends may have significant, broad-scale impacts on multiple environmental services and landscape attributes (MEA 2005*a*). Studies that address the combined impacts of climate change and one or more types of land-use commonly find that the spatial and temporal trends of impacts differ from those where only climate change or land-use is considered (e.g., Asner et al. 2010, Ordonez et al. 2014). Land-use and anthropogenic climate change can also provide positive feedbacks to each other, further enhancing their impacts on ecosystems. For instance, land-use affects the amount of carbon storage available to buffer raising CO_2 levels related to climate warming (Seto et al. 2012, Lawler et al. 2014). Climate change influences the viability of certain types of land-use, such as agricultural production, via the effects of increased temperatures and altered precipitation on crop yields and the amount of water available for crop irrigation (Piao et al. 2010, Lobell et al. 2011). However, predicting the impact of multiple land-uses and climate is complex because combinations, trends, and spatial patterns of these agents of change may not follow historic trajectories and their relative impacts on landscape attributes and ecosystem services vary widely.

Understanding the complex relationships between land-use and climate can inform management approaches for sustaining ecosystem services and socioeconomic stability (Wu 2013). For instance, the Millennium Ecosystem Assessment (2005) incorporates multiple drivers of change in order to assess the vulnerability of ecosystem services at a global scale. However, analyses to evaluate the potential impacts of multiple overlapping drivers of change, such as land-use and climate change, on ecosystem services and landscape attributes are needed at the regional scale or lower to provide information at a scale relevant to many planning processes and management decisions. One approach is to identify the important drivers of change and ecosystem services or landscape attributes for the analysis, characterize trends in space and time for drivers of change, quantify overlap in drivers of change, and develop scenarios to analyze the potential impacts on ecosystem services.

Among ecosystems affected by land-use and climate change, drylands (hyper-arid to subhumid regions) are distinguished by their low productivity, fragile erosion-prone and low-fertility soils, and scarcity of water resources (Maestre et al. 2012). These characteristics increase sensitivity to disturbance which can lead to a shift to a lower productivity state through a process termed “desertification,” which can be difficult to reverse (D’Odorico et al. 2013). Broad-scale changes in dryland systems have the potential to impact 36% of the world’s human population, a large proportion of global biodiversity, and almost half of global carbon reserves (46%, MEA 2005*b*, Dryland Systems).

Here, we examine global change agents on the Colorado Plateau. This area is a prime example of a dryland region where both past and recent trends in land-use and climate suggest the potential for large cumulative impacts on future environmental conditions and society (Schwinning et al. 2008). The Colorado Plateau has a history of cultivated and pastoral agriculture, land-use types which are common to dryland systems worldwide, and is vulnerable to environmental change, which is a common contributing factor leading to desertification (MEA 2005*b*, Dryland Systems). Periods of relatively dry or wet climate over the past millennia of human habitation on the Colorado Plateau are associated with shifts in regional population distribution and the extent of rain-fed agriculture (Benson et al. 2007, Faulstich et al. 2013). Variable climatic conditions combined with high grazing intensity have contributed to the degradation of the some of the region’s grasslands in the past, resulting in increased soil erosion, lower plant productivity, and decreased plant diversity (Fleischner 1994, Neff et al. 2005). We focus on land-use practices of recognized historic importance or with recent high impacts on environmental resources and socioeconomic conditions (Bryce et al. 2012). Specifically, we examined cultivated agriculture; grazing by domestic livestock; population growth; recreation in natural areas; mining for oil, gas, and minerals; and renewable energy development (Table 1). We focused on aridification (drying) as our climate change metric, due to the potential for any increase in dryness to significantly affect a number of environmental properties and socioeconomic factors in the dryland Colorado Plateau.

Some ecosystem services and landscape attributes of the Colorado Plateau, and in dryland ecosystems around the globe, are likely to be especially impacted by the combined effects of multiple types of high-intensity land-use occurring in addition to aridification. We focused on quantifying and mapping the overlap between particular land-use types and aridification trends which were likely to have significant interactive effects on important environmental and socioecological factors in the focal region: water availability (surface and shallow groundwater available for human use and accessible to wildlife and plant species), cropland productivity, soil productivity, vegetation and wildlife habitat, recreation tourism economy, and spiritual and cultural values. Many of these vulnerable landscape attributes and ecosystem services are shared with drylands globally, though their relative importance varies by region (MEA 2005*b*, Dryland Systems).

First, water availability is likely to decline with aridification and is already under pressure from human demands. On the Colorado Plateau, regional water use in 2010 was dominated by irrigation withdrawals, which are 50 times mining usage (includes oil and gas) and nine times domestic use (Arizona, Colorado, New Mexico, Utah; USGS 2012, 2014). Increasing shortfalls in deliveries from the over-allocated Colorado River Basin are projected over the next century with climate change (Christensen et al. 2004, Barnett and Pierce 2009). Groundwater use is unlikely to provide a long-term solution to future water shortages, as regional groundwater resources are declining (Castle et al. 2014), and depletion rates are already severe for many aquifers (Konikow 2013).

Table 1. Description of drivers of change by category with details on units, spatial resolution of original dataset, and temporal period of dataset.

Category	Variables	Units	Spatial resolution	Time period
Climate	Past AI	PET/precipitation	4 km^2	1895–2014, annual
	Future AI	PET/precipitation	~12 km^2	2016–2100, annual
Cultivated agriculture	Cropland ratio	Cropland : area	County	1850–1940, 10 yr and 1945–2012, 5 yr
Grazing	Livestock	Sheep and Cattle	County	1925–2012, annual
	FS grazing	Authorized AUMs, all livestock	Allotment (area varies)	2004–2015, annual
	BLM grazing	Billed AUMs, all livestock	Allotment (area varies)	1998–2014, annual
Population	Past	Population size	County	1850–2010, 10 yr
	Future	Population size	County	2010–2100, 5 yr
Recreation	FS visitors	Visits	National Forest (area varies)	2005–2009, 2010–2014
	BLM visitors	Visitor days	Field Office (area varies)	1999–2014, annual
	NPS visitors	Visits	Park (area varies)	1919–2014, annual
Oil and gas development	Oil and Gas wells	Locations	—	1900–2014, annual
	Undiscovered petroleum resource density	Natural gas liquids: thousand barrels Oil: million barrels Gas: billion cubic feet	Assessment units (based on geology, area varies)	NA
Renewable energy	Wind turbines	Locations	—	Current as of 2016
	Wind energy potential	High potential	200–1000 m^2	NA
	Solar installations	Locations	—	Current as of 2016
	Solar energy potential	High potential	10 km^2	NA
Mining	Mines	Locations	—	1000 (pre-European arrival)–2014

Note: NA, not applicable; AI, aridity index; AUMs, Animal Unit Months; BLM, Bureau of Land Management; FS, Forest Service; NPS, National Park Service; PET, potential evapotranspiration.

Second, declines in water availability are likely to affect agricultural productivity because of the high dependence of the region's croplands and livestock operations on irrigation. Approximately 85% of the region's croplands are irrigated (harvested croplands, 1997–2012; NASS 2014). In the upper Colorado Basin, the vast majority (92%) of irrigated agricultural lands are devoted to hay and pasture for livestock (Cohen et al. 2013). Overland flows for irrigation are not guaranteed if climate drying occurs; for example, a drought year in 2002 was associated with a ~15% drop in irrigated acreage in the upper Colorado Basin (Cohen et al. 2013).

Third, soil productivity provides the foundation for numerous ecosystem services and is likely to be adversely impacted by soil erosion due to a combination of land-use and aridification. Drying trends have the potential to increase dust production by reducing grass cover, exposing soil surfaces to erosion (Munson et al. 2011, Hoover et al. 2015). Dust and increased erosion associated with aridification or land-uses such as grazing (Neff et al. 2008) and off-road vehicle use (recreational and energy-related) can create negative feedbacks to scarce water resources by increasing snow melt (Painter et al. 2007). Soil degradation in drylands, caused by land-use, aridification, or both, can also lead to large-scale carbon emissions, creating a positive feedback to global warming trends (MEA 2005*a*).

Fourth, vegetation and wildlife habitat can be adversely affected by land-use and development in myriad ways, from creating short-lived disturbances to long-term alteration of environments, such as desertification. Species sensitive to climate warming may face range restriction by land-use in addition to climate change and barriers created by human activity may prevent dispersal to favorable climates (Malcolm et al. 2002). In addition, wildlife species can experience higher mortality rates due to roads and traffic associated with energy development or wind turbines or wildlife populations may avoid these developments altogether (Jones et al. 2015). Renewable energy installations are often near protected areas and disproportionally affect certain vegetation types (Hernandez et al. 2015). High visitor numbers to recreation sites may be accompanied by negative impacts such as increased soil erosion and negative impacts on wildlife (Reed and Merenlender 2008, Ballantyne and Pickering 2015). The combination of multiple land-use types also fragments and decreases habitat area; such a scenario has the potential to affect declining species in the Colorado Plateau, such as the black-footed ferret (*Mustela nigripes*) and the greater (*Centrocercus urophasianus*) and Gunnison's (*Centrocercus minimus*) sage grouse (Bryce et al. 2012).

Lastly, recreation tourism is an important economic driver on the Colorado Plateau, as well as a significant source of income in drylands globally, from safari tours in Kenya to beach visitors to the Mediterranean (MEA 2005*b*, Dryland Systems). Visitors are drawn to the high density of major natural and historical sites in the Colorado Plateau, which include 33 national parks, monuments, and historic sites and four United Nations Education, Scientific and Cultural Organization (UNESCO) World Heritage sites. Land-use has the potential to affect this recreation tourism economy by altering visitor experience. Climate warming may alter the timing of peak visitor numbers to National Park lands (Fisichelli et al. 2015) and reduce the ecological integrity of park ecosystems (Hansen et al. 2014, Monahan and Fisichelli 2014). Energy development on the Colorado Plateau could affect recreation use by negatively impacting scenic vistas and increasing noise and/or restricting access. These impacts are currently a concern for petroleum development near Canyonlands and Arches National Parks, two of the most visited parks in the region (BLM 2016). Winter recreation activities may be affected by decreased snowpack, though the viability of developed ski resorts is also influenced by non-climate factors such as artificial snow production and market tolerance to increased ticket prices (Koenig and Abegg 1997, Toeglhofer et al. 2011).

We addressed the potential for co-occurring high-intensity land-use and climate change to affect ecosystem services and landscape attributes of the Colorado Plateau by answering the following questions: (1) What are the trends for land-use intensity and climate change in the past, and is there evidence that these trends will continue or shift in the future? (2) What areas are expected to experience multiple, overlapping, high-intensity land-use practices, with or without severe climate change, and are there areas likely to experience a low degree of change? (3)

Finally, given simple scenarios for land-use and climate drying, which key ecosystem and socioeconomic attributes are likely to be highly impacted by overlapping areas of high-intensity land-use and climate drying?

Methods

Study region: the Colorado Plateau

*Environment and climate.—*The Colorado Plateau is generally defined as the semi-arid region bordered by the Rocky and Uinta Mountains to the east and north, the Basin and Range topography of western Utah and Nevada, and Mogollon Rim and Rio Grande Rift to the south and southeast (Fig. 1). Elevations range from ~400 to 4300 m from the southwestern desert to the Rocky Mountains. The climate is typified by relatively cold winters and monsoonal summer precipitation (Adams and Comrie 1997, Hereford et al. 2002). Precipitation varies widely between years and over multi-year periods; this variability is associated with the Pacific Decadal Oscillation and the El Niño-Southern Oscillation (Hidalgo and Dracup 2003). Climate also varies spatially across the Colorado Plateau, with mean annual temperatures and precipitation ranging from 2° to 23°C and 80–600 mm, respectively

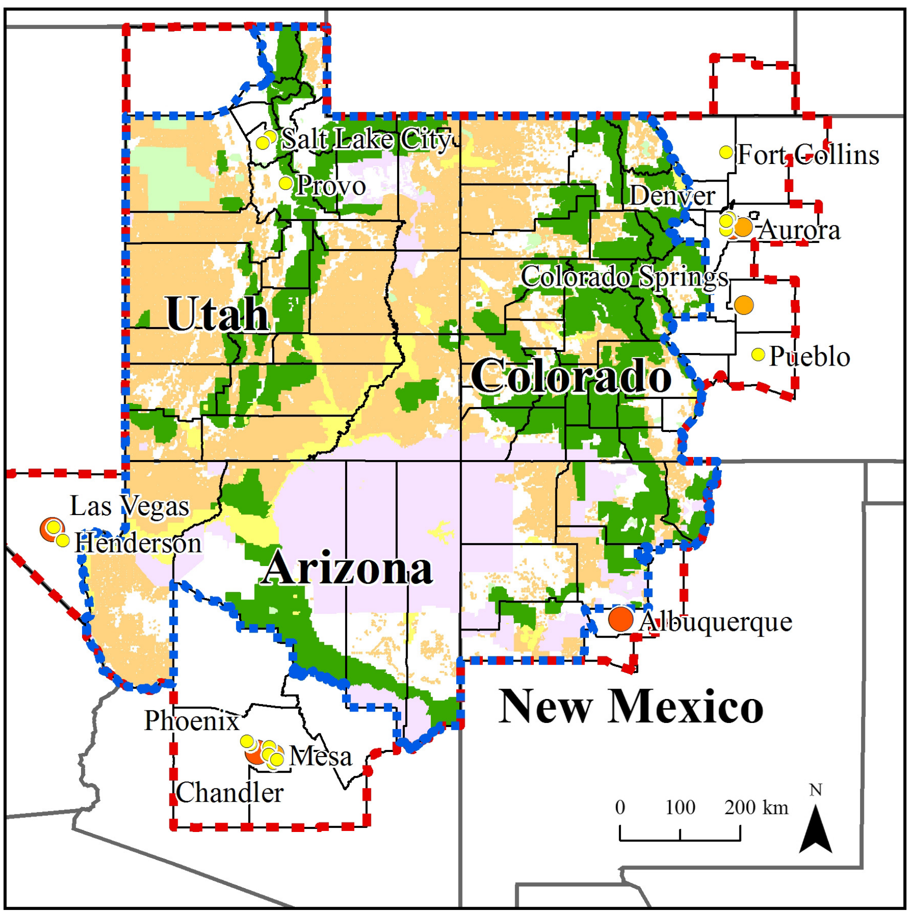

Fig. 1. Map of the Colorado Plateau region with state and county borders (black), tribal lands (purple), Forest Service (dark green), Bureau Land Management (tan), National Park Service (yellow), and other state and federal lands (light green). The population size of large cities (>100,000 population, 2007 U.S. Census) is indicated by the color and size of circle. The smaller definition of the region used for most analyses is outlined in blue, while the area including large nearby urban areas used in the population analyses is indicated by the red dashed line.

(1900–2014; Menne et al. 2015), and a gradient in summer monsoon precipitation from the south/southeast to the north/northwest.

In this study, we analyze trends for a larger extent than typically considered in ecological or geological definitions of the Colorado Plateau (blue dashed line, Fig. 1). The extent definition of the Colorado Plateau we used was driven in large part by data constraints and our desire to represent the impacts of large population centers that are near, but not inside, the Colorado Plateau boundaries. Since most of our land-use data are collected at the county level, many of which straddle the Colorado Plateau ecoregion, we elected to include counties that were on the border of most delineations of the ecoregion (Level III Ecoregions, Environmental Protection Agency and The Nature Conservancy Terrestrial Ecoregions; maps in Appendix S1: Fig. S1a, b). We also included counties that occur outside these definitions in the southern Rocky Mountains to account for socioecological elements (i.e., connecting hydrology, large proportions of federal land) and drivers of change (e.g., increasing oil and gas development, high levels of recreation tourism to natural areas) that cross the boundaries of these ecoregions. We also considered a larger area for analysis in order to include the principal large cities at the periphery of the region because urban growth is likely to impact conditions within the region, by increasing the number of visitors to natural areas and the pressure on water resources (red dashed line, Fig. 1).

*Society and land-use history.—*The Colorado Plateau has a long history of human habitation with land-use patterns shifting in response to climate and cultural change. Evidence of cultivated agriculture dates from ~2500 B.C.E. (maize) and likely began much earlier (~4300 B.C.E, Piperno and Flannery 2001). A diversity of crops and irrigation techniques were used (Doolittle 1992), some of which are still practiced by Native Americans in the region (Soleri and Cleveland 1993). Climatic fluctuations, particularly prolonged droughts, periodically affected agricultural viability and may have contributed to shifts in population and culture (Benson et al. 2007).

The arrival of the Spanish in the mid-1500s profoundly affected the diverse Native American groups of the region including Pueblo cultures such as the Hopi, Zuni, Tewa, Tiwa, Towa, and Keres people, as well as the Navajo, Apache, Yavapai, Havasupai, Hualapai, Ute, and Shoshone people. Negative impacts of European arrival on Native Americans included introduced disease, forced relocation, degradation of natural resources, massacres, and war. After the region was ceded to the United States in 1853, the U.S. government began to implement a series of policies which curtailed native people's rights, eroded tribal autonomy, and sought to eliminate spiritual practices and language. Today, tribal governments manage a large proportion of the region (15%) relative to the proportion of tribal lands for the entire United States (2%).

Grazing became an important land-use in the region in the early 1600s with the arrival of Spanish settlers. By the 1700s, the Navajo had widely adopted grazing practices and were raising sheep and horses as sources of food, fiber, and transportation (Bailey 1980, Bailey and Bailey 1986). By 1850, the Navajo may have had as many as 200,000–500,000 sheep in the Four Corners region (Bailey 1980, Bailey and Bailey 1986). "Open-range" cattle grazing by Euro-Americans became widespread in the late 1800s due to policies encouraging grazing on public lands adjoining settlers' private property (Rundle 2004) and railroad connections in the 1880s which greatly increased the profitability of cattle grazing (Bailey and Bailey 1986). Cattle drives across the Colorado Plateau from south to north took months to years, impacting broad areas of the landscape through shifting grazing. Peak numbers of cattle and sheep grazing were reached in the late 1800s, with ~5.9 million sheep in 1883 and ~2.3 million cattle in 1891 in Arizona and New Mexico (Bailey and Bailey 1986). Abundant livestock were associated with rangeland degradation, which led to restrictions to open-range grazing on public land with the 1934 Taylor Act and subsequent regulations (Rundle 2004). Bureau of Indian Affairs officials culled the majority of the sheep, cattle, and horse herds on the Navajo Nation in response to perceived over-grazing in the 1930s (Bailey 1980), a decision with long-lasting effects on practices and politics of grazing on Navajo lands (Bailey 1980, Henderson 1989).

Euro-American settlement in the Colorado Plateau in the latter half of the 19th century rapidly increased the population and altered land-use patterns. Hundreds of far-flung agricultural settlements in Utah and northern Arizona were established rapidly following the Mormon migration to Salt Lake City, Utah, in 1847. Gold and silver discovered in the Rocky Mountains created boom towns in the late 1800s, while the central Colorado Plateau region experienced a uranium mining boom from the 1950s to the 1980s. Drilling for oil and gas began in the early 1900s and continues today. In the early to mid-1900s, construction of massive dams and canal networks and drilling for groundwater provided water to cities and farms and altered riparian systems. Several national parks were established in the 1900s, and tourism to federal and tribal lands is now an important contributor to regional economic activity (Arizona Hospitality Research & Resource Center 2011, Leaver 2014). For example, Grand Canyon National Park, one of the most heavily visited parks in the National Park system, contributed an estimated US$711 million and 7900 jobs to local economies in 2014 (Thomas et al. 2014).

Drivers of change

Climate change (aridification).—We used an aridity index (AI, precipitation divided by potential evapotranspiration [PET]), as our principle metric for climate trends because of the importance of water availability to ecosystem productivity in the region. We chose this AI because of its applicability across the study region, which includes a variety of seasonal precipitation patterns, simplicity, given the lack of detailed regional evapotranspiration data, and widespread use (e.g., global desertification atlas, UNEP 1997). We calculated past annual and seasonal AI for 1925–2014 (spring: March–May; summer: June–August; fall: September–November; winter: December–February) with mean, maximum, and minimum spatially interpolated temperature and precipitation (PRISM 2015; see Table 1 and Appendix S2). We calculated future annual and seasonal AI using monthly temperature and precipitation data extracted from 10 General Circulation Models from the Coupled-Model Intercomparison Project, Phase 5 (CMIP5) downscaled to 1/8° spatial resolution (details in Appendix S2; Bureau of Reclamation 2013). The models were selected for their independence (Knutti et al. 2013) and performance, assessed by comparing model hindcast results and observed climate values in the Pacific Northwest (Rupp et al. 2013) and southwest United States (David E. Rupp, *personal communication*). We selected projections based on the highest representative concentration pathway, or emissions scenario, available for CMIP5 projections, RCP8.5, which assumes "baseline" response to climate change without mitigation (8.5 W/m^2; Riahi et al. 2011, see Appendix S1: Fig. S2a for comparison with RCP4.5 and Appendix S2 for details). We used the median prediction (average of the median two models out of ten) for each cell for the two variables (temperature and precipitation) to account for model variability. We calculated aridification trends as the slope of change from 2016 to 2075 (60-yr period) for the entire study area and within three ecoregion groups, mountains, plateaus, and basins and deserts, by combining terrestrial ecoregions defined by The Nature Conservancy (see Appendix S1: Figs. S1b, S2). We scaled the values within each ecoregion from 0 to 1 by calculating the difference between each pixel value and the minimum value for the ecoregion, dividing by the range of values for that ecoregion, and subtracting 1 so that the maximum value (1) would represent maximum drying. This approach allowed us to identify areas with relatively higher or lower changes in the AI within each of the three groups, which differed widely in the climate conditions.

Cultivated agriculture and grazing.—We defined intensity of cultivated agriculture as the cropland per unit area (cropland ratio) by county from 1850 to 2012 using agricultural records from the U.S. Department of Agriculture (USDA) Census of Agriculture resolved for changes in county outlines over time (Table 1; see Appendix S2 for details). We used two different types of historical grazing and livestock data: (1) county cattle and sheep totals from 1925 to 2012 from the USDA Census of Agriculture (NASS 2012; see Appendix S2 for details) and (2) density of grazing livestock per year on federal lands managed by the Forest Service (FS) and Bureau of Land Management (BLM) with allotment records for Animal Unit Months by area and year (AUMs/km^2/yr, all livestock types, FS: authorized use, 2004–2015, BLM: billed use, 1998–2014). We restricted our grazing analysis to allotments without changes in boundaries or administration which might affect AUM numbers. We did not include grazing on tribal lands, private lands, or National

Park Service (NPS) lands. We used current intensity of cultivated agriculture (cropland ratio, 2012), livestock (total of sheep and cattle, 2012), and grazing (2014 BLM and FS AUMs) in our analyses of high-intensity future land-use overlap, due to lack of projections for these variables.

Population.—Historical county population was calculated using U.S. Census data for every 10 yr from 1850 to 2010 with data adjusted to match current county borders (see Appendix S2). Future county population was based on projections by five-year intervals for the period 2010–2100 from the Spatially Explicit Regional Growth Model (SERGoM; Theobald 2005). SERGoM simulates population based on existing patterns of growth by census block, groundwater well and road density, and transportation distance to urban areas, while constraining the pattern of development to areas outside of protected areas and urban areas (Theobald 2005). For our main analyses, we used projections for a "baseline" growth scenario that assumes a similar trajectory to that of current urban growth; however, we included population projections for other economic growth scenarios in the supplementary material (Bierwagen et al. 2010, Appendix S2). SERGoM accuracy is estimated as 79–99% when compared to 1990 and 2000 census data, with the accuracy varying by urban/exurban/rural categories and increasing slightly with coarser resolution (Theobald 2005). The accuracy of future model predictions with different economic scenarios is most sensitive to fertility rates, which are subject to cultural change, economic recessions, and the current pattern of lands protected from development (Bierwagen et al. 2010). Projections based on scenarios are also expected to be accurate at coarser spatial scales than the base model. We presented "baseline" growth in our core analyses rather than economic growth scenarios; however, we note that future conditions could still vary widely from present growth trajectories and model projection accuracy probably decreases at some unknown rate with time.

Recreation on public land.—We estimated recreation intensity using past visitor information from NPS, FS, and BLM lands. Recreation use on FS lands is tracked at five-year intervals (2005–2009, 2010–2014) at the national forest level (National Visitor Use Monitoring system; English et al. 2002). The BLM estimates visitor days annually by field office (Recreation Management Information System, 1999–2014; Leuders 2015, see Appendix S2 for details). We used annual visitor records for NPS units (Visitor Use Statistics, 1919–2014, varies with park establishment date; NPS 2015). We also gathered information on visitor origin for NPS units from the NPS Visitor Services Project (University of Idaho Park Studies Unit 2015) and from air traveler surveys from the U.S. Department of Commerce (Office of Travel & Tourism Industries 2015). Current (2014) visitor numbers were used to estimate areas of high recreation intensity for overlap analyses in lieu of projections.

Oil and gas development.—Trends in oil and gas development were based on well locations and drilling dates obtained from four state databases (Arizona, Colorado, New Mexico, and Utah; see Appendix S2 for details). Well locations were combined into a density layer at the 10-km^2 and the county scales, due to the low accuracy of some well locations. Areas with high potential for future oil and gas development are based on U.S. Geological Survey (USGS) resource assessments for "undiscovered" petroleum resources, which are resources that have not yet been extensively proven by drilling (USGS 2014). Individual resource assessments describe the amount of petroleum resources in units with similar geologic features. We focused on the amount of undiscovered continuous resources because technological advances have made exploitation of continuous resources increasingly profitable and large amounts remain undeveloped in comparison with conventional resources. We quantified the density of three continuous resource types, oil, gas, and natural gas liquids (NGL), by adding together the amounts in spatially overlapping assessment units and dividing these totals by the area of the polygon. Oil shale deposits are discussed, but largely excluded in the spatial analysis due to lack of past or ongoing commercial-scale development. However, we included one oil shale deposit, the Uteland Butte Carbonate Continuous Sweet Spot in northeastern Utah, because it has particularly high concentrations of readily produced oil and is under development.

Renewable energy development.—Wind turbine locations within 50 km of the border of the Colorado Plateau before 2013 were accessed through the WindFarm database (USGS 2015).

We verified the locations with up-to-date records and added a new wind farm completed in 2016 near Monticello, Utah, to the dataset (Latigo Wind Power; see Appendix S2). Areas with high potential for utility-grade wind power were based on wind energy adjusted to 80 m and excluding protected areas and land-cover types unsuitable for wind installations (NREL 2010; see Appendix S2 for details). Locations of large solar plants (>10 mW) operating, under construction, and under development were obtained from the Solar Energy Industry Association (SEIA 2015). Areas with high solar potential for photovoltaic and concentrated solar power were downloaded from the Renewable Energy Atlas (NREL 2012; see Appendix S2).

Mining activity.—Mine density (per 10 km^2) was calculated with records from the Mineral Resources Data System (USGS 2011). Temporal trends for mine density were not analyzed because of the low proportion of dated records (~6%).

Trend and spatial overlap analysis

Our land-use, population, and climate drivers of change differed in spatial and temporal resolution and period of record as well as availability of future projections (Table 1). We addressed Question 1, regarding the past trends and future projections for land-use and climate, by graphically describing past temporal trends for all land-use and climate drivers of change except mining (few dated records) and renewable energy development (few installations) for the period of record for that variable. Therefore, for estimating potential future conditions, we used projections for population and aridification, potential for development for oil and gas, and current intensity for the other variables. The final set of variables were cultivated agriculture (cropland ratio, 2012), livestock (total of sheep and cattle, 2012), grazing (2014 BLM and FS AUMs), recreation (2014 BLM, FS, and NPS visitors), population in 2100 (baseline scenario), aridification change (slope, AI trend 2016–2075), undeveloped continuous petroleum resources (oil, gas, and NGL), renewable energy potential (high potential for wind or solar: photovoltaic or concentrated), and mining (total mines).

To address Question 2, we identified areas where impacts of multiple land-uses are likely, due to overlap of high-intensity land-use areas, and where they are less likely, due to overlap of low-intensity land-use areas. We converted land-use variables into a 10-km^2 density layers, using area-weighted means for variables where we had data at finer than county resolution. For example, NPS visitor density was calculated by multiplying the number of visitors for each park by the proportion of the park area within the 10-km^2 cell and adding together the weighted totals for all NPS units that intersected the cell. We also calculated county-level density for the above variables (area-weighted, if applicable). We further calculated an index of land-use intensity between 0 and 1 for each variable with taking the value minus the minimum and dividing by the range of values. Values close to 1 represented high intensity for that variable, whereas values close to 0 represented low intensity. This index approach allowed us to calculate areas of relatively high-intensity land-use or climate drying despite variation in units and ranges across variable types. We also simplified the multiple variables related to grazing, oil and gas, renewable energy, and recreation into four variables by adding together index values for each cell for each sub-category of those variables. This calculation equally weights the individual variables; for example, recreation indices of 0.75 for NPS visitors, 0.5 for BLM visitors, and 1 for FS visitors would result in a total of 2.25 for a cell.

We analyzed spatial overlap in areas with present (cropland, grazing, and recreation), potential (petroleum resources), or future (population) high-intensity land-use. The final areas designated as high-intensity land-use represent high intensity relative to the range of values for that variable in this region, either present or future, and do not represent the rate of change, recent or future, for that particular variable. We defined high-intensity areas as ≥75% quantile for that variable over the entire Colorado Plateau and low-intensity areas as ≤25% quantile. We combined grazing and cropland high-intensity areas into one "high agriculture" variable. We also calculated aridification rate and the associated index separately for each of the three ecoregion groups.

We assessed the spatial pattern and extent of potential impacts of spatially overlapping high-intensity land-use and aridification trends on landscape attributes: crop productivity, soil productivity, vegetation and wildlife habitat, and recreation tourism economy, as well as selected ecosystem services (MEA 2005*c*): water availability (provisioning service) and spiritual and cultural values (cultural service, Question 3). We developed scenarios for the combined impact of land-use and aridification trends by assigning each variable weights for their estimated relative impact on each category of ecosystem attribute (total weights = 1, Table 2). These elements were chosen as major categories from a broader number identified by natural resource scientists with a diverse range of specialties and whom work in the region (workshop convened August 5–7, 2014; Appendix S1: Fig. S11). We do not have regional estimates for the impact of each

Table 2. Potential negative impacts on ecosystem services and attributes, water availability, cropland productivity, soil productivity, vegetation and wildlife habitat, recreation tourism economy, and spiritual and cultural values, associated with drivers of change: climate change (as indicated by slope of aridity index trend from 2016 to 2075), population growth (projection for 2100), recreation (2014 BLM, FS, and NPS visitors), oil and gas development (undeveloped continuous petroleum resources for oil, gas, and natural gas liquids), renewable energy potential (proportion in high wind category, solar: photovoltaic and concentrated), and agriculture (cultivated agriculture: cropland ratio, 2012; livestock: total of sheep and cattle, 2012; and grazing: 2014 BLM and FS AUMs).

Ecosystem services and landscape attributes	Potential impacts	Drivers of change	Scenarios			
			Unequal weights	Equal weights	High climate change	High land-use
Water availability	Increasing demand and/or decreasing supply	Climate change	0.1	0.25	0.67	0.34
		Population growth	0.09	0.25	0.11	0.22
		Oil and Gas development	0.04	0.25	0.11	0.22
		Agriculture	0.77	0.25	0.11	0.22
Cropland productivity	Declining yields, altered crop suitability, decreased area due to development	Climate change	0.7	0.5	0.67	0.33
		Population growth	0.3	0.5	0.33	0.67
Soil productivity	Decreased soil health and altered nutrient cycling	Climate change	0.5	0.25	0.67	0.34
		Recreation	0.05	0.25	0.11	0.22
		Oil and Gas development	0.1	0.25	0.11	0.22
		Agriculture	0.35	0.25	0.11	0.22
Vegetation and wildlife habitat‡	Reduced abundance and diversity of native species	Climate change	0.45	0.167	0.65	0.35
		Population growth	0.2	0.167	0.07	0.13
		Recreation	0.05	0.167	0.07	0.13
		Oil and Gas development	0.1	0.167	0.07	0.13
		Renewable energy	0.1	0.167	0.07	0.13
		Agriculture	0.1	0.167	0.07	0.13
Recreation tourism economy	Loss of natural qualities associated with visitor experience	Climate change	0.05	0.333†	0.666	0.333†
		Oil and Gas development	0.475	0.333†	0.167	0.333†
		Renewable energy	0.475	0.333†	0.167	0.333†
Spiritual and cultural values‡	Loss of natural characteristics of spiritual and cultural significance	Climate change	0.45	0.167	0.65	0.35
		Population growth	0.26	0.167	0.07	0.13
		Recreation	0.05	0.167	0.07	0.13
		Oil and Gas	0.08	0.167	0.07	0.13
		Renewable energy	0.08	0.167	0.07	0.13
		Agriculture	0.08	0.167	0.07	0.13

Notes: AUMs, Animal Unit Months; FS, Forest Service; NPS, National Park Service; BLM, Bureau of Land Management. Weighting factors (adding to 1 for each scenario and ecosystem attribute) are listed for each of four scenario types for each ecosystem attribute: unequal weights, equal weights, high climate impact (2/3 of impact, double land-use), and high land-use impacts (2/3 of impact, double climate change). Unequal weights are based on either spatial footprint (cropland and soil productivity and vegetation and wildlife habitat), resource use or effect on resource amount (water availability, altered water deliveries, Barnett and Pierce 2009, water use by sector, Maupin et al. 2014), or a combination of spatial footprint and visual impact (spiritual and cultural values and recreation tourism economy).

† High land-use and equal weights are the same for this attribute.

‡ Same weights for equal weights, high climate change, and high land-use scenarios for these two attributes.

category of land-use variable or aridification on that particular ecosystem attribute, with the exception of water availability. To address this uncertainty, we created a range of scenarios based on the relative impact of land-use and climate drying on landscape attributes. We used published literature and information on spatial footprint from our analysis of land-use and aridification trends to construct a plausible scenario with unequal weights for different impacts of land-use and climate change for each ecosystem attribute. Since many of our unequal scenarios depended on qualitative information rather than modeled quantitative impacts, we applied three other scenarios with standard weighting logic: equal weights of all variables (1/number of contributing land-use variables and climate change), high impact of climate change as indicated by aridification rate (AI trend weight = 2/3, sum of weights for land-use = 1/3), and high impact of land-use (sum of land-use weights = 2/3, AI trend weight = 1/3). We calculated the AI index for the entire region rather than separating the calculation by ecoregion groups, for this analysis.

To estimate unequal weights for impacts on water availability, we used estimates of current usage by sector (Maupin et al. 2014) and altered water deliveries with climate change for the Colorado River (decline of 10–30%, Barnett and Pierce 2009). However, these estimates of water availability do not fully address the complexity of determining water availability across the region. For example, we did not have estimates for potential changes in the relative water usage by different land-use types, measures of spatial variation in impacts of climate change on water availability, or estimates of future water-use impacts on groundwater. For cropland and soil productivity and vegetation and wildlife habitat, we estimated relative impacts based on the spatial footprint and potential contribution. We estimated that cropland productivity would be affected by population growth because urban development often replaces agricultural lands (Bierwagen et al. 2010). We also estimated that cropland productivity would experience relatively high impacts of climate change, via effects on water resources for irrigation and temperature (Lobell et al. 2011). We estimated the negative impacts of climate change and agriculture on soil productivity to be higher than either recreation (soil disturbance from trails and roads) or oil and gas (well pads and roads) because of their higher spatial footprint at higher intensity. For vegetation and wildlife habitat, we estimated relatively high impacts of climate change and population growth, due to the large spatial footprint of these drivers of change and their potential to severely alter natural habitat. We also included negative impacts of renewable energy on vegetation and wildlife habitat based on several studies that indicate negative impacts of wind and solar installations on a variety of species (Jones et al. 2015). For the recreation tourism economy, we estimated unequal weights based on the effect of these variables on scenic characteristics of natural landscapes, assuming higher relative impact of oil and gas development and renewable energy installations because of their non-natural appearance at a distance, and lower impacts of climate change, which might affect visitor experience via reduced density of iconic wildlife species, decreased water flows, and altered plant communities. For spiritual and cultural values, we weighted impacts based on their relative impacts to scenic or natural properties (climate change, oil and gas development, renewable energy, and agriculture) and/or reduced access (population growth) in addition to spatial footprint. As with wildlife habitat, we estimated the negative impacts of agricultural productivity and climate change on spiritual and cultural values to be relatively high due to their higher spatial footprint and effects on natural characteristics, with relatively lower impacts of renewable energy development, oil and gas development, and agriculture.

The intensity indices (0–1) for the land-use and climate change variables were combined using the different weights for each scenario (Table 2) to estimate the magnitude of potential impact of spatial overlap, with higher values indicating greater impact. For each scenario, we defined areas as high- or low-intensity impact according to quantiles (high: ≥75% quantile; low: ≤25% quantile). Since each scenario could result in different spatial patterns of potential impact, we also calculated the area of consensus across all four scenarios in high and low impact categories.

Since some parts of the Colorado Plateau have a very low proportion of cropland, we only analyzed impacts on cropland productivity in areas with higher cropland intensity (>25% quantile).

Similarly, only areas with substantial recreation intensity (>25% quantile) were evaluated for impacts on the recreation tourism economy. Data manipulation and overlay analysis were conducted in R 3.1.3 (R Core Team 2015).

Results

Temporal trends and projections for aridity and land-use

Climate.—Recent trends (1985–2014) show that the southern and central parts of the region are drying at a higher rate than northerly areas (Appendix S1: Fig. S2b–d). However, future climate projections suggest that 99% of the Colorado Plateau will experience drying by 2075 (negative slope for AI, Appendix S1: Fig. S2e, f), with the change in annual aridity driven by greater drying in what is now the wetter winter months (Fig. 2a). The greatest increase in annual aridity (lowest AI) by 2075 was observed in the mountains (−0.099 mean decline in AI), with the lowest increase in basins and deserts (−0.042), closely followed by plateaus (−0.044; Fig. 2a). When the declines are viewed proportionally compared to the mean 1985–2014 values, the increase in aridity was ~17% for all ecoregion groups (basins and deserts, −17.43% AI decline; mountains, −17.51; plateaus, −17.35).

Cultivated agriculture.—The intensity of cropland agriculture increased rapidly in the latter half of the 19th century due to Euro-American settlement, followed by stabilization with about 3% of the current land area in cropland (Appendix S1: Fig. S3a). County land in cropland varies from 0% to 18% (Fig. 2b). Cropland percentage has fallen in some counties and risen in others over the last 30 yr, but there is no clear regional trend (Appendix S1: Fig. S3b, c).

Grazing.—The counties with the highest livestock density are in central Utah and southwestern Colorado (Fig. 2c). Sheep totals have been declining steadily over the past century, while cattle numbers do not exhibit a clear trend (Appendix S1: Fig. S4a). No clear temporal trend in grazing density over the period of record (10–15 yr) was observed on either BLM or FS lands (Appendix S1: Fig. S4b). Areas with high county livestock density and high grazing density on federal lands did not appear to be highly correlated, with the exception of an association between FS grazing density and county livestock in central Utah (Fig. 2c; Appendix S1: Fig. S4c, d). This may be due to differences between types of farms and ranches contributing to county and federal allotment values. For example, total county livestock numbers include large, feedlot-based operations (NASS 2015).

Population.—County population data for the area within and adjacent to the Colorado Plateau indicate that past high growth areas are outside or near the edges of the region, primarily in the areas surrounding Phoenix, Las Vegas, Denver, Salt Lake City, and Albuquerque (Fig. 2d; Appendix S1: Fig. S5a, b). Almost exponential growth has occurred over last several decades in these urban counties (Appendix S1: Fig. S5c, d). In 1950, the total population of the Colorado Plateau was approximately 1.1 million with county populations ranging from 400 to 260,000. The population including urban areas adjacent to the Colorado Plateau was 2.7 million in 1950 and the maximum county population was 390,000. By 2010, the population had increased by almost 400%, to 4.3 million, while the population including adjacent counties increased over 500% to 15.9 million. In 2010, the population of Maricopa County alone was 3.8 million, 70% greater than the population of the entire region and its adjacent urban areas in 1950.

Future population projections suggest some new hotspots of growth in counties near urban areas such as Douglas County (south of Denver; Fig. 2d). The amount of projected increase is highly variable depending on the economic scenario. For example, regional population projections for 2100 range from 5.5 to 12.4 million depending on the scenario (Appendix S1: Fig. S5e). However, future projections for the populations of individual counties do not necessarily correspond exactly to recent trends, with some populous counties projected to grow at faster or slower rates (Fig. 2d).

Recreation.—Recreation trends and intensity vary by federal land management type, with highest visitor density in the southwest deserts and mountainous counties of southern Colorado (Fig. 2e). The recreation intensity on BLM and NPS lands is highest around Lake Mead and Lake Havasu, though recent declines in visitor numbers have also occurred in these management units

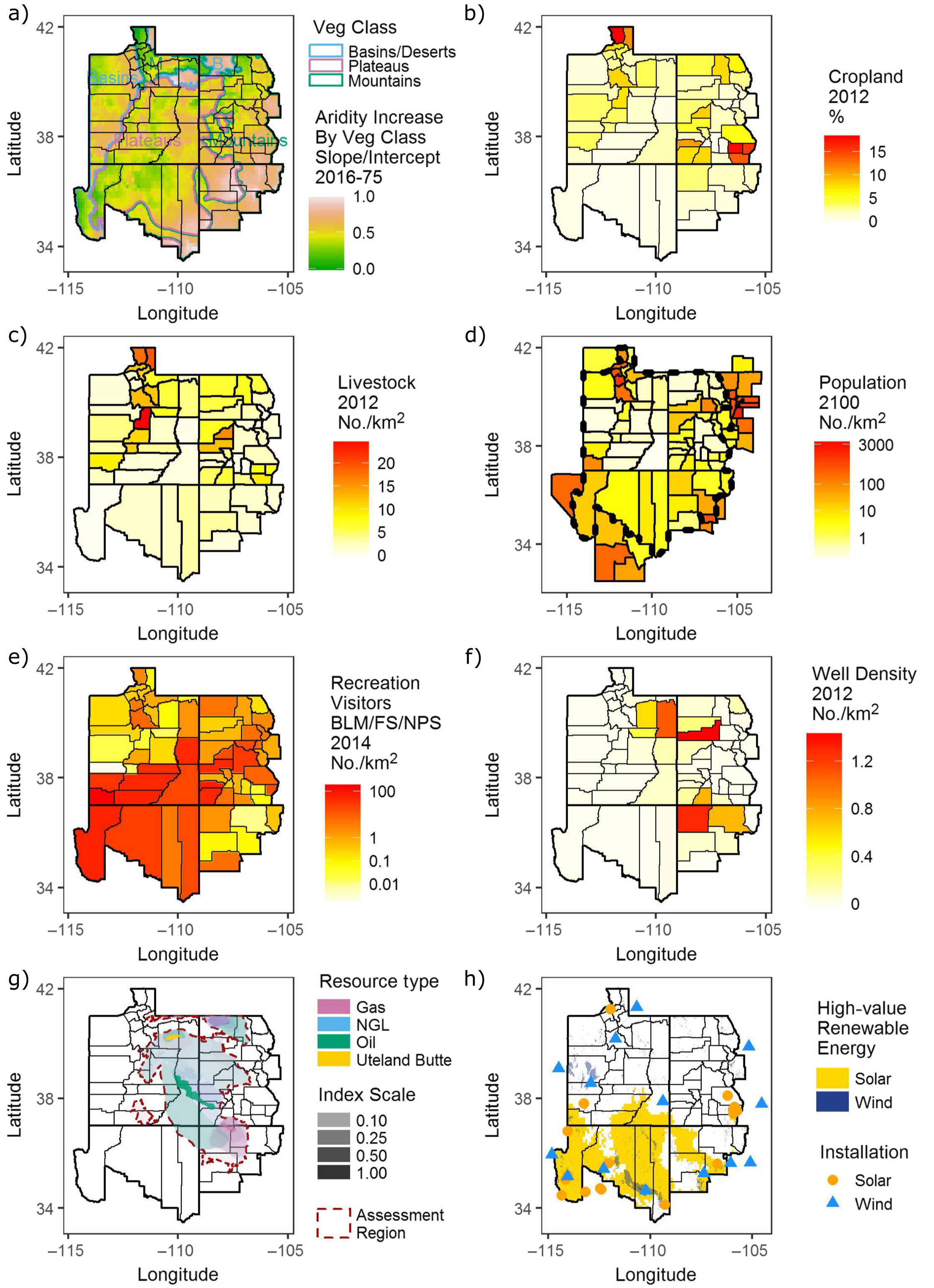

Fig. 2. Maps of either current or projected land-use and aridification patterns. (a) Map of aridification

(*Fig. 2. Continued*)
calculated by ecoregion group (slope/intercept, 2016–2075) and scaled by dividing by maximum values for each ecoregion (maximum increase in aridification = 1). (b) Map of cropland intensity by county (percentage cropland by county, 2012). (c) Map of livestock density by county (sums of sheep and cattle divided by area, 2012). (d) Map of projected population density by 2100 by county (population from baseline economic scenario divided by area, dashed line = smaller Colorado Plateau outline). (e) Map of recreation visitor density by county (2014, sum of National Park Service [NPS], Bureau of Land Management [BLM], and Forest Service [FS] divided by area). (f) Map of well density by county (2012, total wells divided by area). (g) Map of undiscovered continuous petroleum resources by type and scaled by dividing by the maximum for the resource type (maximum value for that resource = 1, area covered by assessments outlined in dashed line). (h) Map of high value areas for solar and wind renewable energy potential and existing large installations.

(Appendix S1: Fig. S6a–d). Forest Service visits are highest in the mountains of north-central Colorado and northern Utah, probably due to ski resort visitation (Appendix S1: Fig. S6e, f). Visits to NPS units increased steeply from 1950 to 1990; however, this trend was punctuated by a few periods of slow growth or even declines in visitor numbers (Appendix S1: Fig. S6g). Many of the parks with the highest total visitors have experienced a recent steep uptick in visitation (Appendix S1: Fig. S6g).

Changes in the numbers of international visitors may significantly contribute to recreation trends in national parks. The number of overseas visitors (excluding overland visits from Mexico and Canada) to national parks and monuments increased ~170% between 1996 and 2014. This trend was accompanied by a 150% increase in total overseas visitors to the United States, a more than doubling of international visitors from 4.5 to 11.7 million over that period (Office of Travel and Tourism Industries 2015). Occasional downward trends in the number of overseas visitors to parks have occurred (e.g., 2003–2006, 2008–2009), likely associated with global economic downturns. Overseas visitors to the United States are expected to increase in the next few years, with a 20% increase projected between 2015 and 2020, for a total of 15 million visitors (Office of Travel & Tourism Industries 2015). This is highly likely to lead to more visitors to national parks within the Colorado Plateau, though the proportion of international visitors does vary among park units. For example, recent surveys reported that 38% of total visitors to Canyon de Chelly National Park were international in origin compared to only 9% of the visitors to Dinosaur National Monument (University of Idaho Park Studies Unit 2015).

Oil and gas development.—Temporal trends for oil and gas development on the Colorado Plateau are characterized by cycles; the last 20 yr saw a dramatic increase in development rate of petroleum resources, while development is currently on a downward trend (Appendix S1: Fig. S7a). Current oil and gas wells are concentrated in a north-central swath in both Utah and Colorado and in the San Raton Basin of northwestern New Mexico (Fig. 2f; Appendix S1: Fig. S7b). High concentrations of undiscovered continuous resources are associated with areas of present high-intensity development, as indicated by well density (i.e., gas and NGL in the San Juan Basin, New Mexico, and oil in the Uinta Basin, Utah; Fig. 2f, g; Appendix S1: Fig. S7c–e). Other areas with potential for development based on the amount of undiscovered resources are not yet intensely developed as indicated by well density; less developed areas with high potential for future development include the Sand Wash Basin of northern Colorado (NGL and gas) and central Utah and Colorado in the Paradox Basin (oil; Appendix S1: Fig. S7d; see Appendix S2 for assessments). The upper Uinta Basin is also a likely area for future development due to high concentrations of tight oil and recent successful production in the Uteland Carbonate Continuous Sweet Spot (see Appendix S2). While large oil shale deposits do occur across much of the region, these are unlikely to be developed in the near term due to high production costs, with only one oil shale operation, in northeastern Utah, currently planned (American Association of Petroleum Geologists 2015). However, if and when petroleum supplies tighten, these reserves could be tapped over the long term. Overall, the relative prices of oil, gas, and NGL are likely to substantially affect the rate and targets for continuous oil and gas resource development. For example, shale gas development is more likely to increase with relatively low oil prices, while an increase in tight oil production is likely only if future oil prices are relatively high (USEIA 2015).

Renewable energy.—Solar and wind power installations are located around the edge of the Colorado Plateau, with the heaviest concentration of solar plants occurring in the San Luis Valley, CO (Fig. 2h). The southwestern part of the region, near Las Vegas, has the highest potential for future solar development (Fig. 2h; Appendix S1: Fig. S8a, b). Other areas with high potential are located in a swath across southeastern Arizona and Utah, near Albuquerque, New Mexico, and in a hotspot near the San Luis Valley, CO (Fig. 2h; Appendix S1: Fig. S8a, b). High-potential wind power areas are more scattered than those for solar, with the highest concentrations along the eastern edge of the region in Colorado, northwestern New Mexico, southeastern Arizona, and western Utah in areas that tend to coincide with the locations of large wind developments (Fig. 2h; Appendix S1: Fig. S8c).

Mining activity.—Mine density is highest in the Rocky Mountains, particularly around Aspen, Ouray, Silverton, and in eastern Montrose County, in Colorado, and near Salt Lake City and Provo, Utah. Some areas have extremely high mine density (46 mines/10 km^2; Appendix S1: Fig. S9). Much lower mining density is common across the region; however, at least one mine is found in 37% of the 10-km^2 cells. We were not able to describe mine size, age, commodity, or potential connectivity between locations (i.e., related mine shafts), all factors that may significantly affect the impact of mining activity on the landscape.

Co-occurrence of low- and high-intensity drivers of change

The spatial pattern of aridification by ecoregion group indicates that the area with the highest aridification rates for the plateau group is in central Utah along the Sevier River drainage; areas with the highest rates for the basin group are in the central northern edge of the region in Moffat County, CO, and overlapping the Great Salt Lake, Utah; and areas with the highest rates for the mountain group are in the San Luis Valley, CO, and the high elevations near Leadville and Aspen in central CO (Fig. 2a).

Overlap analysis showed that high recreation intensity and potential for petroleum development co-occur on 8% and high recreation intensity and population density by 2100 overlap on 6% of the Colorado Plateau (Fig. 3a). High recreation, population, and potential petroleum development overlap on 1% of the Colorado Plateau. High agriculture intensity and potential petroleum development overlap on 3%, while high agricultural intensity and population density overlap for 0.5% of the region (Fig. 3a, b).

Low-intensity areas for multiple land-use types overlap throughout the Colorado Plateau (Appendix S1: Fig. S10). Areas of low intensity for the combination of recreation and petroleum development potential are common (19%) and concentrated in the south-central and northwest portions of the region (Appendix S1: Fig. S10). Low oil and gas development potential and low-intensity agriculture co-occur on 9% of the Colorado Plateau in the southwestern desert region. A relatively small area in the central Colorado Plateau and northern Utah is designated as low intensity for recreation and population (2%). Areas of low agricultural intensity and population overlap completely with areas of low petroleum potential in the southern Colorado Rocky Mountains (<1%). Low agricultural intensity, low oil and gas potential, and low recreation use overlap in the southern parts of the Colorado Plateau (2%). Low intensity for recreation, population, and oil and gas development co-occur in smaller, scattered areas around the region (1%). No areas were designated as low intensity for agriculture, population, and recreation.

Potential impacts on landscape attributes and ecosystem services

The relative impacts of land-use and climate change scenarios on landscape attributes and ecosystem services indicated varied impacts by both scenario type and ecosystem service or landscape attribute. Recreation economy had the highest median impacts for all scenarios based on an index of 0–1 (range: 0.24–0.43), followed by vegetation and wildlife habitat and cultural and spiritual values (0.17–0.24), water availability (0.12–0.23), soil productivity (0.12–0.18), and cropland productivity (0.07–0.10; Fig. 4). The

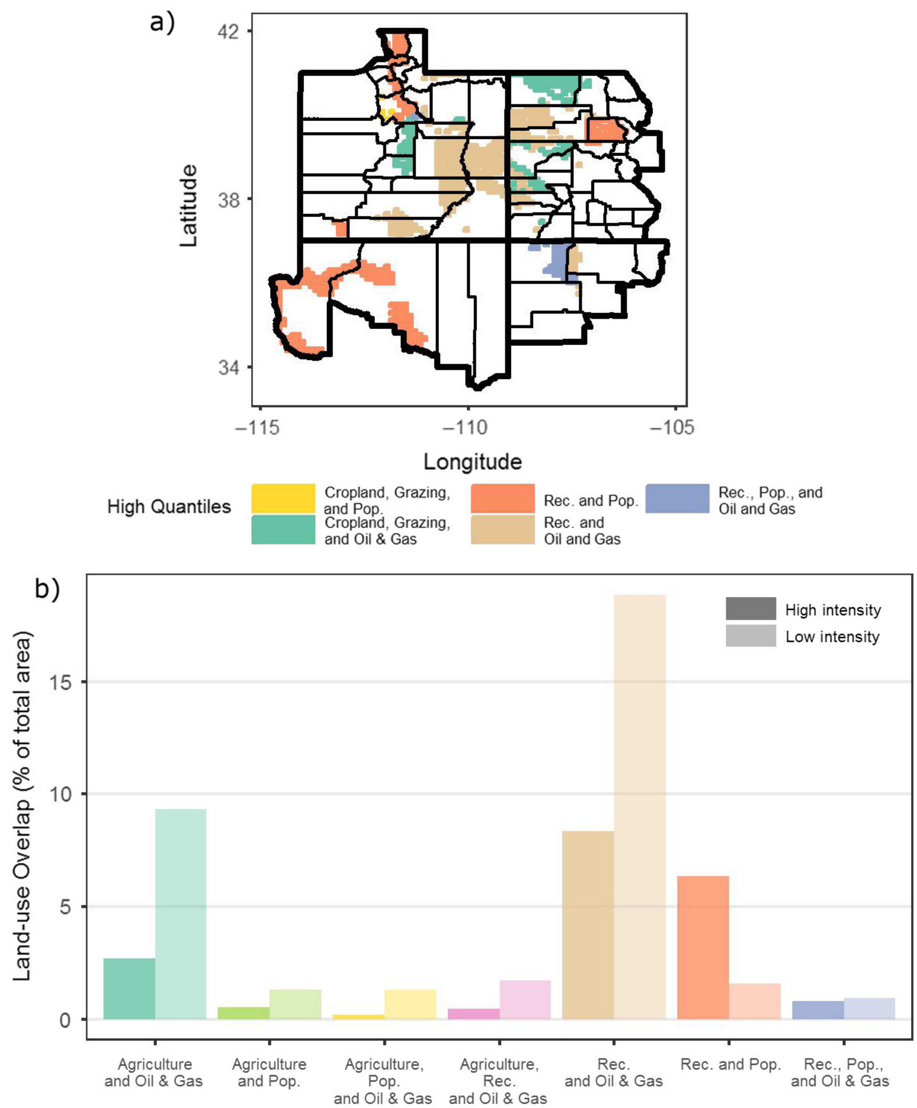

Fig. 3. Area of overlap of land-use quantiles (current agriculture [cropland and grazing], potential oil and gas development, current recreation, and population by 2100) by category. (a) Map of areas of overlap of high-intensity land-use (≥75%) quantiles by category. (b) Percent area of overlap of high-intensity (≥75%) and low-intensity (≤25%) land-use quantiles by category.

unequal scenario type led to the highest median impacts for water availability (0.23 median), cropland productivity (0.10, tied with the high climate change scenario), and recreation economy (0.43). The equal scenario resulted in the highest median impact for vegetation and wildlife habitat (0.24) and cultural and spiritual values (0.24, Fig. 4, spatial variation; Appendix S1: Figs. S12–S17). Among landscape attributes, cropland productivity (19%) had the greatest area estimated as high impact for land-use and climate change based on spatial overlap of all four scenarios. Soil productivity had the second highest percentage of area in the higher impact category (14%), followed by vegetation and wildlife habitat (10%), cultural and spiritual values (9%), water availability (7%), and recreation economy (4%; Fig. 5a–f). Cropland productivity also had the largest area categorized as low impact for all scenarios (22%), followed by soil

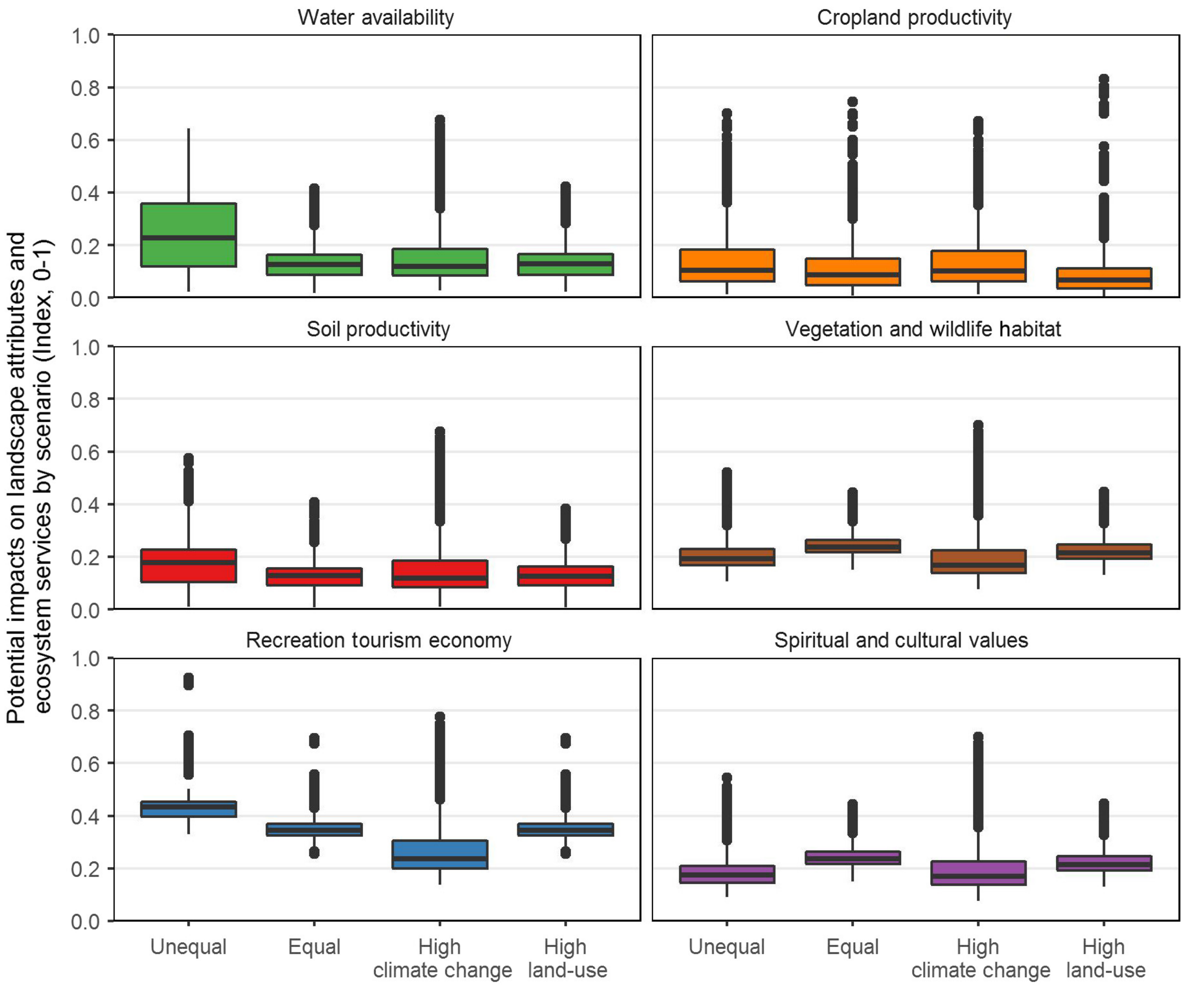

Fig. 4. Boxplot of potential impacts to landscape attributes and ecosystem services by land-use and climate change scenario type (index, ranges from 0 to 1, with higher values indicating greater impact; each point is a 10-km^2 cell in the analysis study area).

productivity (16%), cultural and spiritual values and vegetation and wildlife habitat (both 11%), water availability (9%), and the recreation economy (4%; Fig. 5a–f).

Discussion

Trends, projections, and spatial patterns of drivers of change on the semi-arid Colorado Plateau suggest widespread potential for overlap of multiple areas with high-intensity land-use. We also found that aridification is likely to occur throughout the region, leading to widespread overlap with areas likely to be exposed to high-intensity land-use in the future. We found that croplands and livestock grazing, historically important and spatially extensive land-use types in the region, are declining or relatively static across most of the landscape. In contrast, the rate and pattern of oil and gas development and recreation suggest rapid growth and the potential for high spatial overlap. High rates of population growth in the relatively few urban areas in the Colorado Plateau are also likely to put pressure on major landscape attributes. The effects of overlapping land-use and climate change on landscape attributes vary by weighting scenario and whether the magnitude or area of high impact is considered. For instance, combined scenario results suggest that land-use and climate change will have the highest

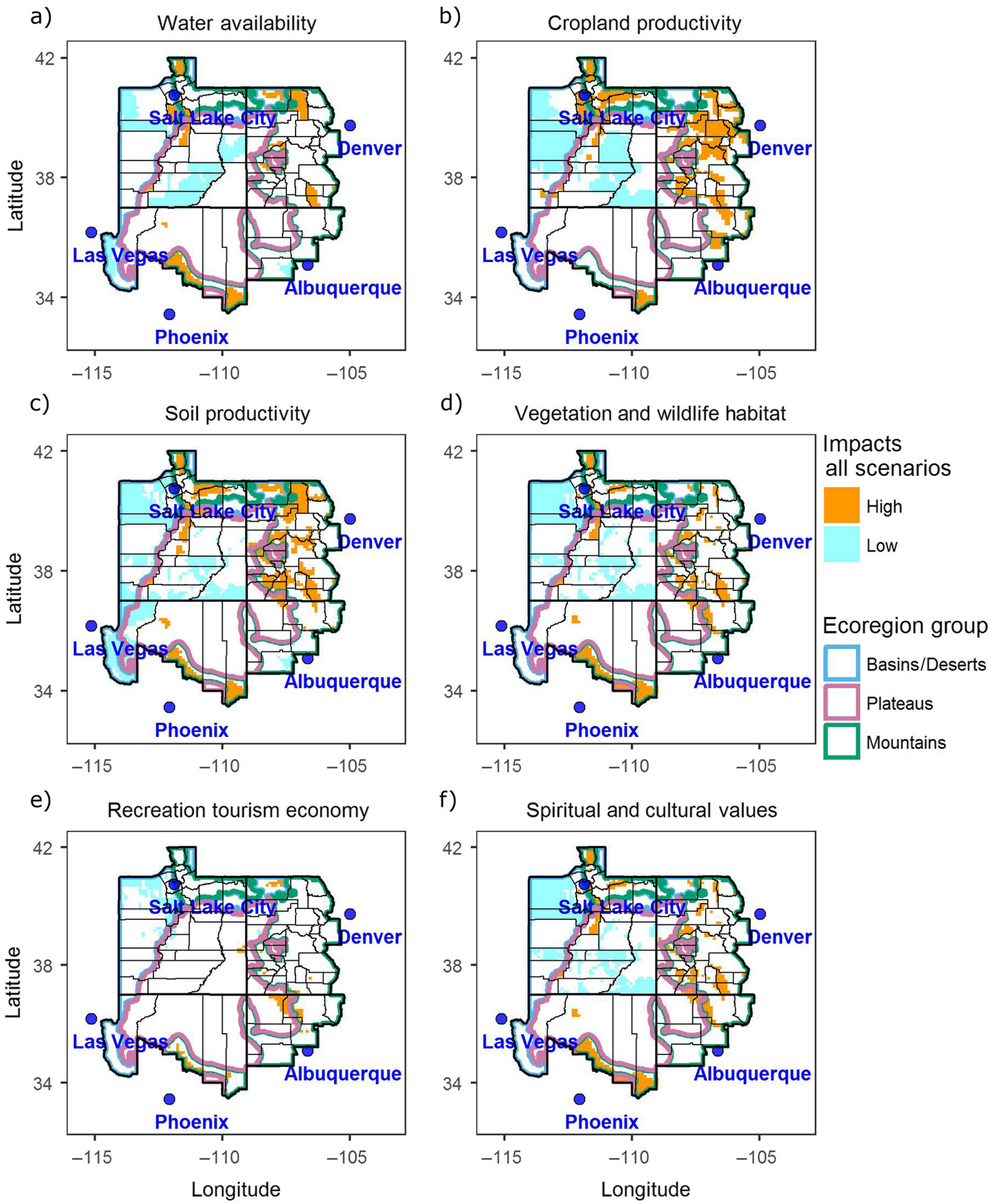

Fig. 5. Areas with high (≥75% quantile) and low potential impacts (≤25% quantile) on ecosystem services and landscape attributes for all four land-use and climate change scenario types with ecoregions and major urban areas: (a) water availability, (b) cropland productivity, (c) soil productivity, (d) vegetation and wildlife habitat, (e) recreation tourism economy, and (f) spiritual and cultural values.

median impacts on the recreation tourism economy, while cropland productivity had the greatest area categorized as relatively high impact. While the scenario results are contingent on the specific drivers of change and ecosystem services or landscape attributes considered, a similar analysis approach could be readily applied in another region or to assess the impacts of overlap for other land-use or climate variables.

Land-use and climate change impacts on the Colorado Plateau

Aridification is likely across most of the Colorado Plateau, potentially impacting landscape attributes and ecosystem services over broad areas and major ecoregion groups. Our analysis indicated that moderate levels of aridification, represented in the scenarios with intermediate weights for climate change relative to land-use (the equal and unequal weight scenarios), led to projections with the highest potential impacts on landscape attributes and ecosystem services. This result is broadly in agreement with projections suggesting significant reductions in future surface water and groundwater in the Colorado River Basin, the principle water source for the majority of the region, as a result of the combined water demands from multiple land-use types and aridification trends (Barnett and Pierce 2009, Castle et al. 2014).

Despite potential for conflict with other land-use types, recreational activity on public lands is likely to increase with positive effects on the tourism sectors of gateway communities in the region (Arizona Hospitality Research & Resource Center 2011, Leaver 2014, Thomas et al. 2014). The economic importance of the recreation economy in the region is increasingly recognized. For instance, the State of Utah actively promotes its national parks with the "Mighty 5" campaign and recreation on federal lands is highlighted in the National Travel and Tourism Strategy, which seeks to promote the United States as an international travel destination (Bryson and Salazar 2012). The congestion of trails and roadways with high visitor numbers can also negatively impact the visitor experience, and the increasing visitor numbers have spurred plans to reduce these impacts in some of the most popular parks in the region (Zion National Park 2016, Visitor Use Management Process, Arches and Canyonlands National Parks 2016, Traffic Congestion Management Plan).

Our analysis suggests that the recreational tourism economy is also vulnerable to negative impacts due to the high degree of spatial overlap of areas with higher visitor numbers and areas of increasing aridification and petroleum and renewable energy development. Though some recreation areas receiving high visitor numbers are largely protected from energy development (e.g., National Parks and Monuments), many of these management units are surrounded by public and private lands with high potential for future high-intensity land-use and impacts to landscape attributes (Hansen et al. 2014, Moab BLM 2016). It is unclear whether these drivers of change will negatively affect visitor numbers, particularly given the diversity of recreation types and sites on the Colorado Plateau. However, higher intensity of land-use and climate warming is likely to lead to increased conflict and added complexity for resource management for ecological integrity, energy production, and recreation.

Implications for other drylands

While the Colorado Plateau has distinctive cultural, economic, and environmental features, it also shares many attributes with drylands in other parts of the world. Due to their sensitivity to disturbance, other drylands globally may be subject to the potentially negative combined impacts of land-use, such as grazing and cultivated agriculture, and aridification, on landscape attributes such as vegetation and soil productivity (Ravi et al. 2010, D'Odorico et al. 2013). As in the Colorado Plateau, tourism related to natural features and historic sites are significant sources of economic activity in some drylands in addition to traditional land-use types such as agriculture (MEA 2005*b*, Dryland Systems). Population growth and urbanization are occurring in many dryland regions, as in the Colorado Plateau, with corresponding shifts in water demand and economic activity (MEA 2005*b*, Dryland Systems). Dryland regions in the Middle East, Africa, and Central Asia also share the characteristic of high rates of oil and gas development with the Colorado Plateau (nine of the top 20 petroleum-producing countries for 2015 are in dryland regions, USEIA 2017). However, fewer countries in dryland regions are notable for high renewable energy development (Spain and Australia in the top 20 non-hydroelectric renewable energy-producing countries USEIA 2017). In addition, even where major land-use types are shared with the Colorado Plateau, historical and modern social and political factors may shift the relative importance of these drivers of change in other dryland regions. Our analysis illustrates a methodological approach for identifying the spatial pattern and potential for risk to landscape attributes from overlapping high-intensity land-use and aridification trends, a potential first step in crafting management approaches to avoid the land degradation which drylands may be susceptible to (Reynolds et al. 2007).

Limitations and additional applications

Our analyses of temporal trends and spatial overlap are affected by resolution and time periods of available land-use and climate data and the uncertainty associated with land-use and climate model projections. For example, grazing and recreation data collection and methods varied between federal management agencies. Even at the scale of the focal region, the Colorado Plateau, the certainty regarding the potential future impacts of land-use and climate change on various landscape attributes of interest is limited by the amount of information available for present conditions as well as existing models for the future at the spatial and temporal scale of the analysis, an issue that also affects other regional analyses similar to this one (e.g., BLM Colorado Plateau Rapid Ecoregional Assessment, Bryce et al. 2012). While we lacked projections for agricultural variables and recreation, the information we gathered on spatial patterns and trends for these variables suggests that using current spatial patterns of high intensity may not greatly affect the results. For example, it is likely that the iconic National Parks with consistently high visitation rates, such as Arches or Grand Canyon, will remain at the high end of the spectrum for visitation in the future. Current forecasts for National Park visitation suggest that warming climate may even push the numbers of visitors higher for NPS units on the Colorado Plateau by increasing the number of visitors during cooler months of the year, with the increase in summer temperatures unlikely to be sufficient to deter visitors (Fisichelli et al. 2015). In contrast, future trends for BLM and FS high recreation areas are less certain, due to less information on past trends, as well as indications that visitors to at least one major BLM recreation area (Lake Havasu Field Office) have declined over the last 15 yr (Appendix S1: Fig. S6d). Nevertheless, the spatial location of major recreation sites on federal land seems unlikely to change in the near future though some areas may receive more or less visitors than in the past relative to other recreation sites.

In contrast to recreation, future trends in cropland and livestock intensity seem less certain, because of the factors such as the changing value of different agricultural products, the uncertainty related to water availability for irrigation with climate change, and the potential for conversion of agricultural areas to urban or suburban lands. Most of these factors, however, would lead to a decline in agricultural productivity but not necessarily a widespread change in the spatial pattern of high-intensity agriculture as measured in this study. For instance, croplands at higher elevations may become more productive, whereas low-elevation area may become less productive; however, this would only change the percentage of counties in cropland if newly favorable areas were converted to crops, which is less likely, given the high proportion of the land-base under federal management, or in the event that less productive areas are completely abandoned. Given these uncertainties, our scenarios related to agriculture are potential outcomes given current agricultural patterns and a starting point for further analyses that incorporate social and environmental factors into more robust projections.

In contrast to ecosystem service analyses that use dollar values to estimate the total potential for loss (e.g., Costanza et al. 1997), our analysis offers an approach for estimating the land-uses and aridification trends as well as identifying the ecosystem services and landscape attributes associated with "hotspots" of overlapping drivers of change. The spatial patterns of impact resulting from our analysis framework are affected by which driver of change we included in scenarios for each ecosystem attribute as well as the weights we chose for those drivers. We explored the potential for this variability to affect our estimated impacts by comparing the results of different weighting schemes with our four scenario types and found broad ranges in the median index of the resulting impact (i.e., the value of the median index for recreation economy varied by 80% between scenarios). In the event that regional models are developed for estimating the impacts of specific drivers of change on the landscape attributes we considered, then the scenarios could be refined to encompass particular story-lines for the effects of development on that attribute (MEA 2005*c*). Even in the absence of those detailed models, our analysis suggests areas of spatial overlap, and categories of overlapping land-use types, which are likely to be relatively important for landscape attributes due to their spatial extent and/or rate of increase.

Ecosystems are increasingly impacted by land-use and climate change around the globe (MEA 2005*a*), and methodological approaches that address the complexity of interacting drivers of change are needed to support sustainable management. We propose that the relatively simple approach used in this analysis could be applied to address questions at different spatial resolutions, with other land-use datasets, or with refined weights based on expert knowledge and/or more detailed data sources. We suggest that assessments at this spatial scale, a region, are a useful link between global-scale (e.g., Foley et al. 2005) and national-scale analyses (e.g., Piao et al. 2010) because they encompass large watersheds (e.g., the upper Colorado River) and multiple management and political units (park networks, states, and counties) which are relevant to regional decision-making and scenario-building. Finally, examining the spatial patterns of overlap, and the identity of the land-use types involved, may indicate where research is needed to address knowledge gaps regarding the vulnerability of particular landscape attributes to specific categories of overlapping land-use intensity.

Many of the land-use types we analyzed could also be significantly affected by political and behavioral factors and adaptive responses at both local and global scales. For instance, different economic growth scenarios in the population growth model alter regional population projections by orders of magnitude (Appendix S1: Fig. S4e; Bierwagen et al. 2010). International regulation of greenhouse emissions will affect the rate of climate change, while decisions within local federal management units may affect grazing permits and oil and gas leases. At a local scale, federal land managers are adapting to changes in land-use and high recreation pressures through complex long-term planning strategies (e.g., the Moab BLM Master Leasing Plan, Zion National Park 2016, Visitor Use Management Plan, Arches and Canyonlands National Parks 2016, Traffic Congestion Plan) and visitor-use management techniques including permit systems, shuttles, and waste management requirements among other efforts (e.g., Zion, Canyonlands, Arches, Grand Canyon National Parks). Adaptation strategies implemented by individual ranchers and farmers could reduce the economic losses in agricultural systems associated with increased climatic variability and warming (e.g., Howden et al. 2007). A change to lower-intensity land-use in response to aridification, such as from cropland to rangeland, has the potential to increase the habitat available for native species and allow for recovery of soil properties (Bestelmeyer et al. 2015). Increased water efficiency has slowed the rate of water use in a number of sectors, and efficiency is likely to continue to increase (Maupin et al. 2014). Similarly, urban development plans that prioritize habitat can reduce the impact population growth on wildlife and vegetation, and renewable energy developments can be planned to maximize energy production and delivery, while avoiding areas of high environmental value (Hernandez et al. 2015). Land management plans to reduce overlap of conflicting uses could decrease the amount of area and the number of attributes experiencing adverse impacts. Broad-scale changes in land-use have occurred on the Colorado Plateau in the past; fields cultivated ~700 yr ago are now historic parks and gold and silver mining are no longer major drivers of the regional economy or population growth. However, it is worth noting that such large shifts in land-use patterns are not without social and environmental costs.

Conclusions

Overlapping areas of high-intensity land-use and aridification have the potential to greatly affect environmental and socioeconomic conditions, and analyses of their combined trends and spatial patterns can identify emerging potential for conflict and cumulative impacts which may result in undesired economic losses and social change. Our analysis approach offers a relatively simple method for scenario development for the potential impacts of overlapping land-use and climate change on ecosystem properties which could be applied to a range of drivers of change, ecosystem services, and regions. Identifying potential areas of overlap may be particularly important in dryland systems such as the Colorado Plateau where resources (i.e., water) are scarce and ecosystem characteristics (e.g., soil productivity) are sensitive to degradation. While regulation of global warming may depend on international agreements regarding carbon emissions, land-use patterns are more likely to be influenced by local, state, or federal decisions. Jointly considering the potential impacts of land-use and climate change on multiple ecosystem services (Appendix S1: Fig. S11) is more likely to lead to informed decisions which may support long-term sustainability of human societies and the ecosystems which support them.

Acknowledgments

We thank the following individuals for providing data and insight: grazing: Larry Lichthardt and Lynnda Jackson (BLM), Chad Horman, Marlene Depietro, Teresa Rhoades, and Dennis Cleary (FS); agriculture: Patrick Willis (NASS); energy: Seth Haines, Sarah Hawkins, and Miguel Villareal (USGS), Holly Copeland (TNC), Steve Rauzi (Arizona Geological Survey); mining: Greg Fernette (USGS); population: David Theobald (Conservation Science Partners); recreation: David Baker (BLM), Donald English (FS), Sabrina Henry, John Keck, Donald Ledbetter (NPS). We thank Jeremy Havens for the original artwork for Fig. S11. We thank Bill Stevens (BLM), Mark Miller (NPS), and two anonymous reviewers for their comments. Any use of trade, product, or firm names in this article is for descriptive purposes only and does not imply endorsement by the U.S. government.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1823/full