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Diverse landscapes, diverse risks: synthesis of the special issue on climate change and adaptive capacity in a hotter, drier Southwestern United States

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Abstract Assessing regional-scale vulnerability of agricultural systems to climate change and variability is vital in securing food and fiber systems, as well as sustaining rural livelihoods. Farmers, ranchers, and forest landowners rely on science-based, decision-relevant, and localized information to maintain production, ecological viability, and economic returns. This paper synthesizes the collection of research on the future of agricultural production in the Southwestern United States. A variety of assessment methods indicate the diverse impacts and risks across the Southwest, often related to water availability, which drives adaptive measures in this region. Sector- or species-specific adaptive measures have long been practiced in this region and will continue to be necessary to support agricultural production as a regional enterprise. Diversification of crop selection and income source imparts climate resilience. Building upon biophysical vulnerability through incorporating social and economic factors is critical to future adaptation planning efforts. The persistence and adaptive capacity of agriculture in the water-

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limited Southwest serves as an instructive example for producers outside the region expecting drier and warmer conditions and may offer solutions to reduce future climate impacts.

1 Introduction

This collection of articles focuses on the impacts of climate variability and change on agricultural production systems of the Southwestern United States, including rangelands, field crops, specialty crops, and forested systems. The market value of agricultural products sold in the Southwest (SW) region approaches $52 billion per year with roughly 60% from crop sales and 40% from livestock enterprises and their products (National Agricultural Statistics Service 2017). Approximately 70% of the livestock revenues in this region are from beef cattle and calves, as well as dairy cattle (Havstad et al. 2016). The SW, primarily California, accounts for more than half the nation's specialty crop production and approximately 90% of the national production of wine grapes, strawberries, and leaf lettuce (Starrs and Goin 2010).

The special issue (SI) evolved from a vulnerability assessment of agriculture and forest ecosystems of the Southwestern US. As one of the first products of the USDA Climate Hub network, vulnerability assessments were written for the regions of the network. These assessments were intended to provide a broad overview of the most vulnerable agricultural and forest systems in each region both to prioritize future work and to broaden understanding of regional impacts of climate change to agricultural and forestry sectors. For a broader view of agricultural vulnerability across the US, this collection should be viewed alongside efforts of the greater USDA Climate Hub network in a companion SI (Steele and Hatfield et al. 2018).

This special issue (SI) includes six articles focused on how a warmer and drier future will likely impact ranchers, farmers, and foresters in the Southwestern US. Given existing water scarcity, projection of increased duration and severity of drought, and reliance of agricultural producers on available water, it is critical to evaluate how climate change may impact regional food production, food scarcity, natural systems, and rural livelihoods. Here, we synthesize the overarching methods and results from the SI and highlight four emergent commonalities (themes) in resilience and vulnerability analyses. A vulnerable system has lost resilience, implying the loss of adaptive capacity (Folke 2006). The resilience perspective incorporates social and ecological drivers and emphasizes how periods of gradual change interplay with periods of rapid change. As described in the papers of this collection, the Southwest (SW) region experiences and is projected to experience a range of exposure, sensitivity, and adaptive capacity leading to a dynamic range of resilience and vulnerability across commodity, space, and time.

Here, we synthesize the overarching results of this SI in four sections. The first section provides the regional context for Southwestern climate change vulnerability. In this section, we give insights to some of the unique aspects of the region, including high topographic, cultural, and agricultural diversity, and existing water scarcity. In the second section, we describe the content of the collection and highlight vulnerability assessment components and methodology. The third section provides emerging themes in the SW based on the findings of the articles. The fourth section highlights knowledge gaps that emerged while compiling this collection. Articles in this collection provide both general and specific details about how climate change may impact specific crops and forest types, particularly from a biophysical–ecological perspective. To our knowledge, this is the first comprehensive assessment of the vulnerability of working lands to climate change in the SW US.

2 Regional context: the Southwestern US

The SW is defined by landscape diversity in terms of natural landforms, elevation gradients, and water availability. The unique and diverse landforms of the SW include mountains, valleys, and plains, including low- and high-elevation deserts, such as the Great Basin Desert, Mojave Desert, Sonoran Desert, and the Chihuahuan Desert (Chabot and Mooney 1985). The broad environmental gradients of the SW support a multitude of forest types including arid woodlands, savannahs, and cool coastal and high-elevation forests. California's Mediterranean climate (unique in North America) and large-scale irrigation systems support specialty crops, which are themselves inherently diverse. Specialty crops are from different botanical families: annuals, biennials, and perennials; they are consumed as fruits, nuts, leaves, stems, and tubers; and they require diverse cultivation practices (Kerr et al. 2017).

Amid a rural landscape managed by various entities are some of the most rapidly growing urban areas of the nation. In terms of human geography, this leads to a vast rural landscape with low population density punctuated by rapidly growing urban areas. The SW is also home to 180 federally registered tribal nations, which occupy 9.4% of the land area in the SW (Redsteer et al. 2013). Within the SW, there are regions of elevated economic and social vulnerability. For example, the border region from the Pacific coast of California to El Paso, TX, has higher poverty, water insecurity, and substandard housing when compared with the broader United States (Wilder et al. 2013). The many agencies and nations with competing water and land management goals, divergent economies, and broad differences in water security pose obvious challenges for climate adaptation to minimize vulnerability. Less obvious opportunities emerge in the task of working collectively to address competing goals while providing for food security and resilient working landscapes.

Climatic variability, water scarcity, and extreme weather define the SW (Sheppard et al. 2002; Wagner et al. 2010). Producers have long adapted to drought with a variety of options related to local conditions and production system (Vásquez-León et al. 2003). While the unprecedented drought in California (2012–2016) had severe local impacts on some producers, agricultural revenue remained fairly consistent as some producers relied on groundwater to supplement surface water shortage (Howitt et al. 2015). Recent scientific evidence clearly links southwestern drought to the increased temperatures of climate change (Mann and Gleick 2015), with drought expected to be of longer duration and higher intensity in the future (Cayan et al. 2010; Cook et al. 2015). The SW may have already transitioned to a drier climatic state leading to higher drought risk (Prein et al. 2016) implying that producers may need to further adapt.

3 Content of the special issue

Against this backdrop, the contents of this SI explore aspects of climate change, agriculture, and forest systems. Steele et al. (this issue) provide background on vulnerability assessment methodology. The authors highlight how vulnerability assessments can assist in developing solutions to the challenges of warming temperatures and water scarcity. The authors emphasize that to fully address necessary responses to climate change, we must consider contextual vulnerabilities, including biophysical, socio-economic, institutional, cultural, and other factors, to develop feasible adaptation options. The authors provide examples of crop specific and geographically identified contextual vulnerability. Elias et al. (this issue) summarize observed and expected temperature and precipitation changes as an introduction to exposure and ensuing impacts at the county level. Cropland vulnerability to climate change is further explored in two articles. Kerr et al. (this issue) evaluate both economic and biophysical vulnerability of the highest value specialty crops in California. Elias et al. (this issue) employ different spatial methods, including a temperature envelope approach, to evaluate the impacts of increased temperature on field crops across a five-state region in the SW US. Thorne et al. (this issue) employ a spatial modeling approach to evaluate how changes in temperature and precipitation may impact different forest types across the SW.

The articles of this collection address climate change vulnerability or the degree to which a system is susceptible to injury. Vulnerability can be defined and assessed from a variety of perspectives and is often described as a function of exposure, sensitivity, and adaptive capacity (Table 1) (McCarthy et al. 2001). Complementary concepts and methodologies to assess vulnerability have evolved which often differ based upon their unit of spatial analysis (field, farm, county, region), unit of focus (single crop, collection of crops, all crops or forest systems grouped into types, or complex landscape or industry), and fundamental assumptions in defining sensitivity, exposure, and adaptive capacity. Definitions from the Intergovernmental Panel on Climate Change (IPCC) are used here to further explain the components of vulnerability. Exposure is the external stress imposed on a system. Some authors of articles in this SI incorporate exposure by assuming a hotter, drier future in the SW based on literature whereas others quantify changes using downscaled climate models at varying spatial scales. Sensitivity is the degree of change induced in a system because of exposure. Three of four articles in this collection developed indexes to estimate sensitivity based upon prior biophysical research. The IPCC defined adaptive capacity as the capability of a system to respond to climatic stimuli or impacts. Adaptive capacity was described and discussed as many broad conditions based on various eventualities in three of four articles. Thorne et al. developed an index to incorporate adaptive capacity based on specific stressor responses in forests. As this collection shows, a consistent or "one size fits all" methodology is not necessary to support agricultural climate change adaptation. Rather, both experiential knowledge and data-driven approaches can be used to support climate change adaptation and build resilient agroecosystems at relevant scales. While differing methodologies are a function of research objectives and data availability, future interdisciplinary efforts to build upon biophysical aspects of vulnerability that include economic and social considerations could be especially valuable for adaptation planning.

4 Emerging themes from varying perspectives

4.1 Theme one: it is essential to evaluate climate impacts using a variety of methodologies and perspectives

Identifying climate risks helps frame adaptation to climatic changes in the agricultural sector by focusing on management for sustainable production and resilient working landscapes (Howden et al. 2007). Ensemble mean climate projections of temperature and precipitation are often used in climate analyses and adaptation planning (Knutti et al. 2010). Means are valuable because they allow for adaptation measures to average conditions; however, addressing different emissions scenarios can inform the possible range of future temperature/ precipitation impacts on the sector of interest. For example, Thorne et al. (this issue) found

Table 1 Definition of vulnerability components (sensitivity, exposure, and adaptive capacity) for four sectoral areas to describe methods of assigning components. TR, thermal range; RCP, representative concentration pathway; CDL, cropland data layer: T_{max}, maximum temperature; T_{min}, minimum temperature; MACA, multivariate-adaptive constructed analogues

	Definition	Sector			
		Rangelands (Havstad et al.)	Forests (Thorne et al.)	Specialty crops (Kerr et al.)	Field crops (Elias et al.)
Exposure	Exposure refers to the nature of the external stress imposed on a system. Complexity of input data for analyses typically defines complexity of exposure metrics and measures	“Unquantified,” however, incorporated via discussion of abiotic stressors (i.e. precipitation, temperature)	Bioclimatic envelope assuming exposed vegetation is within or beyond the most marginal 1% of the current climate space.	Summer T_{max}; Winter T_{min}	a. Summer T_{max}b. Crop-specific thermal tolerance based on historic TRc. Days with temperature > 35 °Cd. Cumulative hours of crop exposure per 1 °C increment from 32 to 34 °C and ≥ 35 °C
Historic	Past climatic conditions (time-period varies by sector and, for field crops, analysis.	na	50-year mean (1950–2000) of 19 bioclimatic variables.	MACA downscaled county-level data; PRISM 30-year normals (1971–2000)	a. PRISM 30-year mean (1971–2000)b. 30-year mean (1971–2000) and USDA CDL (4 km^2). TR is 95% of summer T_{max} coincident with crop location.c. Days > 35 °C April to August using MACA 20 model mean (1950–2005).d. 1950–2005 hourly temperature exposures April to August for 20 MACA models.
Future	Future climatic conditions	na	Two climate models (MRI-CGCM3 and MIROC-ESM-CHEM (2061–2080)	Mean of 20 CMIP-5 models (2040–2069)	a. Mean of 20 CMIP-5 models (2040–2069)b. Same as a. (above)c. Days > 35 °C using mean of the 20 MACA models (2040–2069).d. 2040 to 2069 hourly temperature exposures (T_{max} and T_{min}) April to August for the 20 MACA models.
Emission scenario	RCP from the coupled model intercomparison project 5	na	RCP4.5 and RCP8.5	RCP8.5	RCP8.5

Table 1 (continued)

	Definition	Sector			
		Rangelands (Havstad et al.)	Forests (Thorne et al.)	Specialty crops (Kerr et al.)	Field crops (Elias et al.)
Sensitivity	Sensitivity is the degree of negative or positive change induced in a system because of exposure to the effects of climate change. Sector-dependent definition including abiotic and biotic impacts, as well as socio-economic variables.	Impact-driven from a livestock perspective (biophysical and socio-economic considerations; e.g. land degradation, reduced forage supply, increased heat stress, reduced livestock grazing-carrying capacity; reduced operations options)	Endemic drivers of stress: wildfire, drought, pathogens, and pests (scored from 0 to 3).	Literature synthesis to create a sensitivity index from 1 to 4 to both winter $T_{\min}$ and summer $T_{\max}$.	Biophysical (crop yield effects)a. Literature synthesis for crop sensitivity factor (SF) (scale 1 to 3) to summer $T_{\max}$.b. Shifts in and out of TRc. Areal extent with increased temperatured. Crop yield effects
Adaptive capacity	Adaptive capacity describes management practices for helping the system tolerate changes in the magnitude, frequency, duration, and areal extent of external stressors.	Response and adaptive capacity will rely upon proven management strategies of the past (reduced stocking rates, proper grazing management and diversified income, alternative forage supplies, and practices to reduce heat stress.	Mechanistic species-specific response to disturbance (i.e. sensitivity): presence of fire-adaptive traits, modes of dispersal, seed longevity (scored from 1 to 3).	Impact-based crop acreage/value. Adaptive measures discussed but not modeled (i.e. use of heat- and drought-tolerant crops).	Adaptive measures discussed include increasing irrigation and water security, earlier planting—supported by spatially explicit vulnerability analysis, selecting and developing drought-tolerant cultivars, prioritize adaptation using spatially explicit methods.
Vulnerability	Outcome vulnerability is the potential for climate change impacts on an exposure unit after feasible adaptations. Contextual vulnerability is influenced by biophysical conditions as well as dynamic social, economic, political, institutional, and technological factors (O'Brien et al. 2007).	Contextual	Outcome	Outcome	Outcome

Table 1 (continued)

	Definition	Sector			
		Rangelands (Havstad et al.)	Forests (Thorne et al.)	Specialty crops (Kerr et al.)	Field crops (Elias et al.)
Spatial unit of analysis	Spatial area where variables (exposure, sensitivity, and adaptive capacity) are summarized and impacts evaluated	NRCS Land Resource Regions (LRR)Major Land Resource Areas (MLRAs)Ecological site	1 km^2 grid from LANDFIRE grouped into 10 major categories according to similar species composition, geographical distribution, and ecological function (summarized at SW, forest type, and US level III ecoregion scales).	County level (California)	County level (Southwest US) and 2012 crop locations as defined by the USDA Crop Data Layer
Spatial unit is a function of, but not the recommendation listed above.	Factors used to define spatial unit of analysis	Climate, land use, soils, vegetation	Climate, modeled land types, soils, vegetation	Political administration	Political administration

that the higher emissions scenario (RCP8.5) led to an impacted forest area three times larger than the area predicted by the lower emissions scenario (RCP4.5). It is essential to craft adaptive measures for expected average conditions but also to consider the likely extreme events and resulting social vulnerabilities, systemic resilience, and cascading impacts. Extreme events are important for risk analysis; however, adaptation related to such events is often not successful (Schneider et al. 2000).

Kerr et al. (this issue) found that the choice of metric (relative vs absolute; winter vs summer, and area-based vs value-based) influences the spatial pattern of specialty crop vulnerability. This highlights the value of taking multiple viewpoints to evaluate and describe varying impacts. In this collection, specialty and field crop county-level impacts are reported using two impact metrics (absolute and relative impact). No county ranked in the highest quantile using both metrics for specialty crops ($n = 58$ counties), and only one county (Imperial County, California) ranked in the highest quantile using both metrics for field crops ($n = 152$ counties). Additionally, specialty crops analyses used both economic- and area-based perspectives and found that there is no single locus of agricultural vulnerability in California, but differing areas and crops appearing vulnerable depending upon assessment methods and assumptions (Kerr et al., 2017).

Using the county as a fundamental mapping unit encourages the use of climate change projections within existing institutional structures like cooperative extension (CE). Sometimes, a rapid analysis of climate impacts on a particular crop/location can provide enough information to support management or indicate if more in-depth analysis is necessary. For example, most prior assessments of specialty crops in California were conducted on perennial specialty crops, but analysis in this SI showed that annual strawberry production in California may impart significant vulnerability to Coastal California counties and warrants additional analysis.

4.2 Theme two: there will be widely varying impacts across the Southwest, often related to water availability

As highlighted in "Section 2," water availability is paramount in the SW. The articles of this collection further illustrate this point based on the varied impacts of precipitation changed on differing production systems. Thorne et al. (this issue) show that in forested ecosystems of the region, the wetter modeling scenario predicts considerably less exposure (see Table 1) to climate change (27% vs. 78% exposed), thereby decreasing forest vulnerability (Thorne et al. 2016). As described by Havstad et al. (this issue), rangeland is similarly at the mercy of annual precipitation that supports forage production, thus supplemental feed is vital to support regional livestock production. In contrast, the large majority of specialty crops in the region are irrigated, and approximately half of this irrigation is supplied by groundwater. Thus, unlike rainfed agriculture, un-supplemented rangeland systems, and forest systems, specialty crops would not be expected to respond dramatically to precipitation changes in the short-medium term (Kerr et al. this issue). Vulnerability to precipitation changes is inherently varied and defined by production system.

As described by Elias et al. (this issue), changes in exposure will vary across the region, as temperature will not increase uniformly across all counties. Coastal counties are projected to have a 2C lower mean temperature increase than inland counties of the SW. Similarly, minimum temperatures are anticipated to increase more rapidly than maximum temperatures in the region (Gershunov et al. 2013) disproportionately affecting annual and perennial crops. Growing conditions may not be climatically suitable for many key perennial specialty crops in the region, whereas annual specialty crop temperature–yield relationships are more complex, with both positive and negative impacts of climate change, indicating a need to evaluate impacts on a crop-by-crop basis to account. Even among annual crops, impacts will be different for different crops because species exhibit varied thermal tolerance. For example, by midcentury, area suitable for maize cultivation is projected to decrease, while area suitable for cotton cultivation expands northward and nearly doubles in extent. Heat stress already reduced historic (1950–2005) yields in the region and is predicted to reduce cotton and maize yields by 37% and 27%, respectively, compared to potential yield by midcentury.

Growers can alleviate crop heat stress by increasing irrigation (Haim et al. 2008), which enhances evaporative cooling. This is a common adaptation strategy for many crops cultivated in the SW (Nicholas and Durham 2012; Radin et al. 1994). However, delivering adequate water to reduce heat stress and maintain yields may be a challenging or even impossible adaptation strategy with predicted reductions in water supply and increased water scarcity (Schoups et al. 2005). Water availability may be the most critical factor impacted by a changing Southwestern climate. Though beyond the scope of this collection, surface water quantity and quality, diminishing and over-tapped groundwater resources, and continued competing demands are critical to many sectors of the region and described more completely in articles of this collection and elsewhere.

From a livestock perspective, animal agriculture is highly adaptive, but producers need to understand the ecological characteristics of their specific landscapes to cope with emerging climatic changes. For example, Havstad et al. (this issue) report that the most lucrative beef cow revenues surpassed $30 M per county in the 14 counties of the Great Salt Lake Area (MLRA 28a). Surface water is used to grow animal feed crops as 27% of MLRA 28a is private cropland used in support of livestock production. Even in the more arid regions of the SW, regionally available-harvested forages from irrigated croplands are vital to support beef calf–cow operations and support the essential need for water for agriculture.

The hotter and drier conditions predicted in a changing climate represent a “new normal” that could exacerbate crop yield declines from unexpected irrigation interruptions and rangeland productivity due to decreased precipitation (Diffenbaugh et al. 2015; Seager et al. 2007). If drought conditions become the “new normal,” then groundwater reserves would likely decline (Taylor et al. 2013) effectively removing the secondary source responsible for buffering severe drought effects.

4.3 Theme three: spatial analysis supports informed adaptation, within and outside the Southwest

The articles of this collection indicate that adaptation measures could be targeted at vulnerable locations for particular forest or crop types. Thorne et al. (this issue) report that some forested regions were at risk in all climate scenarios tested whereas some areas were less impacted, indicating locations where planned adaptation is necessary with higher certainty. The most widespread forest type in the SW, pinyon juniper woodland, was less exposed. In contrast, redwood forests and oak woodlands were highly vulnerable in all four analyses. There is a growing need for forest adaptation management that anticipates landscape-scale climate change effects. Spatial analyses provide information to identify suitable sites of higher elevation where sensitive conifers might be replaced by other conifer species via adaptive management (Lenihan et al. 2003).

From a crop perspective, spatial analysis of Elias et al. (this issue) provided an initial means to rank order which regions should be examined more rigorously. For example, the four North

Central Valley California counties (Butte, Colusa, Glenn, and Sutter) with large rice cultivation area (76–95%) were less impacted than other counties with similar area under cultivation but composed of different crops. Conversely, Yuma, Arizona, was more impacted than other counties with similar cultivation area due to production of sensitive crops near the upper bounds of optimal temperatures. Thus, spatial analyses provide information for targeted responses.

While it is intuitive to assume that some systems are already detrimentally impacted in the arid SW, regional temperature–yield analysis of this SI supports this assertion. Estimates of yield reduction from heat stress for maize and cotton indicate that heat stress reduced cotton yield by 26% and maize yield by 18% compared with potential yield. Spatial analyses for cotton, alfalfa, and maize highlight how thermally suitable production areas are projected to shift. Some locations will shift outside thermal range by midcentury; however, impacts are crop-dependent. While the potential area for maize cultivation is projected to decrease by 20%, a few regions will shift into the thermal range for maize. Cotton cultivation area expands northward and nearly doubles by midcentury (Elias et al. 2017a,b); so, given adequate soil quality and water resources, other areas could learn from the Arizona and California cotton-growing regions.

Moreover, some locations outside of the Southwestern US will transition to similar climatic conditions in the future. Southwestern agriculture has learned to function adaptively to support resilient communities. The knowledge base that supports Southwestern resilient agriculture can be valuable to producers in other areas possibly facing similar conditions for the first time. Climate analogue analysis (Ramirez-Villegas et al. 2011), which operates on the premise that there are present locations able to represent future climate, though at different geographic locations, could be valuable to producers both within and outside the SW. Therefore, adaptive capacity can be conferred by both experiential knowledge of similar events (i.e. previous droughts) and similar landscapes (i.e. climate analogues).

Producers typically use past experiences of weather and related agricultural impacts to assess and manage future risks (Wilke and Morton 2017). While we may not simply linearly extrapolate future climatic conditions based on historical trends (e.g. non-stationarity; Milly et al. 2008), adaptation and management responses in the Southwest may act as analogues for other producers in areas expected to experience warmer and drier climates. The SW may act as a harbinger of things to come; however, the resilience of SW producers serves as an example to build adaptive capacity here and elsewhere (Wilder et al. 2010).

4.4 Theme four: adaptation has long been practiced in the region and will continue

An alternate understanding of adaptation has been noted among rural residents of the Southwest who understand, respond to, and plan for weather and climate (Brugger and Crimmins 2013). Humans are seen to co-evolve with the climate, acquire experiential knowledge, adjust activities to long-term climate, and be motivated by an attachment to place and rural values.

Irrigation is a long-practiced adaptation strategy in the Southwest; the evaporative cooling effect allows crops to persist in locations hotter than reported thermal ranges. Five of the states with the highest total irrigation water use in the US are located in the Southwest. Water was the most frequently mentioned climate- and weather-related topic in an assessment of Arizona producers (Brugger and Crimmins 2013). In the Southwest, most adaptive solutions will involve water. Growers may select drought-tolerant cultivars or, where possible, practice deficit irrigation to ensure enough available water during critical periods, such as flowering.

Adaptation and enhancing adaptive capacity to climatic impacts encompasses many options beyond the cursory examples mentioned here.

Regional water availability will be directly and indirectly impacted by elevated temperatures. In addition, elevated temperatures may necessitate earlier planting to adjust for temperature shifts. However, earlier spring planting can increase frost damage risk (Kim et al. 2014); therefore, shifting planting dates to accommodate warming trends may not be a consistently viable adaptation option. Similarly, forest managers will need to decide to manage for resilience, resistance, or allow forests to change (Millar and Stephenson 2015). A full range of active forest management activities will likely occur across the span of southwestern forests (Thorne et al. 2016).

Harvested forages from irrigated croplands are a vital adaptive strategy in times of lower available rangeland forage production. The thermally suitable area for irrigated alfalfa production will decrease by 14% by midcentury in multiple areas of the SW (Elias et al. 2017a,b). The alfalfa cultivation regions impacted by changing future temperatures are California's Imperial Valley, the lower Colorado River Valley along the California–Arizona border, and the Gila River corridor west of Phoenix. From a rangeland perspective, some areas of diversification to impart resilience include using other sources of water (degraded water) for irrigation, expanded production of drought-tolerant feeds (Joyce et al. 2013), and using cattle well-suited to lower forage production and non-grass forages, such as Raramuri Criollo cattle (Anderson et al. 2015).

Transformative practices to sustain animal agriculture, such as the promise of Criollo cattle, are highlighted by Havstad et al. (this issue). Numerous long-term studies on the grazing effects of large-cattle breeds with genetics from northern Europe, which are typically used in the Southwestern United States (i.e. Angus, Hereford), indicate that these breeds tend to focus their grazing along well-defined cattle trails as well as near water sources, such as wells and tanks (Bailey 2004). From an environmental perspective, these behaviors are associated with perennial grass losses (Nash et al. 1999), erosion, and dust emissions. From an economic perspective, these behaviors translate into requirements for expensive supplemental feed, especially during severe drought. A markedly different type of cattle has been identified based on weight, genetic origin, and adaptation to harsh desert environments, which may be better-suited to a warmer, drier Southwest. Research is underway to describe why the impact of Criollo on arid and semi-arid landscapes seems to be minimal compared to larger breeds (Peinetti et al. 2011). Preliminary results indicate that the Criollo will travel further from water, utilize pasture more uniformly, and use ecological/states that differ markedly from the large-cattle breeds, all of which translate to a smaller environmental impact. Criollo cattle may serve as an alternative to larger breeds to enhance livestock production adaptive capacity on Southwestern rangeland systems.

5 Knowledge gaps

The Southwestern US contains vast and complex water infrastructure and systems, both physical and legal, to cope with variable and uncertain water availability. Many studies have projected longer and unprecedented drought conditions (Ault et al. 2014; Cayan et al. 2010; Cook et al. 2015; MacDonald 2010; Prein et al. 2016; Seager et al. 2007) and systemic pressures associated with additional stress on water supplies already near or beyond their natural limit in the future (Dettinger et al. 2015). However, how humans will respond to decreased available water and the impacts at a local and a regional scale remain uncertain. Economic analyses imply that, broadly, water will likely be transferred from agricultural to municipal uses (Hurd and Coonrod 2008). Other options, such as cooperation between agriculture and municipalities and technologies supporting water reuse, represent adaptation solutions to help ameliorate anticipated water stress. The collective, community-based (i.e. water banks) and individual responses to diminished water resources will drive local production in the SW. This calls for more interdisciplinary research incorporating decision-making, economics, and hydrologic information to identify ways to sustain rural livelihoods and food production given limited, variable, and uncertain water resources.

The interplay between climatic and economic forces must be considered when evaluating adaptive options. For example, melons are heat and drought tolerant and could replace more sensitive crops; however, demand for melons is static and inelastic, so increasing production may lead to price crashes and unsold product (Kerr et al. this issue). The economic feasibility of changing cropping patterns to cope with warming temperatures is uncertain in many cases. There is a pressing need to incorporate economic, social, and political information into vulnerability and resilience analyses of climate change in agriculture broadly and in the SW region. Supporting interdisciplinary and collaborative efforts to better understand contextual vulnerability could evoke broader adaptation efforts in the SW and beyond.

SI authors also report a lack of information in certain instances. There was a lack of published data on some crops (onions, garlic, carrots, and avocados). Information on the impacts of climate on agricultural pests is limited. While the potential of warming temperatures to cause systemic shifts leading to insect-related devastation is apparent in other systems (i.e. bark-beetle outbreaks in western forested systems), there is a paucity of data for the impact of climate change on other insect-related outbreaks. Understanding the interactions of climate with both helpful and harmful insects and pathogens is essential to understanding how climate change will impact Southwestern agriculture.

6 Conclusions: building resilience in the SW and beyond

The impacts of climate change on Southwestern agriculture will be manifested through various pathways, some of which are well-documented and others that require further analysis. A majority of adaptive measures to support Southwestern agriculture into the future will involve coping with more variable and less available water in addition to a warmer climate.

Authors contributing to this collection were tasked with assessing systemic vulnerability. A variety of methods were used and using different methods provided different perspectives about which areas are vulnerable. While a variety of assessment frameworks exist, there is no single correct way to assess vulnerability. Spatial analysis allowed for the prioritization of species and locations in need of future adaptation to cope with climate change. Rapid, county-level analyses available to CE and advisors can indicate which areas and crops might be vulnerable to future climatic conditions and prioritize locations and crops for more in-depth analysis. While differing methodologies are a function of research objectives and data availability, future interdisciplinary efforts to build upon biophysical aspects of vulnerability that include economic and social considerations could be especially valuable for adaptation planning.

Producers can rely upon a new network of climate extension specialists, the USDA Climate Hubs, and agricultural and natural resource advisors. Considering adaptive measures now can support adaptive production. As a first step, producers can look at anticipated average county-level changes in temperature and precipitation (Elias et al. 2017a). Information about changes in seasonal temperature and precipitation provides the foundation for both dialogue and conceptualization of how changes might impact specific components of a crop growth cycle or a management practice. For example, knowledge about warmer summer temperatures may lead to earlier planting dates. Similarly, predictions of wetter weather during a typical harvest period may lead to innovation of alternate methods to cope with climate stressors on the agricultural production system. In forested systems, knowledge of vulnerable forest locations may lead to planting climate-adapted trees in anticipation of future conditions.

Adaptation has been woven into the fabric of Southwestern agriculture and will continue into the future. Collaboration in both science and agricultural management is vital in this region. Working broadly across different disciplines and sectors allows for the development of creative ways to incorporate social and cultural knowledge into climate adaptation. Sustaining rural livelihoods is directly tied to agricultural production and economics. Limited recent adaptation efforts related to the large, observed variation in temperature and precipitation portend substantial future agricultural losses without unprecedented adaptation measures (Burke and Emerick 2016). This finding highlights the need to think creatively and beyond currently employed adaptive measures to ensure future food security both nationally and internationally. The resilient agricultural system of the SW can serve as an instructive example, both in climate analogue analyses and in the collaborative groups that have evolved and the diversified nature of production here, to cope with a warm climate with variable precipitation. Just as others can learn from the Southwestern experience, we can learn from others to support Southwestern production in a variable and changing climate.

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References

Anderson DM, Estell RE, Gonzalez AL, Cibils AF, Torell LA (2015) Criollo cattle: heritage genetics for arid landscapes. Rangelands 37:62–67

Ault TR, Cole JE, Overpeck JT, Pederson GT, Meko DM (2014) Assessing the risk of persistent drought using climate model simulations and paleoclimate data. J Clim 27:7529–7549

Bailey DW (2004) Management strategies for optimal grazing distribution and use of arid rangelands. J Anim Sci 82:E147–E153

Brugger J, Crimmins M (2013) The art of adaptation: living with climate change in the rural American Southwest. Glob Environ Chang 23:1830–1840

Burke M, Emerick K, (2016) Adaptation to Climate Change: Evidence from US Agriculture. American Economic Journal: Economic Policy 8 (3):106–140.

Cayan DR, Das T, Pierce DW, Barnett TP, Tyree M, Gershunov A (2010) Future dryness in the southwest US and the hydrology of the early 21st century drought. Proc Natl Acad Sci 107:21271–21276

Chabot, B. F., and H. A. Mooney, 1985: Physiological ecology of north American plant communities. Chapman and Hall

Cook, B. I., T. R. Ault, and J. E. Smerdon, 2015: Unprecedented 21st century drought risk in the American Southwest and Central Plains. Vol. 1

Dettinger M, Udall B, Georgakakos A (2015) Western water and climate change. Ecol Appl 25:2069–2093

Diffenbaugh NS, Swain DL, Touma D (2015) Anthropogenic warming has increased drought risk in California. Proc Natl Acad Sci 112:3931–3936

Elias, E., T. S. Schrader, J. T. Abatzoglou, M. Crimmins, J. Weiss, and A. Rango, 2017a: County-level climate change information to support decision-making on working lands within USDA climate hub regions. Clim Chang

Elias, E., Julian Reyes, Caiti Steele, Albert Rango, 2017b: Vulnerability of field crops to midcentury temperature changes and yield effects in the Southwestern United States. Climatic Change, Under Review

Folke C (2006) Resilience: the emergence of a perspective for social–ecological systems analyses. Glob Environ Chang 16:253–267

Gershunov, A., B. Rajagopalan, J. Overpeck, K. Guirguis, D. Cayan, M. Hughes, M. Dettinger, C. Castro, R. E. Schwartz, M. Anderson, A. J. Ray, J. Barsugli, T. Cavazos, and M. Alexander. 2013. "Future Climate: Projected Extremes". In Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment, edited by G. Garfin, A. Jardine, R. Merideth, M. Black, and S. LeRoy, 126–147. A report by the Southwest Climate Alliance. Washington, DC: Island Press.

Haim D, Shechter M, Berliner P (2008) Assessing the impact of climate change on representative field crops in Israeli agriculture: a case study of wheat and cotton. Clim Chang 86:425–440

Havstad KM, Brown JR, Estell R, Elias E, Rango A, Steele C (2016) Vulnerabilities of Southwestern U.S. rangeland-based animal agriculture to climate change. Clim Chang:1–16

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. Proc Natl Acad Sci U.S.A 104:19691–19696

Howitt, R., D. MacEwan, J. Medellin-Azuara, J. Lund, and D. Sumner, 2015: Economic analysis of the 2015 drought for California agriculture

Hurd, B. H., and J. Coonrod, 2008: Climate change and its implications for New Mexico's water resources and economic opportunities. Technical report 45

Joyce LA, Briske DD, Brown JR, Polley HW, McCarl BA, Bailey DW (2013) Climate change and north American rangelands: assessment of mitigation and adaptation strategies. Rangel Ecol Manag 66:512–528

Kerr, A., J. Dialesandro, K. Steenwerth, E. Elias, and N. Lopez-Brody (2017) Vulnerability of California specialty crops to projected mid-century temperature changes. Climatic Change, https://doi.org/10.1007/s10584-017-2011-3.

Kim Y, Kimball JS, Didan K, Henebry GM (2014) Response of vegetation growth and productivity to spring climate indicators in the conterminous United States derived from satellite remote sensing data fusion. Agric For Meteorol 194:132–143

Knutti, R., G. Abramowitz, M. Collins, V. Eyring, P. J. Gleckler, B. Hewitson, and L. Mearns, 2010: Good practice guidance paper on assessing and combining multi model climate projections. Meeting report of the Intergovernmental Panel on Climate Change expert meeting on assessing and combining multi model climate projections, IPCC Working Group I Technical Support Unit, T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, and P. M. Midgley, Eds., University of Bern

Lenihan JM, Drapek R, Bachelet D, Neilson RP (2003) Climate change effects on vegetation distribution, carbon, and fire in California. Ecol Appl 13:1667–1681

MacDonald GM (2010) Water, climate change, and sustainability in the southwest. Proc Natl Acad Sci U S A 107:21256–21262

Mann ME, Gleick PH (2015) Climate change and California drought in the 21st century. Proc Natl Acad Sci 112: 3858–3859

McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White, 2001: Climate change 2001: impacts, adaptation, and vulnerability. Cambridge University Press

Millar CI, Stephenson NL (2015) Temperate forest health in an era of emerging megadisturbance. Science 349: 823–826

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier D, Stouffer RJ (2008) Stationarity is dead: whither water management? Science 319:573–574

Nash MS, Whitford WG, de Soyza AG, Van Zee JW, Havstad K (1999) Livestock activity and Chihuahuan Desert annual-plant communities: boundary analysis of disturbance gradients. Ecol Appl 9:814–823

National Agricultural Statistics Service, 2017: U.S. Department of Agriculture, National Agricultural Statistics Service, quick stats: http://quickstats.nass.usda.gov/ Accessed: February 23, 2017

Nicholas KA, Durham WH (2012) Farm-scale adaptation and vulnerability to environmental stresses: insights from winegrowing in Northern California. Glob Environ Change-Human Policy Dimensions 22:483–494

O'Brien K, Eriksen S, Nygaard LP, Schjolden A, (2007) Why different interpretations of vulnerability matter in climate change discourses. Climate Policy 7 (1):73–88.

Peinetti HR, Fredrickson EL, Peters DP, Cibils AF, Roacho-Estrada JO, Laliberte AS (2011) Foraging behavior of heritage versus recently introduced herbivores on desert landscapes of the American Southwest. Ecosphere 2:art57

Prein AF, Holland GJ, Rasmussen RM, Clark MP, Tye MR (2016) Running dry: the U.S. Southwest's drift into a drier climate state. Geophys Res Lett 43:1272–1279

Radin JW, Lu Z, Percy RG, Zeiger E (1994) Genetic variability for stomatal conductance in pima cotton and its relation to improvements of heat adaptation. Proc Natl Acad Sci 91:7217–7221

Ramirez-Villegas, J., C. Lau, A.-K. Kohler, J. Singer, A. Jarvis, T. Osborne, and J. Hooker, 2011: Climate analogues: finding tomorrow's agriculture today. Working paper no. 12

Redsteer, M. H., K. Bemis, K. Chief, M. R. Gautam, B. Middleton, and R. Tsosie, 2013: Unique challenges facing southwestern tribes. Assessment of climate change in the Southwest United States, G. Garfin, A. Jardine, R. Meredith, M. Black, and S. LeRoy, Eds., Island Press

Schneider SH, Easterling WE, Mearns L (2000) Adaptation: sensitivity to natural variability, agent assumptions and dynamic climate changes. Clim Chang 45:203–221

Schoups G, Hopmans JW, Young CA, Vrugt JA, Wallender WW, Tanji KK, Panday S (2005) Sustainability of irrigated agriculture in the San Joaquin Valley, California. Proc Natl Acad Sci U S A 102:15352–15356

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, C. Li, J. Velez and N. Naik (2007). "Model projections of an imminent transition to a more arid climate in southwestern North America." Science 316(5828): 1181–1184.

Sheppard PR, Comrie AC, Packin GD, Angersbach K, Hughes MK (2002) The climate of the US Southwest. Clim Res 21:219–238

Starrs, P. F., and P. Goin, 2010: Field guide to California agriculture. University of California Press, 475 pp.

Steele R, Hatfield JL (2018) Navigating climate-related challenges on working lands: a special issue by the USDA Climate Hubs and their partners. Climatic Change 146 (1-2):1–3.

Taylor, R. G., B. Scanlon, P. Doll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J. S. Famiglietti, M. Edmunds, L. Konikow, T. R. Green, J. Y. Chen, M. Taniguchi, M. F. P. Bierkens, A. MacDonald, Y. Fan, R. M. Maxwell, Y. Yechieli, J. J. Gurdak, D. M. Allen, M. Shamsudduha, K. Hiscock, P. J. F. Yeh, I. Holman and H. Treidel (2013). "Ground water and climate change." Nature Climate Change 3(4): 322–329.

Thorne, J. H., H. Choe, P. Stine, J. C. Chambers, A. Holguin, A. Kerr, and M. W. Schwartz, 2016: Climate Change Vulnerability Assessment of Forests in the Southwest U.S. Climatic Change

Vásquez-León M, West CT, Finan TJ (2003) A comparative assessment of climate vulnerability: agriculture and ranching on both sides of the US–Mexico border. Glob Environ Chang 13:159–173

Wagner JDM, Cole JE, Beck JW, Patchett PJ, Henderson GM, Barnett HR (2010) Moisture variability in the southwestern United States linked to abrupt glacial climate change. Nat Geosci 3:110–113

Wilder M, Scott CA, Pablos NP, Varady RG, Garfin G, McEvoy J (2010) Adapting across boundaries: climate change, social learning, and resilience in the US–Mexico border region. Ann Assoc Am Geogr 100:917–928

Wilder, M., G. Garfin, P. Ganster, H. Eakin, P. Romero-Lankao, F. Lara-Valencia, and S. M. A. A. Cortez-Lara, C. Neri, and F. Muñoz-Arriola (2013). Climate Change and U.S.- Mexico Border Communities. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. A. J. G. Garfin, R. Merideth, M. and a. S. L. Black. Washington, DC, A report by the Southwest Climate Alliance: 340–384.

Wilke A, Morton LW (2017) Analog years: connecting climate science and agricultural tradition to better manage landscapes of the future. Climate Risk Management 15:32–44