

Review

Crop Vulnerability to Weather and Climate Risk: Analysis of Interacting Systems and Adaptation Efficacy for Sustainable Crop Production

Emile H. Elias ^{1,*}, Robert Flynn ², Omololu John Idowu ³, Julian Reyes ¹, Soumaila Sanogo ⁴, Brian J. Schutte ⁴, Ryann Smith ⁵, Caitriana Steele ^{1,3} and Carol Sutherland ⁶

¹ United States Department of Agriculture Southwest Climate Hub, Jornada Experimental Range, 2995 Knox Street, Las Cruces, NM 88003, USA; Julian.reyes@usda.gov (J.R.); caiti@nmsu.edu (C.S.)

² Agriculture Science Center at Artesia, New Mexico State University, Artesia, NM 88210, USA; rflynn@nmsu.edu

³ Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003, USA; jidowu@nmsu.edu

⁴ Department of Entomology, Plant Pathology and Weed Science, New Mexico State University, Las Cruces, NM 88003, USA; ssanogo@ad.nmsu.edu (S.S.); bschutte@nmsu.edu (B.J.S.)

⁵ Natural Resources Conservation Service, 3530 W. Orchard Ct. Visalia, CA 93277, USA; Ryann.smith@usda.gov

⁶ Extension Plant Sciences Department, New Mexico State University, Las Cruces, NM 88003, USA; csutherl@nmda.nmsu.edu

* Correspondence: emile.elias@usda.gov; Tel.: +1-575-636-3639

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Abstract: Climate change is increasing mean and extreme temperatures in the Southwestern United States, leading to a suite of changes affecting agricultural production. These include changes in water, soils, pathogens, weeds, and pests comprising the production environment. The aim of this synthesis is to describe the anticipated leading agricultural pressures and adaptive responses, many of which are near-term actions with longer-term consequences. In the semiarid Southwestern United States, climate change is expected to increase water scarcity. Surface water shortage is the leading reason for recent diminished crop yields in the Southwest. Drought and lack of water represent the leading regional weather-related cause of crop loss from 1989 to 2017. Thus, water scarcity has been and will continue to be a critical factor leading to regional crop vulnerability. Soils, pathogens, weeds, and insects are components of the agricultural production environment and are directly influenced by near-term weather and long-term climate conditions. Field crops, vegetable crops, and perennial crops have unique production requirements and diverse management options, many already used in farm management, to cope with production environment changes to build climate resilience. Farmers and ranchers continuously respond to changing conditions on a near-term basis. Long-term planning and novel adaptation measures implemented may now build nimble and responsive systems and communities able to cope with future conditions. While decision-support tools and resources are providing increasingly sophisticated approaches to cope with production in the 21st century, we strive to keep pace with the cascading barrage of inter-connected agricultural challenges.

Keywords: weather and climate; vulnerability; agriculture; adaptation; Southwestern United States; pests; crops

1. Introduction

In the Southwestern U.S. (SW), future crop production, rangelands, and forests are projected to be impacted by increased temperatures and shifting precipitation patterns [1]. Agricultural production in

the region is already challenged by limited water resources, drought, and temperature variability. In semiarid and arid regions, agricultural production can be expensive or unsuccessful due to drought conditions and lack of irrigation water. Warmer temperatures place an increased burden on scarce water resources both in terms of quantity [2–4] and quality [5,6]. Climate trends point towards continued warming, increasing average maximum temperatures, and more variable, unpredictable, extreme, and limited precipitation [7]. Management actions can determine how critically the impacts of near- and longer-term weather and climatic events will affect agricultural vulnerability.

The aim of crop production is to optimize performance by a diligent manipulation of inputs that minimize the impact of plant stressors, such as extreme temperatures, excess moisture, pests, and pathogens, while enhancing the efficacy of plant biostimulants, which are microbial and non-microbial substances designed to improve plant nutrition and plant tolerance or resistance to stresses [8]. Extreme weather events and the ensuing changes in the near-term production environment can impact the management of plant stressors and plant biostimulants. Under a changing climate, biotic stresses related to pathogens, weeds, and pests are projected to affect crop growth and yields. Soil health and available water quality and quantity will affect the ability of an agroecosystem to respond to increases in temperature and changes in precipitation patterns. Crop producers face numerous obstacles; however, with intentional management efforts, adapting to a changing environment can help producers overcome production limitations [9,10]. Here, we discuss the interacting components and vulnerabilities of agroecosystems, as well as adaptive measures to reduce near- and long-term climate risk.

1.1. Vulnerability Framework

Climate variability has long affected agricultural production. However, warming is expected to continue and influence many facets of the integrated system supporting agriculture. A broad framework to assess vulnerability to climate risk relies on exposure (temperature, precipitation, and CO₂), sensitivity, and adaptive capacity [11]. Risk is the potential for negative consequences and depends upon the probability of hazardous or extreme events [12]. Here, we describe the expected impacts of projected exposure on components of crop production while highlighting systemic sensitivities and specific actions to enhance adaptive capacity. We discuss adaptive measures that reduce vulnerabilities in one component of the system that influence other components to create an integrated agroecosystem framework. Considering biotic and abiotic components simultaneously helps identify options for increasing systemic resilience and agricultural sustainability and reduces climate-related risks. Components of the agroecosystem operate within a complex system, including institutional, socio-economic, and environmental conditions, that can be somewhat reflected in management options.

1.2. Climate Adaptation in an Agricultural Context

Although climate change poses unprecedented risk to U.S. agriculture [13] and broad descriptions of regional climate change effects are readily available [7], each ranching and farming operation will be uniquely impacted by climate change. Adaptive responses in agriculture may be the same as on-farm practices already used to build near-term agricultural resilience [10]. Farmers and ranchers continuously respond to changing conditions, such as changes in pests, market price, water availability, labor, and weather. Additional adjustments may be needed to respond to future extreme weather events and increased climate variability [10]. A discrepancy in beliefs about climate change can lead to challenges in working with some agricultural stakeholders to promote climate adaptation [14], but changes to build agricultural resilience (i.e., changes in tillage practice, improved soil health, and planned water management) can confer both near- and long-term benefits. Advisors typically consider and advise on near-term operational decisions rather than long-term tactical and strategic decisions [15]. Often, actions designed to build near-term resilience in agricultural systems will lead to climate change adaptation benefits, even if climate change was not an initial consideration. Resource and land managers implement practices considered as climate change adaptation, but with the primary goal of supporting short-term profitability, production, and stewardship. Given the need to directly

address both near- and long-term adaptation options in agriculture, we describe adaptation options by resource and propose long-term impacts (Table 1), such that if the action is implemented in the near term, it could lead to a long-term impact.

Table 1. Selected adaptation actions for specific systems or resources noting the long-term intent of the adaptation action.

Action	System	Primary Adaptation Intent
Olla Irrigation	Water	Reduce evapotranspiration; Farm-scale water savings *
Rainwater harvest	Water	Home or farm scale water savings *
Deficit irrigation	Water	Water savings to optimize crop yield *
Increasing irrigation efficiency	Water	Farm scale water savings *
Slow irrigation (drip)	Water	Increased efficiency, water savings *
Nocturnal irrigation	Water	Reduced evapotranspiration, increased efficiency, water savings *
Fallowing land	Water	Prioritize highly productive areas, water savings *
Shift crop patterns	Water	Shift to less consumptive crops to save water *
Increase groundwater use	Water	May be maladaptive; aids flexibility
Reservoir expansion	Water	Aids flexibility; may be maladaptive; potential ecosystem consequences
Irrigation scheduling with soil water measurements	Water	Water savings, science-based management *
Maintain suitable drainage	Water, soils	Maintain healthy soils and plants *
Increase organic matter	Water, soils	Build healthy soil *
Organic mulching	Water, soils	Build healthy soil *
Soil amendments	Soils	Build healthy soil *
No-till farming	Soils	Build healthy soil, reduce erosion *
Cover cropping	Soils	Possible increased organic matter *
Integrated nutrient management	Soils	Economic and ecosystem benefits *
Minimize wind and water erosion	Soils	Long-term soil health effects *
New cultivars	Crops	Adds flexibility; resilience to heat and drought
Adjusting plant/harvest dates	Crops	Optimize crop production timeframe
Diversified farming activities	Crops	Confers enterprise resilience *
Using forecasts to reduce farm risk	Crops	Minimize farm scale vulnerabilities *
Transitioning to organic systems	Crops	Building soil fertility, reducing GHG emissions *
Low water-use vegetables	Vegetables	Maximize scarce water resources *
Transplanted vegetable crops	Vegetables	Reduce exposure and water use *
Knowledge of crop specific pests and diseases	Vegetables	Informed management *
Use shade structures	Vegetables	Minimize heat stress/damage
Increase crop diversity	Vegetables	Decrease pest pressures; minimize losses *
Intercropping	Vegetables	Increase cover density; utilize variable growth rates *
Provide adequate irrigation	Perennial	Sustain healthy perennial systems
Maximize use of low-salinity water	Perennial	Sustain soil quality in the long term
Mechanical control	Weeds	May be a shorter window for future mechanical control
Herbicide application	Weeds	Varied/complex positive and negative changes in herbicide efficacy
Biological Control	Weeds	Potential lack of synchrony between biocontrol agents
Scout for new weed species	Weeds	Anticipate and respond to new weeds *
Evaluate outcomes of control tactics	Weeds	Prioritize future efficacious actions *
Pheno Forecasts	Insects	Anticipate/respond to pests *
Soil salinity	Pathogens	Positive and negative impacts on pathogens *
Soil moisture	Pathogens	High soil moisture exacerbates pathogens *
Use of microbiomes	Pathogens	Sustain healthy plants *
Use beneficial microbes	Pathogens	Sustain healthy plants *
Kaolin-based particle film	Crops and Pathogens	Mitigate heat stress and reduce disease *

* Adaptation impacts similar for near- and long-term adaptation.

1.3. Climate Variability and Change

The SW offers a wide diversity of ecosystem types over a large geographic area with highly variable topography and climatic conditions, but crops are grown only in select areas, typically with access to surface or groundwater sources (Figure 1) [16,17]. All agricultural areas of the region have seen a notable increase in the warmest temperature of the year [18], number of extremely hot days (maximum temperature over 38 °C), and number of warm nights (minimum temperature over 21 °C). The total annual average temperature range across the SW is very large [19]. The topography leads to large variations in precipitation throughout the region. There are major spatial regions with differing patterns of typical monthly varying precipitation, with deserts receiving mostly monsoonal precipitation. Hazardous and costly weather and climate events in the region include droughts, winter storms, floods, and temperature extremes. There is variability in the SW climate from month to month, year to year, and decade to decade. Climate change is expected to produce considerably more drought by the end of the 21st century, with depleted soil moisture events that persist for more than a decade and remarkably warm summers [20]. Some of the significant impacts of climate change in an arid and semi-arid ecosystem typical of the region include increases in mean and extreme temperature, reduced water availability, and frequent occurrences of extreme weather events [21].

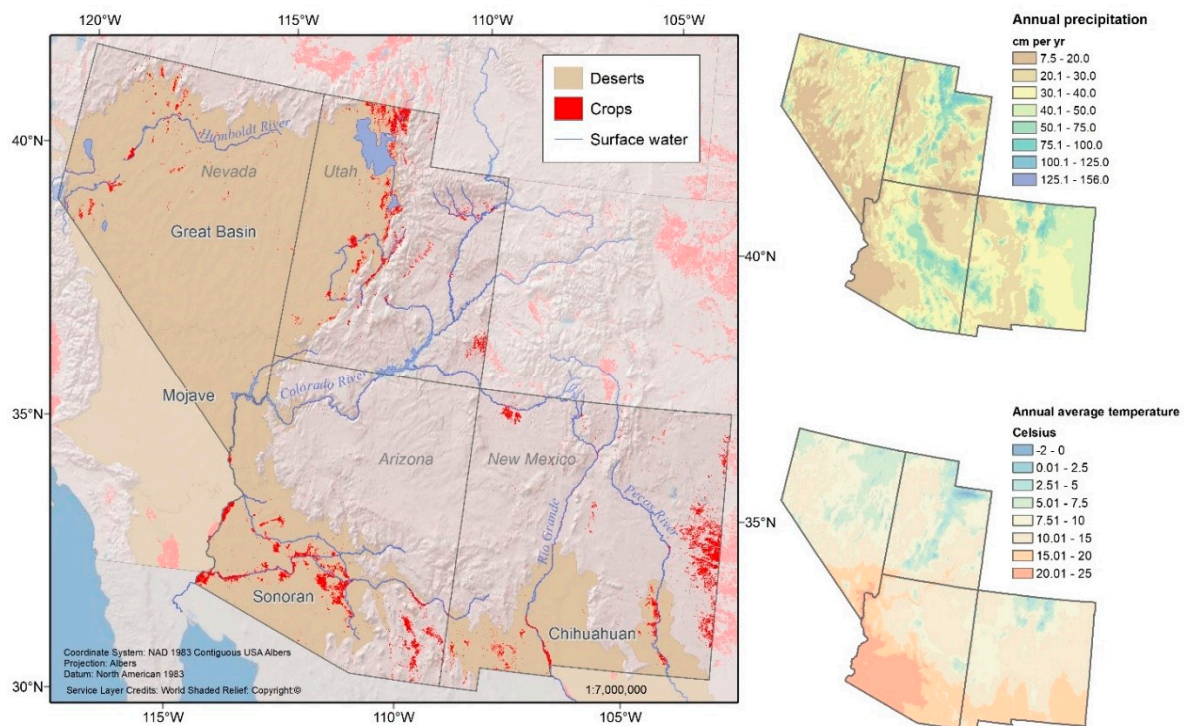


Figure 1. Crop production regions of the Southwestern United States (red) with 1981–2010 Climate Normals [22].

1.4. Problem Definition

The SW is one of the hottest and driest regions in the nation. Climate change will further challenge agricultural production by increasing mean and extreme temperatures. This may lead to specific responses in the components supporting agriculture, including water resources, soils, weeds, insects, and pathogens. Field crops, vegetable crops, and perennial crops will have varying pressures and adaptive responses, most of which are near-term actions, some with longer-term consequences. We describe selected adaptive actions and tools to respond to current and anticipated agricultural pressures. The topics addressed in Section 2 were identified by organizers of a sustainability conference as the most important to agricultural stakeholders in the SW.

2. Crop Production Environment

2.1. Water Resources, Irrigation, and Climate Change in the Southwest U.S.

This region has long faced limited and variable water supplies [2]. Without sufficient irrigation, agricultural production has constrained potential in arid and semi-arid regions. Irrigation water sources vary considerably across the SW, with agriculture supported nearly exclusively by groundwater or surface water in specific regions [17]. Vulnerabilities vary by water source. SW states have distinct regional and temporal variation in the amount of total groundwater used to support agriculture. Between 1955 and 2010, the agricultural groundwater fraction declined in Arizona (AZ), increased in Nevada (NV) and Utah (UT), and remained fairly consistent in New Mexico (NM). In 2010, less than half of the total agricultural water use derived from groundwater on a state-wide basis (NM, 47%; NV, 41%; AZ, 38%; UT, 18%), but areas within the region rely almost exclusively on groundwater to support agricultural production [17]. Groundwater levels have been declining, with maximum depletion rates in the more recent records [23]. There is a growing concern over the depleting Ogallala Aquifer, leading to less water use under the center pivot irrigation systems [24]. Declining water levels also lead to higher energy requirements to pump water from deeper wells. Apart from water scarcity, poor quality water can severely limit water use in some regions. Approximately 75% of groundwater in NM is too saline for most uses [25] and salinity is projected to increase in dryland river systems in the future [26]. Irrigating with saline water can increase salinity concentrations, leading to the general effect of a reduced growth rate, but all salinity effects may not be negative [27].

While adequate storage capacity exists to store surface water in a network of reservoirs, often only a small fraction of available capacity is used due to limited water availability arising from recurrent and persistent droughts. Decreases in reservoir storage in the four reservoirs along the Canadian River have been attributed to declines in rainfall since 1990 [28]. A survey of SW farmers indicates that diminished yield due to irrigation interruption is often caused by surface water shortage (38% to 69% of the total in 2013), groundwater shortage (12% to 21% of the total), and irrigation equipment failure (5% to 25% of the total), with the remaining generally attributed to a variety of other causes (National Agricultural Statistics Service 2015) (Figure 2).

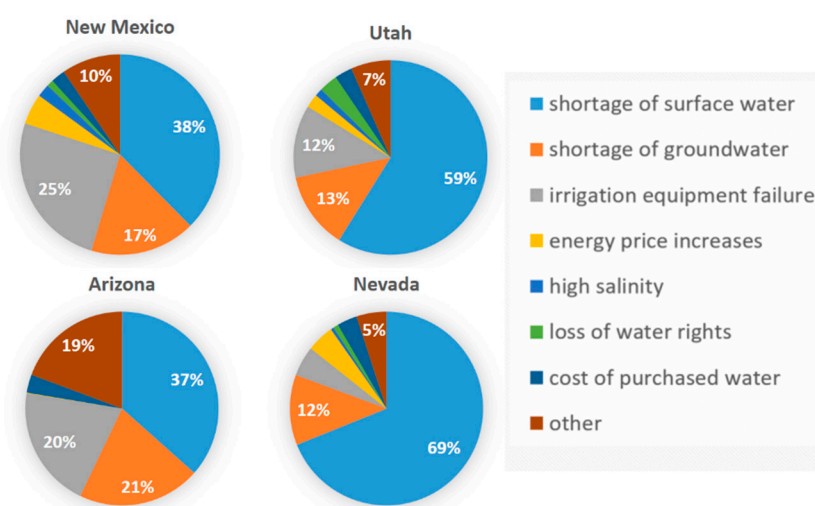


Figure 2. Reported cause of diminished crop yield by state from the 2013 Farm and Ranch Irrigation Survey [29].

Climate change pressures will be acutely felt via impacts to water availability and scarcity. Climate change is expected to result in less snow water equivalent, earlier runoff, and less soil moisture across the SW [2], thereby impacting an already water-limited agroecosystem. Predictions indicate ecosystems and agricultural water use are at greatest risk of water supply disruptions associated with climate

change, as water will be increasingly transferred to maintain urban and industrial uses [30]. In the snowmelt basins of the Upper Rio Grande, peak runoff is projected to be earlier, and daily hydrographs show lower streamflow in June and July future climates [31]. Climate model projections coupled with paleoclimate information indicate that the risk of a decade-scale drought in the SW is at least 80%, potentially posing unprecedented water challenges in the region [32]. With more constraints on the available water supply, growers must consider creative irrigation adaptation to support sustainable long-term agricultural production.

The impacts of high temperatures on crop yields appear minimal in irrigated agriculture as compared with rainfed systems [33]. Adaptive strategies to maintain crop irrigation during critical phenological phases provide an option to cope with water scarcity. For small farms and gardens, the use of traditional Olla irrigation and rainwater harvesting may increase the water supply. Olla irrigation is the use of unglazed clay vessels for subsurface irrigation. It reduces evaporation and directly supplies water to the plant root zone. Other adaptive strategies include changing crop planting date, using deficit irrigation, and increasing irrigation efficiency [34]. Deficit irrigation, or limiting water applications to drought-sensitive growth stages, aims to maximize water productivity and stabilize yields. It requires precise knowledge of the crop response to drought stress, but high irrigation efficiency can be accomplished using deficit irrigation [35]. Water requirements change through the season, and deficit irrigation can be practiced to apply water only during critical plant stages, such as germination, transplant, flowering, fruit set, and vegetable growth [36,37].

Slow irrigation through drip or soaker hose systems allows water to infiltrate further down the soil profile, aiding in healthy and deep root growth. Switching to drip irrigation in the upper Rio Grande is projected to increase farm income, crop production, irrigated land, and total water-related economic benefits for the basin [28]. Other options to improve irrigation efficiency include interruption during windy conditions, using efficient sprinklers, and emphasizing nocturnal irrigation. However, improving local efficiency may impact the regional hydrologic balance. Improving irrigation efficiency may save water for other uses, but it also impacts shallow recharge to the local aquifer. The system inefficiency provides the benefit of recharging and sustaining the local aquifer [38]. Flood irrigation is a significant source of shallow groundwater recharge in northern NM [39]. New irrigation scheduling approaches using remotely sensed data and field evapotranspiration measurements appear promising to improve water management [40]. Employing efficient and intensively managed irrigation practices can aid in adapting to drought conditions in water-limited agricultural areas. Adaptation measures also include fallowing land, shifting cropping patterns, increasing groundwater pumping, and expanding reservoir storage. Expanding reservoir storage for the Gila River basins was projected to increase regional farm income by 30% [41]. Near- and long-term strategies to cope with water limitation and excess are necessarily site specific. Here, we provide some examples to consider at the plot or farm scale (Olla irrigation and rainwater harvesting) and at broader scales (changing irrigation technology) and reflecting specific environmental conditions (minimizing use during windy conditions) and plant conditions (deficit irrigation). Many other policy, engineering, and management options exist to augment these examples as conditions warrant.

2.2. Agricultural Soils and Climate Change in the SW U.S.

Soil temperature is a function of the amount of heat that enters or leaves the soil and the thermal properties of the soil itself. Soil temperature affects seed germination, plant emergence, root growth, nutrient uptake, plant development, and the decomposition of plant residues (carbon mineralization) [42]. Several factors affect soil temperature, including geographical location, type of tillage, and soil cover. In fields, crop residue is an insulator and reflects solar radiation away from the soil surface. If beds are used, then those beds with southern exposure will have a higher temperature. Level soil surfaces will also have lower soil temperatures than those with ridges [43].

An early season goal of most production systems is to have uniform, vigorous seed germination, and good early season growth. Soil temperature, soil moisture, and oxygen availability govern stand

establishment. The optimum temperature for germination is specific for each crop and can be controlled to some extent by water content since moist soils are cooler than dry soils. Mulches incorporated into the upper soil layer change the thermal properties of surface soil by increasing the air content. Tillage or the incorporation of mulch in the upper soil profile will warm soils more quickly near the surface during periods of rising temperature but maintain cooler temperatures in the subsoil [44]. Research has generally shown that there are optimum temperatures for root growth that vary by species. The roots of cotton plants grow best between 28 °C and 35 °C, with both lower and higher temperatures limiting the growth rate [45]. Root growth generally slows if soil temperatures increase above 35 °C in the root zone [46–48], after which growth declines [49–51].

Environmental factors, such as temperature and soil moisture, impact the uptake of nutrients by plants. Low soil temperatures, for example, reduce phytosiderophores, and the resultant mobilization and uptake of iron by grasses [52]. High soil temperatures could also decrease iron uptake by grasses by increasing the microbial decomposition of phytosiderophores [53]. In calcareous soils, iron deficiency could result from the stimulation of microbial activity, which would increase CO₂ production [54]. Coupled with low soil temperatures, there could be an increase in bicarbonate levels in the soil solution, thereby increasing the severity of iron deficiency. High soil temperatures could also increase the uptake of phosphorus by plants and the severity of P-induced iron deficiency [55,56]. Boron uptake by corn increased nine-fold as soil temperatures rose from 20 to 31 °C. Soil temperatures above 20 °C likely increase the availability of organically bound boron [52]. As soil temperature increases, manganese (Mn) solubility and microbial activity increases. Zinc (Zn) availability in soils is believed to be metabolically controlled [57] whereby Zn absorption increases as soil temperatures increase. Mycorrhizas play important roles in plant nutrition and soil chemistry and enhance the uptake of Zn and other elements [58,59]. Mycorrhizas are much more active in warm soil temperatures than cold, suggesting that Zn deficiencies are minimized by these soil organisms in warm soils.

How well crop residues decompose depends on the chemical composition of the residue and the soil environment. Warm temperatures under moist conditions promote microbial activity that brings about decomposition. The residue itself determines the rate of decomposition. Factors include the carbon:nitrogen (C:N) ratio, lignin content, age, particle size, and the microbial community [60]. High C:N residues take longer to decompose than low C:N materials given the same temperature and moisture levels.

Climate change threatens to reduce soil quality and increase soil erosion [61]. Management decisions that impact soils can contribute to short- and long-term climate resilience. Soil that is well-drained with suitable organic matter increases watering efficiency. Soil amendments, organic mulching, and additions of compost or manure can increase aeration, moisture, and water holding capacity. Sustainable land management options to increase both net primary production and soil organic carbon include no-till farming, cover cropping, integrated nutrient management, and soil amendments, such as biochar on croplands [61,62]. Both wind [63,64] and water erosion are expected to impact soils in the future; however, in certain instances, changing management practices can be sufficient to offset erosion [65]. Extreme precipitation often leads to fast moving surface runoff, but soil with organic matter, mulches, or vegetation can often resist these forces. Protecting and enhancing soil increases resilience amidst changing environmental conditions.

2.3. Weeds, Weed Management, and Climate Change in the SW U.S.

Agricultural weeds are considered ubiquitous crop pests because they are likely to occur in every field, every year. For SW cropping systems, agricultural weeds severely reduce attainable yields because they disproportionately acquire one or more factors for growth at the expense of the crop [66–69]. Agricultural weeds that do not directly compete with crops can reduce farm profitability by harboring economically important crop pathogens [70,71] and increasing costs associated with crop production and harvest [72,73]. In addition to agricultural weeds, pestilent vegetation also includes invasive plants that threaten the natural and uncropped areas that support the livelihoods, aesthetic

standards, and cultural values of people living in the region [74,75]. Most notably, invasive plants lessen the functionality of rangelands [76] that provide both ecosystem services critical for sustainable crop production (e.g., soil conservation, carbon sequestration, and habitat for beneficial wildlife) [77] and locations for livestock production—an agricultural activity that provided over \$2.3 billion in cash receipts to NM producers in 2015 [78]. Environmental impacts and life history strategies can differ between agricultural weeds and invasive plants; however, for simplicity, these different types of pestilent vegetation are collectively referred to as “weeds” in this paper.

Diminished productivity on croplands, rangelands, and natural areas compels weed management programs that eliminate both weeds and opportunities for future weed infestations. Weed management programs benefit from predictive knowledge on control outcomes, as well as reasonably accurate estimates of efficacy for preventive strategies. Such information allows farmers and land managers to select and schedule the most appropriate set of tactics for their specific weed problem.

Climate change will likely alter optimum implementation strategies for commonly used weed control tactics. For mechanical tools that are most effective after weed seed germination but prior to extensive root growth and full expansion of true leaves (i.e., tillers and cultivators [79]), temporal windows for successful control might shrink in response to increased temperatures that accelerate weed growth and development [80]. Periods for successful tilling and cultivating could also be shortened by CO₂-enriched atmospheres that promote the photosynthesis and growth of some weed species [81–84]. However, not all weed species increase photosynthesis and growth in response to elevated CO₂ [85], and thus, elevated CO₂ effects on optimum timings for tilling and cultivating will be weed species specific. Complex interactions among the environment, weed, and herbicide prevent generalities on climate change effects on chemical weed control [86]. Nonetheless, previous research informs expectations for the performance of specific herbicides under a changing climate. For example, herbicides that inhibit pigment production and photosynthesis are hypothesized to become more efficacious with rising CO₂ or temperatures [87]. Herbicides that target the production of amino acids, most notably glyphosate, might be less efficacious with increased CO₂ [82,88–90]. Low-dose applications of glyphosate can stimulate plant growth [91,92], suggesting that glyphosate applications made ineffective by elevated CO₂ potentially promote weeds and worsen subsequent weed control problems. Climate change might be especially disruptive to biological control programs that generally require temporal and spatial synchrony between biocontrol agents and targeted weeds [93]. It is feared that a climate-induced lack of coincidence between weeds and biocontrol agents, as well as climate-provoked alterations in both the abilities of biocontrol agents to locate host plants [94] and host plant biochemistry [95], will negatively affect the ability of specific biocontrol agents to suppress weed infestations.

The expected effects of climate change on weed control, coupled with compositional and structural changes in weed communities [96,97], will likely result in new challenges in weed management. Unfortunately, forecasting novel weed threats is difficult because both weeds and weed management are context specific. To prepare for anticipated, yet unpredictable, weed management challenges, farmers and land managers should: (1) Routinely scout for occurrences and reports of new weed species, (2) systematically evaluate the outcomes of weed control tactics, and (3) promptly address and communicate unusual weed species and unexplainable failures in weed management programs. These activities will better enable individual farmers and land managers to cope with local weed problems that result from climate change.

2.4. Insects and Climate Change in the SW U.S.

Agriculture in the SW is somewhat protected from insects by having rather far-flung cultivated agricultural areas that are further isolated by miles of hostile, dry desert lacking alternate hosts for many insects. The longer distance dispersal of some insects via air currents and wind aids insect movement to new areas to establish if hosts are available. Insect movement and establishment is aided if at least one life stage can be overlooked and thereby transported by people or animals.

Relatively few arthropods are economically important pests for agriculture but that could change if foreign insects appear, leaving behind natural enemies and ecological features that previously controlled populations in their native habitat. For example, the potato psyllid migrated to California several times in the 20th century, but populations lasted only for one year because of cool winter temperatures. However, the potato psyllid migrated to California in 2000 and has established large, year-round populations [98].

With climate change, the distributions and seasonal availability of plant hosts may change. Herbivores unable to find sufficient food, water, or shelter must adapt, move, or die. Many arthropods have two features that favor quick adaptation to change: Short life cycles and high fecundity. As host availability changes, pest mobility becomes increasingly important. In the northern hemisphere, insect populations are already migrating northward [98,99]. Some species are independently mobile while others can move on goods in transit.

Predicting which insects might become prominent pests for agriculture in the future is difficult but some possible scenarios follow. Of the 160 known species of grasshoppers in NM [100], 40 to 50 species are currently common plant pests. With climate change, wingless species and those in higher elevations may disappear due to a lack of food. Long distance fliers with a wide host range (e.g., some *Melanoplus*) could survive as they access and compete for increasingly distant feeding sites.

Mosquitoes, fleas, and ticks are common pests of humans, livestock, and wildlife. Many of these have a history of transmitting serious diseases to humans. Malaria, West Nile virus, dengue, plague, Rocky Mountain spotted fever, and tularemia are potential health management problems for the future as are emerging pathogens, such as Zika virus. Domestic and wild animals also are at risk. Managing existing and emerging animal pathogens in the future is also of great concern. Simulation results show an extension of mosquitos' activity period and disease risk [101] and a longer mosquito season [102]. While it is expected that the increasing temperatures of climate change will expand the distribution of some tick species to northern latitudes and higher altitudes, further studies are needed to improve our understanding of the complex interactions driving this movement [103,104] (Dantas-Torres 2015; Ostfeld and Brunner 2015).

Certain insects are well known vectors of plant pathogens. For example, *Neoliticus* (= *Circulifer*) *tenellus* (beet leafhoppers) are vectors of curly-top virus for high-value crops, like chili. Invasive aphids, whiteflies, and their relatives can transmit possibly new crop pathogens. Eradication or containment may not be possible for either the beet leafhoppers, invasive aphids, or their relatives. While research for management options proceeds, agricultural producers might suffer difficult economic consequences.

Spider mites are infamous plant pests favored by hot, dry, and dusty conditions. Producers can easily select for insecticide resistance in these rapidly reproducing plant killers when growing conditions are adverse and the same acaricides (or members of that chemical 'family') are applied repeatedly.

Thirty years ago, NM beekeepers dealt with three microbial diseases: American and European foulbrood and chalkbrood. In the late 1980s, several exotic bee pests began invading the region: Honey bee tracheal mite (*Acarapis woodi*), *Varroa* mite, various bee viruses transmitted by *Varroa* mite, and most recently, small hive beetle, *Aethina tumida*. *Varroa* mites have been associated with lower lipid levels, higher titers of deformed wing virus, and higher overwinter losses [105]. Africanized honey bees invaded southern NM in 1993. They have since become established throughout most of the state where they and feral hybrid bee colonies are 'reservoirs' for all previously named honey bee parasites and diseases. Honey bee colony viability and effective pollination are increasingly serious issues for beekeepers and crop producers nationwide. Since a decline in wild bee populations could imperil pollination services, the effect of climate change on wild bee communities is also of major concern. Recent research found that while increasing future temperatures will lead to a decline in bee species richness, increased natural habitat can somewhat mitigate the effect of increasing temperatures [106].

In the last 30 years, invasive, exotic insects (e.g., Russian wheat aphids, sugarcane aphids, alfalfa weevils, white-fringed beetles, apple maggots, ash whitefly, and spotted wing *Drosophila*) established plant-damaging populations in the region. Global trade and efficient transportation for people and

goods have increased risks for invasion by alien pests from other countries. Climate change adds uncertainty as to which pests from where might successfully establish and challenge our producers. Hopeful recent research into the physiological responses to stress in insects indicates the ability to respond to adverse environmental stimuli with rapid, coordinated changes in metabolic activity [107].

Increasingly sophisticated approaches to dealing with production problems in the 21st century are evolving. The National Phenology Network (NPN) launched Pheno Forecasts to help determine when insect pests and invasive species can be found in a certain location during critical life stages for monitoring and management (<https://www.usanpn.org/data/forecasts>). The forecasts indicate the invasive pest life cycle stage across the United States for more than 10 insect pests and provide recommended management actions. Apple maggot, bagworm, emerald ash borer, and lilac borer are already impacting the SW, and the NPN can help producers cope with weather-related expansion. For example, apple maggot larvae damage ripening fruit and can spread across apple, plum, pear, cherry, and hawthorn trees if left untreated. Since all treatments are most effective when adults are emerging from the soil, daily Pheno Forecast maps indicate when adults are likely to emerge in specific locations, allowing growers to protect apples using mechanical or chemical methods.

2.5. Plant Pathogens and Climate Change in the SW U.S.

Several studies have examined and projected the behavior of plant pathogens under predicted changes in the climate [108–110]. It is useful to examine the change in the behavior of plant pathogens along the four main components of their life cycle that include survival, dispersal, plant infection, and reproduction. Each of these facets of the life cycle may be affected to the benefit or detriment of crops.

Predicted changes in precipitation patterns include both drought and excessive moisture. In the case of drought, especially in areas with limited surface water, utilization of groundwater could increase. Related to this increased utilization is the issue of water quality, especially increased salinity. An extensive literature has documented the influence of salinity on a wide array of plant pathogens [111]. While some studies have indicated an increased disease level under saline conditions, still others have reported the converse. A pathogen of global impact in the production of vegetable crops is *Phytophthora capsici*, an oomycete pathogen typified by the production of zoospores, swimming spores that enable the pathogen to delve in moist soil environments [112]. Salinity predisposes pepper plants (*Capsicum annuum* L.) to infection by *P. capsici* although the reproduction of the pathogen was decreased with increasing salinity levels [111]. This implies that infection efficiency could be enhanced by salinity.

In scenarios of high soil moisture, pathogens adapted to these environments may become prevalent. Such is the example of *P. capsici*, as mentioned above. There is a consensus that high moisture exacerbates the activities of these pathogens [112] by enhancing their reproduction and dispersal, and by exerting predispositional effects on the plants.

Resilient crop management approaches, under extreme changes in the moisture spectrum, could include the development and utilization of drought-tolerant and flood-tolerant crop cultivars. Crop tolerance to extreme moisture events coupled with genetic resistance to plant pathogens should afford crops with characteristics necessary to perform optimally in the presence of moisture stressors [113]. Because of the possible increased impact of salinity on crop performance, resilient management of plant pathogens under increased salinity conditions would need an integration of salt-tolerant crop cultivars that are resistant or tolerant to the targeted pathogens.

Another arsenal for resilient crop management is the utilization of microbiomes that help plants to withstand extreme events, such as mycorrhizae, which have been shown to provide a wide array of ecosystem services encompassing: (i) Increased plant tolerance to stressors, such as drought, salinity, mineral deficiency, and pests and pathogens; and (ii) improvement of soil properties, such as soil structure, through the production of glomalin (a protein produced by mycorrhiza, capable of enhancing soil aggregation) and enhancement of microbial populations via the excretion of exudates. Mycorrhizae can improve plant physiological response, and thereby increase crop tolerance to salinity and drought [114,115].

Another component of developing resilient crop management tools is the utilization of a combination of beneficial microbes with adaptation across a wide spectrum of temperature and moisture levels. For example, fungal species in the genus *Trichoderma* are well known for their antagonistic activities against a wide range of plant pathogens, and their activities in stimulating plant growth [116]. Many *Trichoderma* species are capable of withstanding low and high temperatures. Two isolates of *Trichoderma* from soil samples collected from various regions of India withstood a heat shock of 52 °C and prolonged exposure to temperature of 37 °C while maintaining high tolerance to salinity [117]. Information from this study and others may be used to build a resilient tool that combines *Trichoderma* species based on their temperature and salinity response. For example, a possible target management could be to combine winter cover crops with low-temperature species, such as *T. atroviride*, prior to cultivation of the main spring/summer crops. Then, high-temperature species, such as *T. harzianum*, could be used during spring/summer cropping. Extreme temperature can increase heat load or heat stress in crops and impair many physiological and biochemical processes [118], and crop response to biological stresses, such as plant pathogens [119]. Application of kaolin-based particle film can be used to mitigate heat stress in crops and reduce disease problems [120]. Historically, molecular biologists rarely studied plant acclimation under multiple stresses, but recent studies indicate a different plant response to multiple abiotic stresses that cannot be directly extrapolated from the response of plants to each stress applied individually [121]. Plant response to multiple stressors, especially those mimicking field conditions, should be the focus of future research efforts.

3. Crop Production Systems

Climatic challenges to crop production in the SW include short growing seasons at higher elevations and unpredictable and limited rain at lower elevations. Changes that impact water and soils confer subsequent positive and negative impacts to crop production (Table 2).

Table 2. Projected impacts of climate change to crop production in the Southwestern United States.

Positive Impacts	Negative Impacts
Milder winters with longer frost-free periods	Increased periods of severe heat
Longer growing season	Increased disease and pest pressure
Higher carbon dioxide can help some plants	Increased drought and water scarcity
	Increased rates of soil and water salinization
	Increased extreme weather events

3.1. Field Crop Production Systems

Major field crops grown in the region (corn, cotton, beans, alfalfa, and others) are expected to be significantly affected as climate change persists, which is the hottest and driest region in the U.S. [21]. Agricultural stakeholders need to be prepared by learning how to develop agricultural systems that will prove resilient to expected changes.

Increasing atmospheric CO₂ concentrations are expected to enhance photosynthesis and reduce crop water use, but there is uncertainty about the global implications for future crop production and agricultural water requirements under climate change [122]. Several studies have shown that increasing CO₂ in the atmosphere could prove positive for the yields of field crops, with C3 plants, such as wheat, showing better yield responses to elevated CO₂ than C4 plants, such as corn [123]. Recent studies have questioned the relatively high yield expectations set by these earlier studies, which used closed chamber experiments to evaluate the impact of rising CO₂ on yields. New methods using free-air concentration enrichment (FACE) experiments, which is a more realistic simulation of future elevated CO₂, have given much lower yield estimates due to CO₂ fertilization [124]. In addition, the effect of the increasing CO₂ benefit may be limited by the simultaneous increase in temperature. Although C4 plants may not benefit much from CO₂ fertilization in comparison to C3 plants, under moisture-stressed conditions, C4 plants have higher water use efficiency and less affected yields

compared to C3 plants with increasing CO₂ in the atmosphere [125]. With the projected decrease in water availability in the SW resulting from climate change, the extent to which C4 plants will be able to compensate for the reduced water availability will be dependent on drought severity [126]. The ultimate results of plant performance in the arid SW under increasing CO₂ levels will most likely be complicated by a concomitant increase in water stress and atmospheric temperature [127]. Since there are many climate variables interacting together to affect the crop performance, adaptation strategies need to focus on how cropping systems' resilience can be affected by a combination of climatic factors. A study conducted in a semi-arid region reported that an elevated CO₂ level, combined with an increase in temperature by 1.8 °C, led to reduced wheat yield [128], highlighting the regional variability in potential impacts of increasing CO₂ [122]. With the projection of significant temperature increases in the region, increases in CO₂ may not deliver yield benefits to the cropping systems due to simultaneous increases in temperature. In another study, the simulated yield increases of soybean due to increased CO₂ fertilization reduced to zero as the drought condition intensified [129]. The study concluded that the rise in CO₂ was not enough to counteract the effect of drought on plant productivity, because drought modified stomatal functions and the canopy energy balance. This further highlights the synergistic effects of climate variables on crop growth.

Temperature increases have been projected for the region, which will have multiple direct and indirect effects on field crop production. Crop physiological development, such as pollination, maturity, and ripening, may be accelerated, thus leading to major shifts in the seasonal growth patterns of crops [130]. Higher temperatures can affect the physiological stages of field crops, leading to yield reductions, especially when the temperature exceeds the thresholds for the crop [131]. Generally, yield reductions are expected for several field crops, including maize and soybeans, as temperatures increase [130,132].

Temperature increases may affect the timing of management practices, such as seeding, irrigation, fertilization, and harvest [133]. Temperature increases may also make current crop production zones less suitable for the crops that are presently being produced in the region, because of the major shifts in seasonal patterns. An indirect effect of temperature increases will be high evapotranspiration from agricultural systems [134].

One of the most important potential effects of climate change in the region will be the reduced water availability for field crop production. Recurrent droughts [135] led to the rationing of surface irrigation water and over-exploitation of groundwater reserves. Future reductions in surface water availability could put further demands on groundwater, which could lead to water quality depreciation of deep wells in the region. Limited water availability has affected field crop production by the reduction of acreages put into crop production, especially during the years of severe droughts [136]. As freshwater resources become scarcer, an increased use of low-quality water for crop production can lead to a salinity build-up in soils. This can reduce crop yields or lead to crop failure, depending on the salinity tolerance of the crops being grown.

The extreme and unexpected weather occurrences being predicted as some of the regional consequences of climate change could affect field crop production significantly by interfering with reproductive processes (in cases of extreme temperatures), causing direct crop damage (in cases of severe flooding) and limiting the ability of farmers to carry out management operation (in cases where planting, harvest, or fertilization is impeded due to excessive rainfall) [137]. Projected U.S. corn production losses due to extreme rainfall events may be about \$3 billion per year by 2030 [138].

3.2. Vegetable Crop Production Systems

Crop species familiarity is vital for successful management as it affects irrigation planning, successful transplanting, temporal planning, and susceptibility to disease or pests. Crop capabilities drive crop adaptation to both current weather conditions and changing environmental conditions. Vegetable production challenges related to temperature, precipitation, and wind can be somewhat reduced based upon crop and cultivar selection [139]. Cultivars of the same species can have varying

water requirements, germination rates, responses to transplanting, and days to maturity. Thus, careful selection of vegetable crops supports adaptation to changing climatic conditions. Warm season crops, such as squash (*Cucurbita* spp.), melons, tomatoes (*Solanum lycopersicum*), eggplant (*Solanum melongena*), and chile and bell peppers (*Capsicum* spp.), can be injured or killed by frost and may stop the setting of fruit at high temperatures (> 35 °C). Cool season crops, such as broccoli (*Brassica oleracea*), carrots (*Daucus carota*), spinach (*Spinacia oleracea*), lettuce (*Lactuca sativa*), and swiss chard (*Beta vulgaris*), can tolerate frost. Temperature increases in Arizona are projected to decrease crop yield by 12% per °C increase [140]. Beyond yield reduction, specialty crop quality can also be affected [141].

In water-limited systems, low water-use vegetables may be advantageous. Tepary beans (*Phaseolus acutifolius*), blackeyed peas (*Vigna unguiculata*), okra (*Abelmoschus esculentus*), asparagus (*Asparagus officinalis*), and squash are some species that require little water and are adapted to warm temperatures. Asparagus is particularly tolerant of heat, drought, and salinity. However, transplanting crops like asparagus is time consuming, labor intensive, requires hardening, and some vegetables are not suited for transplanting. When possible, transplanted vegetable crops can help producers adapt to a host of environmental limitations by conferring a shorter time to maturity, reduced exposure time, and reduced water use. Planting and harvesting seasons vary within and between vegetable species, based on suitable germination and growing conditions. A keen sense of typical timing and conditions paired with accurate local environmental awareness aids in adapting to changing environmental conditions. Finally, varying threats in the forms of diseases or pests can affect crop growth and yields. Knowledge of the pests or diseases often associated with specific crop species is vital to an effective response.

At varying scales, there are additional adaptation methods a producer can employ [61]. The crop environment can be modified to accommodate temperature extremes. Structures can control ambient temperatures and evaporation rates, and protect plants against extremes. Applying surficial covers like mulch can protect the soil surface from erosion, provide a thermal barrier, protect against weedy species, and decrease evaporation rates. Capitalizing on the varying structure and function of different species aids neighboring crops. Trap cropping, symbiotic nitrogen fixation, seed soaking, biochemical pest suppression, physical spatial interactions, and nurse cropping serve to utilize specialized plant adaptations to combat pests or overcome adverse conditions. A key activity that increases crop security is spatial heterogeneity or increased diversity. Mixing cultivars of broccoli showed reduced aphid pressure [142]. Planting two or more species in the same space, or intercropping, increases cover density and takes advantage of different growth rates. Diversity helps minimize loss during less than ideal growing conditions. Seed saving helps producers capitalize on locally adapted plants that will help with long-term survival and production. Actively recording cultivar performance amidst drought conditions can help producers with planning for future conditions.

3.3. Perennial Production Systems

We focus on pecan as one example of a common perennial crop in the region. Pecan is a plant species native to the Mississippi River Valley. The first pecan trees were planted in NM around the 1900s and the first commercial plantings date from the 1930s in the Mesilla Valley [143]. Since that time, commercial production in NM has continued to rise, with the state output now accounting for around 29% of the U.S. production [144]. As a perennial crop, pecan orchards have a long establishment, so pecan farmers make considerable investment in their crop years before realizing maximum productivity.

The potential impacts of a warming climate on NM pecan growers can be viewed from the perspective of the impact of warming temperatures on tree physiology and how this will drive demand for surface and groundwater resources. Pecan trees need high amounts of water for optimum vegetative growth and nut production, particularly during embryo development in late summer [145]. Farmers are advised to maintain soil water suction above saturation and below 30 to 40 centibars [146].

Climate change projections over the region suggest hotter temperatures and increasing evaporative demand over a longer growing season. In a simple sense, this means that pecan orchards will require increased irrigation to prevent production losses or damage to crop quality. For example, late-season

water stress can cause poor nut filling or nuts that fail to open [145]. However, future changes in the availability of surface water relative to the groundwater supply will add complexity to these impacts. Pecans are very susceptible to salinity-induced stresses, which can mimic the effects of drought. Projected warmer winters and earlier spring over the Rio Grande headwaters affects high elevation snowpack, thus reducing the amount of surface water available for irrigation in the Rio Grande valley downstream. Groundwater has a much higher salt content than surface water and if, in the future, growers are required to rely more heavily on groundwater, there is the potential for increased soil salinity. Further, when water with greater salt concentrations is used for irrigation, then total quantity of irrigation water must be increased [146] to leach the salts beyond the rooting zone.

Warmer spring temperatures alone can cause issues with pollination because the maturation rates of male and female flowers respond differently to warming temperatures [147]. When combined with dry winds, warmer springs could trigger further pollination failures, thus reducing pecan yields in the region. Warmer, drier air causes anther desiccation, increasing the rate of pollen dispersal and thus shortening the pollination period [147].

Climate change could bring benefits to pecan producers, although these must be weighed against the potential challenges, such as the quantity and quality of the available irrigation water. Warmer future temperatures could lengthen the growing season. Standard pecan cultivars require a frost-free period of at least 190 days and periodically, this can be shortened by a late spring or early fall freeze [148]. Under a warming climate, the threat of late spring or early fall freezes is reduced.

Although it is difficult to ascertain how precipitation might change under a warming climate, the analysis of the North American Monsoon (NAM) suggests that while total precipitation amount during the NAM is unlikely to change significantly, the timing of the NAM has been projected to shift with greater quantities of precipitation falling in September–October [149]. This time coincides with the period of pecan embryo development and therefore may benefit pecan growers.

4. Interacting Systems and Adaptation: Building Resilience in Crop Production Systems

Adaptation strategies include developing new field crop cultivars that are more tolerant of heat stress and drought, improved soil moisture conservation in agricultural systems, adjusting planting and harvesting dates, diversified farming activities, using climate forecasting to reduce farm risk, and transitioning to more sustainable crop production management, such as organic systems [133,150,151]. Organic agriculture systems have a strong potential for building resilient food systems in the face of uncertainties through farm diversification and building soil fertility with organic matter [150,152].

Coping with unpredictable changes in weather patterns is aided by the development of decision support tools to help with optimum planting dates for crops, which can vary annually depending on weather patterns [153]. Setting planting dates for agricultural crops has become difficult as the traditional calendar dates that were used in the past can no longer be relied upon. Many agricultural extension services are encouraging farmers to base their planting decisions on specific weather parameters to minimize their crop loss risks. Farmers are being advised and trained on how to monitor the soil temperature before a planting decision is made. For example, for cotton production, farmers are generally advised to make sure that the soil temperature has attained a minimum of 16 °C before planting and ensure that no cold weather is forecast for about five to seven days after planting. Some more advanced planting decision models use the accumulated growing degree days or probability of frost occurrence to minimize the risk of damage to the emerging seedlings. For example, the Crop Weather Program (CWP), a web-based tool developed by Texas A&M [154], provides weather data information and decision making tools to aid cotton producers [155]. Another recent web based tool, the Cotton Planting Conditions Calculator [156], uses observed temperature and precipitation for the current day plus forecasted temperature and precipitation data for the next seven days for the user-selected location to predict the probability of successful cotton establishment [157]. The Cotton Planting Conditions Calculator has a wide applicability across the U.S. cotton belt since the weather data that feeds the model is based on the National Oceanic and Atmospheric Administration's real Time

Mesoscale Analysis, while the forecast data is from the National Weather Service's National Digital Forecast Database. These weather-based approaches to planting decisions and crop management will become increasingly important as tools that can be used for climate change adaptation.

Another tool useful in adaptation is the AgRisk Viewer (<http://swclimatehub.info/RMA>), a web-based platform providing accessible, discoverable, and usable federal crop insurance loss data originally from the United States Department of Agriculture Risk Management Agency [158]. Information about historic crop loss highlights regional spatial and temporal vulnerabilities related to weather events. Crop insurance is an important risk management tool used by producers to mitigate crop price declines and weather- and climate-related events. Assessments of historic weather- and climate-driven agricultural losses, especially insurance payments, offer insight that can be factored into risk management decisions [158]. Historic causes of crop loss (e.g., drought, hail) can inform possible risk management strategies for frequent or recurring events, or adaptation strategies based on producers' risk tolerance. Analyses of past crop loss events may be more salient to producers in their near-term operational management, and more effective in supporting climate-informed decision making [158,159]. Retrospective analyses of crop losses may inform producers' decision making and risk management strategies.

Long-term crop insurance loss data in the SW indicate spatially variable agricultural risk to both biophysical and economic factors (Figure 3). The top 12 causes of crop loss (COL) include weather- and climate-driven events (e.g., drought, hail, etc.), as well as losses related to price declines.

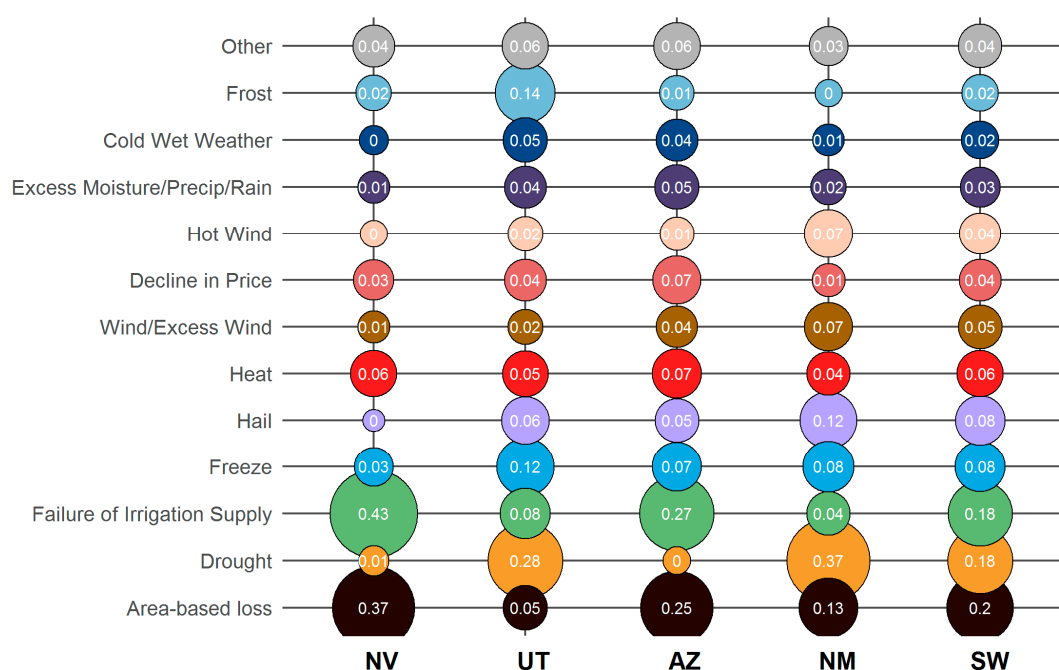


Figure 3. Relative fraction of aggregated indemnities by the top 12 regional causes of loss from 1989-2017. The size of the individual bubbles represents the contribution of specific causes of crop loss by state and for the Southwest region.

Across the four-state region, the leading COL from 1989 to 2017 is attributed to Area Risk Protection Insurance (ARPI) (Figure 3). Since this plan provides protection against widespread loss of revenue or widespread loss of yield in a county, the losses are not tied to a specific weather event. If the final county yield or final county revenue is less than the trigger yield or revenue, then indemnities are paid. ARPI accounted for 20% of the total indemnities in the four-state region between 1989 and 2017. Drought and lack of water (e.g., failure of irrigation supply) represent the leading weather-related COL, representing 18% of total regional indemnities each. Wind and hot wind account for 9% of the

total COL. Freeze, hail, and heat are also important COL in the SW, each representing 6% to 8% of the total COL. Decline in price accounts for only 4% of the regional total COL.

On a state-by-state basis, the leading COL related to weather were drought (28% in UT and 37% in NM) and lack of water (e.g., failure of irrigation supply; 27% in Arizona and 43% in Nevada). Utah is more susceptible to COL from cold weather (frost, 14%; freeze, 12%, cold wet weather, 5%) than the other states. On a seasonal basis, lack of water and freeze are most prevalent in the spring whereas hail, heat, and drought are more prevalent in the summer (Figure 4). Drought was reported as a consistent COL during each season in both NM and UT. Decline in price was only a top COL in AZ in the fall.

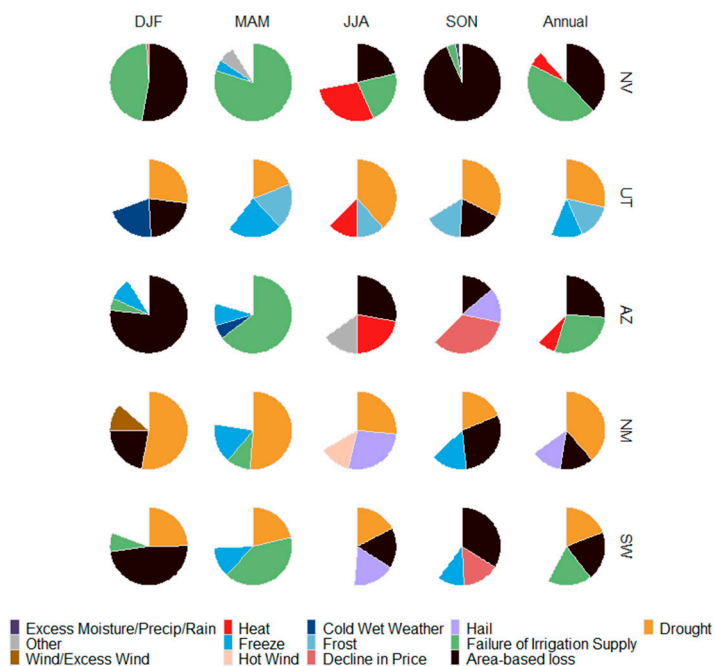


Figure 4. Top three indemnities by cause of loss on a seasonal basis for each state and the Southwest.

Indemnities by crop give insight into where adaptive measures for specific crops may foster future sustainable production. While 20% of the indemnities were associated with “other” crops in the SW, forage production, wheat, cotton, grain sorghum, and apples account for at least 10% of the state-wide total indemnities in at least one state (Figure 5). Forage production and pasture, rangeland, and forage accounted for 53% of indemnities in NV and 14% in AZ. Wheat loss resulted in the highest indemnities in UT (35%) and NM (38%). Cotton losses comprise nearly half of all indemnities in AZ. Apple loss accounted for 13% of UT’s total indemnities by crop. Adaptation measures or assistance programs could be targeted to minimize the loss of these crops by supporting targeted outreach events via agricultural service providers to showcase adaptive measures and knowledge co-production sessions to learn about growers’ needs and perceived limitations and barriers to adoption.

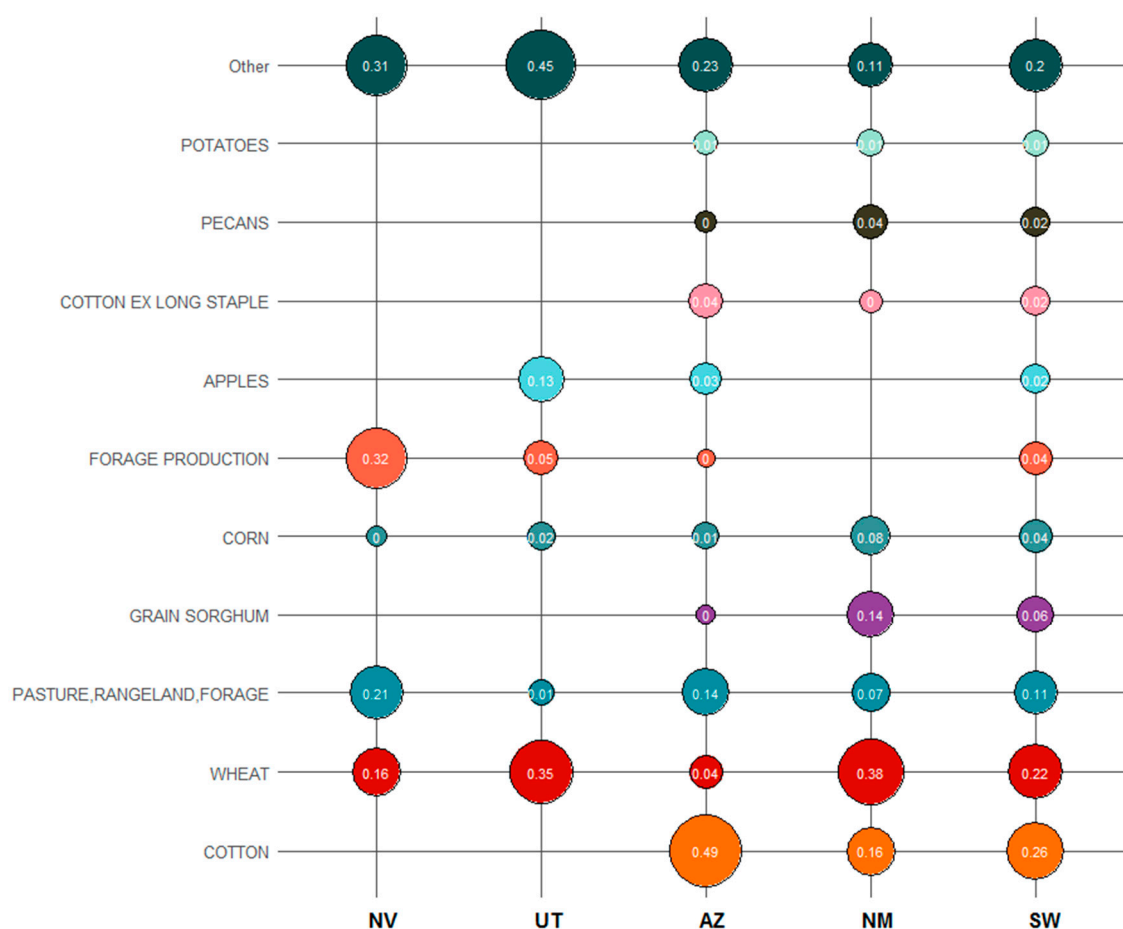


Figure 5. Relative fraction of indemnities by crop from 1989 to 2017.

5. Discussion

Resiliency in crop management under a changing climate encompasses improvements of existing practices and the design of new approaches to minimize the direct and indirect impacts of climate change on crop performance. The challenge to crop management under climate change lies in sustaining optimal crop performance by reducing the negative effects of abiotic and biotic stressors. Proactively selecting and establishing measures to enhance adaptive capacity will decrease systemic vulnerability to climate change stressors.

Management with a robust understanding of the biotic and abiotic factors that influence production give a producer an advantage in the face of uncertain and volatile weather. Familiarity with crop species, improving soil health, efficient water use, growing environment modifications, saving seed, diversifying crops, keeping records, and knowing local conditions are all ways that producers can thrive amidst a warmer and drier climate.

Producers need information on how to adapt their production systems to cope with climate change through specific farm practices that can enhance sustainability and reduce risks. Some adaptation practices may involve investment in novel strategies or growing new crops and these will demand changes in growers' attitudes towards the management of natural resources and possible infrastructure changes to remain productive. It is important to note that producers are not in this alone, neighboring producers, alliances and cooperatives, county extension agents, local USDA-NRCS field offices, or Soil and Water Conservation Districts provide decision-relevant agricultural knowledge in the face of weather and climate production stressors. While we have increasingly sophisticated approaches to dealing with production problems in the 21st century, we strive to keep pace with the cascading barrage of inter-connected challenges presented by climate change.

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