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Vulnerability of field crops to midcentury temperature changes and yield effects in the Southwestern USA

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Abstract Increased temperatures in the Southwestern USA will impact future crop production via multiple pathways. We used four methods to provide an illustrative analysis of midcentury temperature impacts to eight field crops. By midcentury, cropland area thermally suitable for maize cultivation is projected to decrease, while area suitable for cotton cultivation expands

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northward and nearly doubles in extent. The increase in area exposed to daily temperatures > 35 °C was highest for oat and maize. Estimates of yield reduction from heat stress for both maize and cotton indicate that historically, SW heat stress reduced cotton yield by 26% and maize yield by 18% compared to potential yield. By midcentury, we predict yield reduction from heat stress will reduce cotton and maize yields by 37 and 27%, respectively, compared to potential yield. Our results contradict the notion that the warmest counties cultivating field crops will be the most impacted. Rather, future temperature, total crop area and crop sensitivity contribute to more complex county-level impacts. Identification of representative target environments under future temperature regimes can inform development of farm-based networks to evaluate new crop germplasm with increased heat tolerance and viable adaptation and management strategies to respond effectively to future temperatures.

1 Introduction

Assessing the magnitude and spatial extent of the impacts of climate change on crop yields is vital for meeting the needs of increasing populations and improving food security despite diminishing land available for agricultural expansion. By midcentury, the Southwestern USA (SW) is projected to experience higher temperatures and more frequent, intense and longer heat waves (Gershunov et al. 2013). Field crops (FC) in the SW are vulnerable to increased temperatures, which can accelerate crop growth, leading to earlier and often reduced yields, and also lead to heat stress or crop failure, particularly during certain phenological phases. The contraction of developmental stages in a warmer climate and consequent shift in regional crop suitability is a well-documented impact of climate change (Craufurd and Wheeler 2009; Walthall et al. 2012).

Warming impacts are crop-specific due to the unique temperature response thresholds at which optimal growth and crop failure occur (Robertson et al. 2013). Elevated temperatures may benefit crops currently below their optimal temperature threshold but reduce the growth of other crops near or past their thresholds (Lobell and Gourdji 2012; Marshall et al. 2015). Increased mean temperatures above the optimal threshold can shorten the growth cycle and grain filling period of wheat (Rosenzweig and Tubiello 1996), with an average yield reduction of 6% for each degree (°C) of temperature increase (Asseng et al. 2015). Maize yields are reduced at daily maximum temperatures > 29 °C (Schlenker and Roberts 2009). Above 32 °C, cotton yields fall due to a decline in leaf area, shoot biomass, and flowering (Schlenker and Roberts 2009). Alfalfa can be productive in warm climates when irrigated, yet temperatures > 30 °C result in earlier flowering and reduced yield, poorer quality, and diminished suitability for lactating dairy animals (Al-

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Hamdani 1990; Greenfield and Smith 1973; Vough and Marten 1971). For crops in areas that are near such optimal temperature thresholds, such as maize and cotton in parts of the SW (Schlenker and Roberts 2009), additional warming could further reduce yield, which could impact food prices and security (Lobell et al. 2009). Beyond optimal temperatures, many crops fail as temperatures approach 35 °C (Table 1), though cotton can be grown at temperatures > 40 °C. Complete crop failure is often due to reproductive failure during specific phenological phases (Baker et al. 1995; Lobell et al. 2007; Robertson et al. 2013).

This study examines the potential detrimental impacts of projected temperature shifts on eight FC that are cultivated widely in the SW, including small grains (wheat, barley, and oats), alfalfa, maize, cotton, rice, and safflower. These crops were grown on 5.2-M acres at a production value of $6.9B in the SW in 2012. The yield per area of most FC has increased in the SW since the 1880s, while the acreage of the barley, oats, wheat, and cotton has decreased in more recent times (1980 to present) (Online Resource (OR) 1). These crops vary in their spatial extents and growing temperature ranges; for example, hay is cultivated ubiquitously across the region, but other crops such as rice, cotton, and safflower are more geographically constrained. Much of the SW FC production provides food for livestock. In 2012, hay represented 35% of the total regional FC acres harvested. Maize occupied 10% of the total FC acres harvested. Wheat, cotton, and rice each comprised 6–9% of the 2012 total. Some analyses presented here focus on select crops. For example, the thermal range analyses include only alfalfa, maize, and cotton because of the higher spatial data accuracy, large cultivated acreage (alfalfa and cotton), and historic importance to indigenous people (maize) (Lynn et al. 2013). Maize and cotton were selected for yield analyses because of their differing temperature thresholds (Walthall et al. 2012) and cultivation in many parts of the region (National Agricultural Statistics Service 2013). We specifically seek to understand which FC and geographic regions of the SW may be most sensitive to projected changes in temperature.

2 Methods

Four analyses at varying spatial scales were conducted to assess impacts of temperature change by midcentury (2040–2069) on eight common FC grown across the SW USA.

2.1 County-level impact assessment

A county-level assessment was performed using county-by-county harvested FC area from the most recent US agricultural census (NASS 2013; Fig. 1), projected estimates of increased temperature and a crop sensitivity factor (SF) to estimate impact. The assessment of climate impacts on regional FC was based upon the framework defining vulnerability as a function of exposure, sensitivity, and adaptive capacity (Glick et al. 2011). The exposure of crops (wheat, barley, oats, alfalfa, maize, safflower, rice, and cotton) in each county to rising temperatures was represented by the projected future midcentury temperature for each county from the county-level summer (June–July–August) future maximum temperature ($T_{\max}$) compiled from Multivariate Adaptive Constructed Analogs (MACA, Abatzoglou and Brown 2012) 20-model mean downscaled data for the 2040–2069 time period from the Representative Concentration Pathway 8.5 (RCP8.5) experiment (Elias et al. 2017).

The sensitivity of FC to changing temperatures was estimated using a literature-derived SF on a scale of 1 to 3 to represent general thermal sensitivities where crops classified as 1 are the

Table 1 Literature defining field crop temperature sensitivity, applied sensitivity factor (SF), and analysis results

Crop	Area (km^2)	SF	TR analysis	July > 35 °C > 15 days	Optimum temperature (T_{opt}), maximum temperature at after which yields decline (T_{max}), and failure temperature ($T_{failure}$) for reproductive yield
Maize *Zea mays*	1038	2	2012 area declines 12%; potential area declines 20% 95% TR = 29.5–40.7 °C	Past (35%) Future (84%)	T_{opt} = 18–22 °C (Muchow et al. 1990); $T_{failure}$ = 35 °C (Herrero and Johnson 1980)
Cotton *Gossypium*	2442	1	2012 area declines 6% in area with extensive cotton cultivation; potential area doubles 95% TR = 32.5–41.5 °C	Past (88%) Future (99%)	T_{opt} = 25°26 °C (Reddy et al. 2005; Oosterhuis 1999); 20–32 °C (Burke et al. 1988; Reddy et al. 1991); 28–32 °C (pollination; (Brown 2008; Snider et al. 2011)); $T_{failure}$ = 35 °C (Reddy et al. 1992, 1997)
Rice *Oryza sativa*	2263	1		Past (80%) Future (100%)	T_{opt} = 23–26 °C (Baker et al. 1995; Horie et al. 2000); $T_{failure}$ = 35 °C (Baker et al. 1995)
Wheat *Triticum*	3326	3		Past (50%) Future (84%)	T_{opt} = 15 °C (Chowdhury and Wardlaw 1978); 20 °C (White et al. 2012); $T_{failure}$ = 34 °C (Tashiro and Wardlaw 1990)
Barley *Hordeum vulgare*	569	3		Past (52%) Future (74%)	T_{opt} = 15–17 °C; $T_{failure}$ = 35 °C (Robertson et al. 2013)
Oats *Avena sativa*	110	3		Past (39%) Future (82%)	T_{opt} = 15 °C (Hellewell et al. 1996; O'Donnell and Adkins 2001); T_{max} = 36 °C (Robertson et al. 2013)
Alfalfa *Medicago sativa*	9185	2	2012 area declines 14%; potential area increases 2% 95% TR = 26.5–41.5 °C	Past (43%) Future (70%)	T_{opt} = 16–21 °C (Al-Hamdani 1990; Arbi et al. 1979; Vough and Marten 1971) T reduced yield = > 30 °C (Al-Hamdani 1990); T_{max} = 43 °C (Breazeale et al. 1999)
Safflower *Carthamus tinctovius*	192	1		Past (43%) Future (64%)	T_{opt} = 20–30 °C (Fageria 1992); T_{max} = 35 °C (Torabi et al. 2015)

Thermal range (TR) is the summer maximum temperature where 95% of the crop was cultivated in 2012 with analyses reflecting changes in 2012 area and potential cultivation area. July > 35 °C > 15 days represents the percent crop area with more than 15 days with T_{max} > 35 °C. Corn, cotton, rice, and wheat temperature information adapted from Climate Change and Agriculture in the United States: Effects and Adaptation (Walthall et al. 2012)

1 low sensitivity, *2* moderately high, *3* high sensitivity

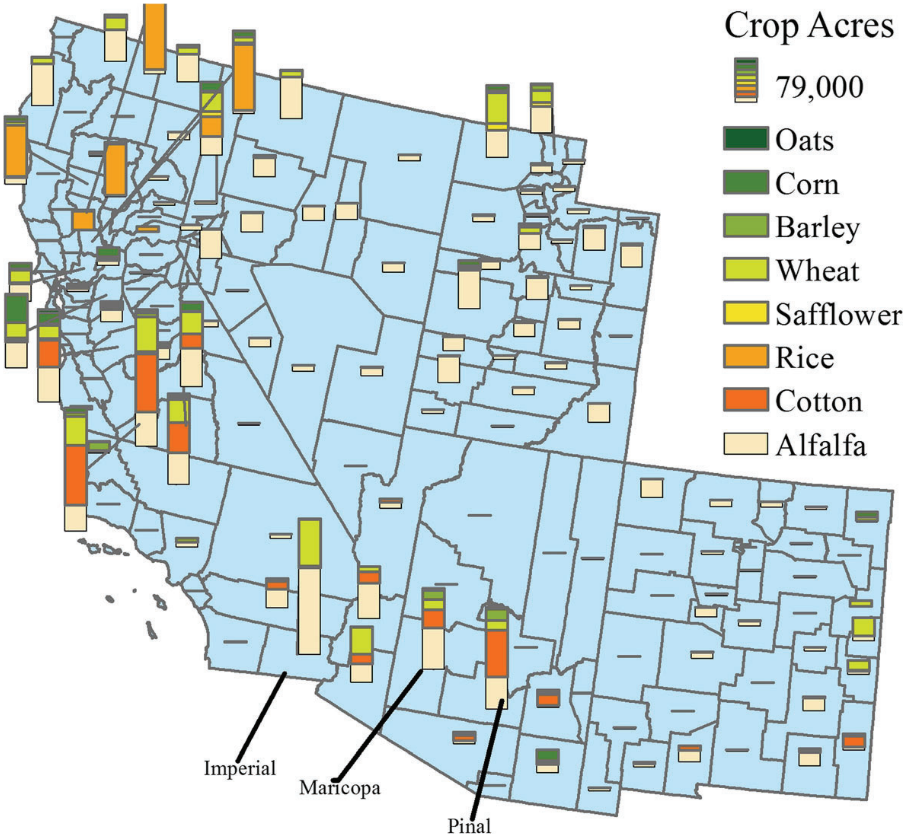

Fig. 1 County-based location of eight common field crops grown in the Southwestern USA in 2012

least sensitive to heat stress (cotton, rice, and safflower) and crops classified as 3 are the most sensitive to heat stress (small grains). Counties were indexed by i where $i = \{1,\ldots,152\}$. Crops are indexed by j where $j = \{1,\ldots,8\}$. To calculate the absolute sensitivity (sensitivity$_{\mathrm{ABS}}$) of an individual crop within a county, we multiplied the area of a specific crop in a county (A_{crop}) by the crops' SF value. We then summed the crop sensitivities for each FC for each county (Eq. 1). Relative sensitivity was calculated by dividing sensitivity$_{\mathrm{ABS}}$ by the total FC acreage of the eight crops evaluated per county (Eq. 2).

$$Sensitivity_{ABS(i)} = \sum_{j=1}^{8} \left(Acrop_{ij}\right)\left(SF_j\right) \tag{1}$$

$$Sensitivity_{REL(i)} = \frac{SensitivityABS_{(i)}}{county\ field\ crop\ area_i} \tag{2}$$

Absolute impact (Impact$_{\mathrm{ABS}}$) of changing temperatures was calculated for each county by multiplying crop area, sensitivity, and $T_{\max}$ (Eq. 3). The county products for each crop were summed, weighting counties with more FC more heavily.

$$Impact_{ABS(i)} = \sum_{j=1}^{8} \left(Acrop_{ij}\right)\left(SF_j\right)\left(Tmax_i\right) \tag{3}$$

$$Impact_{REL(i)} = \frac{ImpactABS_{(\mathrm{i})}}{county\ field\ crop\ area_{\mathrm{i}}} \tag{4}$$

The impact$_{\mathrm{ABS}}$ was divided by the total area of FC (up to eight) analyzed in the county to calculate relative impact (Eq. 4).

Absolute values depict counties with a larger FC area and higher SF as more vulnerable to increased midcentury temperatures, whereas relative values show counties with a higher proportion of sensitive crops as more vulnerable to increased temperatures. The metrics are complementary and describe FC vulnerability from both an area and composition perspective.

2.2 Shifting thermal range for alfalfa, maize, and cotton

The geographic distribution of suitable land for cultivating three FC (alfalfa, cotton, and maize) was modeled based on thermal ranges (TR) for historic and future climate. The fundamental assumption of this component of the spatial FC assessment was that crops are presently grown in locations well-suited to their thermal tolerance. The FC for this analysis were selected due to regional importance and crop classification accuracy or how well the USDA cropland data layer (CDL) represents field-verified data (OR2). The CDL is crop-specific land cover data created annually for the contiguous USA using satellite imagery and extensive physical verification (i.e., ground-truthing).

The normal TR for each crop was generated using 2012 crop distribution of USDA CDL and summer (June–August) 30-year mean temperature normal (1971–2000) from PRISM (Daly et al. 2008). The TR was defined by the 95% range (2.5–97.5 percentile) of climatological summer temperature coincident with the location of each crop of the CDL.

The future summer $T_{\max}$ was based on the MACA 20-model midcentury (2040–2069) multi-model mean temperature (RCP8.5) (Abatzoglou and Brown 2012). This dataset used PRISM and hence there are nominal differences between 30-year normals from historical climate experiments and observations from 1971 to 2000, hence allowing us to directly use and compare temperature projections from downscaled data with the TR developed from historical PRISM data. Public lands, urban areas, and water bodies were removed from analyses as they are unlikely to transition to agricultural land. Temperature rules were defined based upon the minimum and maximum temperatures bounding the normal 95% TR for alfalfa, maize, and cotton to produce change detection maps showing areas predicted to shift into or outside the TR.

2.3 Days with temperatures > 35 °C

Since temperatures > 35 °C can be associated with reproductive failure, we analyzed the number of historic and future days by percent crop area where daily maximum temperature > 35 °C for April–August. Daily maximum temperature for both historic (1950–2005) and RCP8.5 experiments using the mean of the 20 models of MACA were obtained for each ~ 4-km pixel where crops were grown in 2012 per the CDL.

2.4 Effects of temperature on yield

Effects of historic (1950–2005) and midcentury (2040–2069) temperature on maize and cotton yields were estimated based on non-linear relationships between yields and hourly temperature exposures (Schlenker and Roberts 2009). Schlenker and Roberts found statistical relationships between yield declines and the number of hours at each degree interval for corn and cotton during the growing season (OR3). Accordingly, we constructed hourly temperature estimates by temporally disaggregating daily summer T_{max} and T_{min} for April–August for all 20 models included in MACA historical and midcentury time periods, using a modified sinusoidal curve function (Linvill 1990). The cumulative number of hours of crop exposure to each 1 °C increment from 32 to 34 °C and > =35 °C were calculated for each pixel and time period. Measures of heat exposure were multiplied by the yield reduction factors of Schlenker and Roberts (2009). Since yield reduction factors are time-separable and additive, they were summed to estimate the total effect of heat stress on historical and midcentury maize and cotton yields. Cotton and maize exposure were based upon the 2012 location and density from the CDL. Each pixel was weighted by the fraction of area cultivated by each crop to calculate the average yield reduction factors for maize and cotton (NASS 2016).

3 Results

3.1 County-level assessment

County-level analyses of midcentury climate impacts on FC depict regions expected to be particularly vulnerable (Fig. 2). Absolute sensitivity and impact highlights the southern portion of California's Central Valley and counties along the California-Arizona border with higher sensitivity and impact to FC than other parts of the SW. Two areas of particular relative vulnerability are California's Central Coast and eastern New Mexico, as they both cultivate a high percentage of small grains. Only Imperial County, California is in both the highest absolute and relative impact classifications, indicating it may be especially vulnerable.

3.1.1 Sensitivity

Imperial County, California sensitivity$_{\mathrm{ABS}}$ was highest in the region because it contained both the largest FC area and a large percentage of crops with a high SF value (35%) (OR4). The

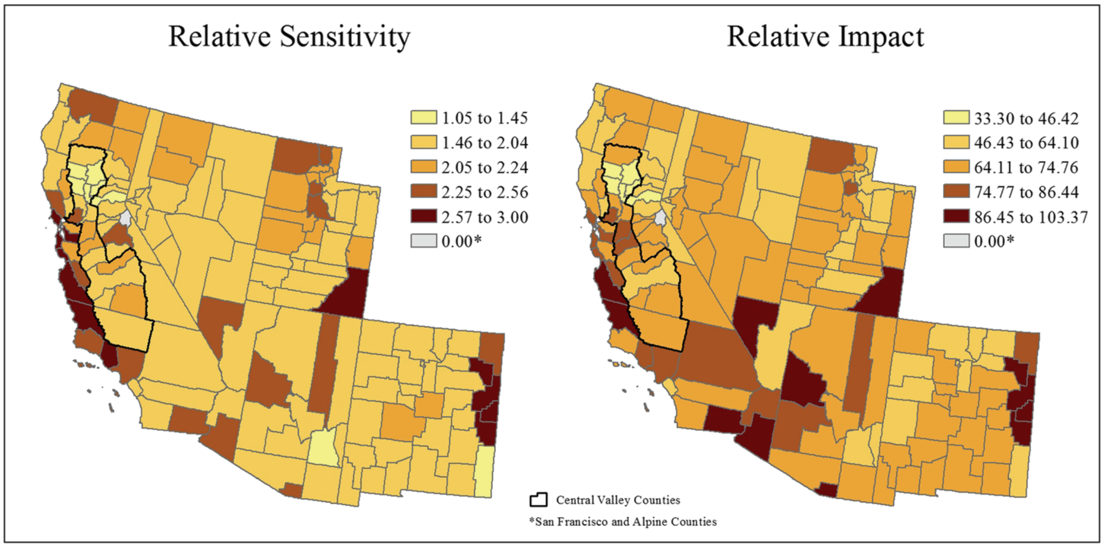

Fig. 2 Relative sensitivity and impact of field crops common to the Southwestern USA. For absolute sensitivity, 1 represents the least sensitive category

southern Central Valley was a sensitive region based upon sensitivity$_{\mathrm{ABS}}$, reflecting the large FC acreage dominated by alfalfa and wheat production. In contrast, north Central Valley counties have a large FC acreage, but lower sensitivity$_{\mathrm{ABS}}$ because rice, classified with a lower SF, comprises a large proportion of the total FC area. Other counties with high sensitivity$_{\mathrm{ABS}}$ had a high total FC area.

Sensitivity$_{\mathrm{REL}}$ enables the intercomparison of counties within the region according to FC composition. Counties with the highest sensitivity$_{\mathrm{REL}}$ (2.57 to 3.00) grew small grains as more than half the total FC area (57–100%). Eastern New Mexico had high sensitivity$_{\mathrm{REL}}$ because of cultivation of small grain crops, comprising at least 73% of the total FC production. The southern Central Valley appears moderately sensitive based on sensitivity$_{\mathrm{REL}}$ but highly sensitive using absolute values. Similar to sensitivity$_{\mathrm{ABS}}$, the north Central Valley is a region of lower sensitivity due to the larger fractional area devoted to rice cultivation. The two counties with cotton comprising the largest proportion of total FC growth (Kings and Fresno, California) were classified with the highest sensitivity$_{\mathrm{ABS}}$ but low sensitivity$_{\mathrm{REL}}$.

3.1.2 Exposure

Exposure is incorporated into impact$_{\mathrm{ABS}}$ and impact$_{\mathrm{REL}}$ analyses as the midcentury summer $T_{\max}$ by county (OR5). Future values range from 23 to 43 °C, approximately 2.4–4.0 °C warmer than historical values, with the warmest temperatures in counties of the Sonoran Desert.

3.1.3 Impact

The four counties with large rice cultivation area (76–95%) had lower impact$_{\mathrm{ABS}}$ than other counties with similar area under cultivation but composed of different crops (OR6). Conversely, Yuma, Arizona, had a higher impact$_{\mathrm{ABS}}$ than other counties with similar crop area due to cultivation of nearly 50% sensitive crops (48% wheat) near the upper bounds of optimal temperatures ($T_{\max} \sim 40$ °C). Future $T_{\max}$ is projected to be 43.2 °C. Imperial, Fresno, and Kings County, California had the highest impact$_{\mathrm{ABS}}$ partially due to high FC acreage. Some adjacent counties had moderately high impact$_{\mathrm{ABS}}$ suggesting groups of counties or regions of higher vulnerability.

Normalized to county area, impact$_{\mathrm{REL}}$ emphasizes the role of crop composition within a county to assess impacts of increasing temperatures on FC. Counties with a higher proportion of resilient crops were less affected by increased temperatures. The correlation between impact$_{\mathrm{REL}}$ and percent low-sensitivity FC (safflower, rice, cotton) grown in each county exhibited a negative correlation ($r = -0.21$; $p = 0.01$). By contrast, impact$_{\mathrm{REL}}$ was positively correlated with the percent of high-sensitivity FC (wheat, barley, oats) grown in each county ($r = 0.28$; $p = 0.0004$). While the Central Valley appeared less impacted based on impact$_{\mathrm{REL}}$ than impact$_{\mathrm{ABS}}$, counties of eastern New Mexico growing wheat appeared more impacted, with Quay County (90% wheat) having the highest impact$_{\mathrm{REL}}$. The Central Valley had counties with high impact$_{\mathrm{ABS}}$ primarily because of the large FC cultivation in that region whereas eastern New Mexico had a high impact$_{\mathrm{REL}}$ because of cultivation of sensitive crops. Only Imperial, California was in the most affected category using both impact$_{\mathrm{ABS}}$ and impact$_{\mathrm{REL}}$ (OR6).

3.2 Thermal range

Projected increases in midcentury temperatures cause the area that is thermally suitable for cotton production to double by midcentury, with a northward expansion of potential area for cotton cultivation (OR7). However, 6% (158 km^2) of the 2012 cotton cultivation area, located in parts of California, Arizona, and Nevada, is projected to shift outside cotton's TR (32.5–41.5 °C) by midcentury, for a net gain in suitable area of 207,000 km^2 in the SW.

The alfalfa cultivation area (2012) within the 95% summer $T_{\max}$ normals (26.5–41.5 °C) will decrease by 14% (1508 km^2) by midcentury. Regions impacted by 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. Across the SW, the area where alfalfa could be grown and remain within its TR (i.e., potential area) will increase by 2% by midcentury, for a net gain of 11,600 km^2.

Twelve percent (300 km^2) of maize cultivation area (2012) (2504 km^2) will shift outside the TR (29.5–40.7 °C) by midcentury. The potential area within maize's TR in the SW is projected to decrease by 20% for a net loss of 88,900 km^2. Regions of northern New Mexico along the Rio Grande Valley will shift into maize's normal TR, whereas portions of southern Arizona will have temperatures above maize's TR (OR7).

3.3 Crop exposure to elevated temperature

The projected number of days with maximum temperatures > 35 °C will increase by midcentury across the region, varying by both month and crop (OR8 and OR 9). For all crops, July had the most days > 35 °C across the greatest spatial extent. Based on 2012 crop locations, the crops exposed to more than 15 days > 35 °C in July ranged from a low of 35% (maize) to a high of 88% (cotton). By midcentury, this range increases to 64% (safflower) to 100% (cotton and rice). The increase in area > 15 days > 35 °C was highest for oat and maize, indicating that they may experience the broadest change in area impacted by midcentury July heat stress.

3.4 Effects of temperature on yield

Historically (1950–2005), between April and August, corn received an average of 426 h > 32 °C. Average temperatures at historic (1950-2005) cotton cultivation locations (2012 CDL) were higher than corn cultivation locations, with average exposure of 622 h > 32 °C for cotton. Using our temperature-yield effects model (Eq. 1; OR3), heat stress reduced historical yields (1950–2005) by 18% for maize and 26% for cotton (OR3). Average historical yields (1950–2005) were 7,774 kg/ha for maize and 1140 kg/ha for cotton, so yield potentials without heat stress would have been 9420 and 1540 kg/ha for maize and cotton, respectively. By midcentury (2040–2069), corn will have an average exposure of 665 h > 32 °C (88 h at 32 °C, 85 h at 33 °C, 81 h at 34 °C , and 411 h at 35 °C or greater). Cotton exposure was 918 h > 32 °C (101 h at 32 °C, 96 h at 33 °C, 89 h at 34 °C, and 632 h at 35 °C or greater) by midcentury. Consequently, heat stress would reduce yields by 27% for maize and 38% for cotton. Assuming all factors other than temperature are consistent, midcentury yields will be reduced by 12 and 15% of historic yields for maize and cotton, which would be 6860 and 964 kg/ha for corn and cotton, respectively. The southern Central Valley, eastern New Mexico, and southern Arizona would suffer the greatest impacts by midcentury.

4 Discussion

4.1 Temperature impacts on specific crops

Small grains The relatively high sensitivity of small grains to elevated temperatures led to increases in county impact$_{\mathrm{REL}}$ in counties with a higher proportion therein. In the future, a larger portion of the area currently occupied by barley, oat, and wheat across the SW will have more days > 35 °C. Already, early planting of small grains, or sowing in fall and harvesting in late spring or early summer, serves as a heat stress adaptation strategy.

Alfalfa Alfalfa is cultivated in nearly all SW counties, but Imperial County, California, grows the largest acreage. The projected shift outside the 95% TR by midcentury for nearly all the alfalfa cultivation area in Imperial County underscores the need to use strains with broad adaptation to elevated temperature to support both yield and quality (Arbi et al. 1979). Portions of northern California and Arizona will provide a thermal regime similar to the historic TR and may be better suited to growing future high-quality, high-yield alfalfa. Our results showed 70% of the SW alfalfa cultivation area with > 15 days > 35 °C in July by midcentury. This increase may cause decreased evaporative cooling, increased heat stress, and summer slump in yield and quality (Putnam and Ottman 2013).

Maize TR analyses showed that maize grown in southern AZ will be outside historic summer temperatures by midcentury. Most maize in the SW is grown in the Central Valley (CA), where mean summer $T_{\max}$ is projected to remain within the normal TR (OR7). However, monthly analysis reveals that the area encompassing the Central Valley is projected to be > 35 °C for > 20 days in July and August and may hinder future production. Yield analyses estimate that heat stress will reduce potential maize yield across the SW by 27% by mid-century, an additional 12% decline over historic impacts of heat stress on yields (OR3). Others have reported sensitivity of maize to projected climate changes in the region (Hatfield et al. 2011).

Cotton Counties with high cotton cultivation generally had a moderate to high sensitivity$_{\mathrm{ABS}}$ and impact$_{\mathrm{ABS}}$ because they also had a large total FC area. The lower sensitivity$_{\mathrm{REL}}$ and impact$_{\mathrm{REL}}$ reflect its SF value. Still, the cotton TR is projected to double by midcentury due to its northward expansion. The CA cotton region will remain within the normal TR, with some northern areas transitioning into the normal TR. Other parts of the SW may pose a challenge for future cotton cultivation despite low sensitivity and broader TR. Specifically, areas projected to transition from the historic TR are located in counties presently with large cotton cultivation (Pinal and Maricopa, Arizona).

Since cotton is normally planted in April in Arizona and California and generally takes 2 months from planting to first flower, June temperatures are important indicators of crop failure due to heat stress during reproduction. In the past, 30% of the cotton area had > 15 days > 35 °C in June. By midcentury, this number increases to 80%, potentially leading to diminished yields due to impacts on floral development and boll abortion 15 days post-flowering (Brown 2008). Cotton cultivation area with an average of more than 26 days > 35 °C in July is projected to increase from 20 to 66% by midcentury. Heat stress was projected to reduce yields by 15.4% compared to historic yields and 38% compared to potential yields if future production remains in the same location as the 2012 CDL. However, the northward expansion of cotton's TR indicates that production could relocate to a more suitable TR and thereby maintain acceptable yields, given suitable soils and available water.

Rice Rice is cultivated only in seven counties in northern CA where early planting in April or May increases yields (Linquist and Espe 2016). Planting early maximizes the use of solar radiation. It also diminishes potential exposure to temperatures > 35 °C at flowering, which increases rice sterility (Satake 1995). Early planting will become increasingly important by midcentury, since July and August are projected to have 5 to 10 days with $T_{\max} > 35$ °C (OR9).

Safflower Safflower prefers hot, arid conditions and accordingly nearly half of the nation's safflower is grown in the SW. Even though current acreage represents the crop with the smallest percentage > 15 days > 35 °C in July, its midcentury cultivation area with > 15 days > 35 °C increases by 21%. Most safflower is not irrigated so the cumulative effects of increased temperature on water and heat stress could impact production.

4.2 Yield effects

The timing of extreme heat events has important repercussions on plant physiology. Heat increases the rate of crop development, which consequently decreases growing time (Lobell et al. 2007). This can simply reduce yields or can result in physiological defects. Yield reduction may occur because plants close their stomata at temperatures above the temperature optimum. The effect of temperature on photosynthesis depends on the current temperature compared to the optimum (Rosenthal et al. 2012); maximum summer temperatures are already near the upper optimal limits for maize and cotton (Schlenker and Roberts 2009), so increased heat will likely decrease photosynthesis for both crops. During reproduction, heat stress may reduce the effectiveness of pollinators, reduce grain set, and even cause sterility (Lobell et al. 2007).

4.3 Reducing temperature risk

The identification of thermal vulnerabilities guides adaptive responses to reduce temperature risk. Growers can mitigate crop heat stress by increasing irrigation (Haim et al. 2008), which provides evaporative cooling, allowing crops to persist in locations hotter than reported thermal ranges. Crop production is supported by the SW's extensive surface water infrastructure managed by various agencies. These systems transport water over large distances, geographically decoupling water sources, such as high-mountain snowpack, from water users. Without access to surface water conveyance networks, growers consequently rely upon groundwater. Some counties, including those in eastern NM, do so to support all agricultural production. While groundwater's strategic importance for global food security increases (Taylor et al. 2013), groundwater tables are declining in parts of the region (Konikow 2013). Delivering adequate water to mitigate heat stress and maintain yields may be a challenging or even impossible adaptation strategy with predicted changes in precipitation (Langford et al. 2014), reductions in water supply (Schoups et al. 2005), and increases in water scarcity (Averyt et al. 2013).

Another adaptation option for elevated temperatures may be earlier planting to adjust for temperature shifts. Different field crops are typically sown and harvested at different times throughout the year (OR10) (National Agricultural Statistics Service 2010). The crops considered here were cultivated during part or all of the summer (June–July–August). Some crops, such as oat and barley in California, have two different planting cycles with both spring and fall planting phases. Others have very different growth periods due to geography. Planting and sowing dates for winter wheat, for example, cover only 4 months in colder states (NV and UT) as compared with 9 months in Arizona. Thus, warming may extend growing seasons in parts of the region. However, using Arizona growers as an example, which generally practice single season planting and harvesting, extended warming may not elicit cultivation of multiple yields within 1 year. Sowing date and time of flowering and maturity in cereal phenology by 2040 may advance by 1–3 weeks in Northern and Central Europe under a changed climate (Olesen et al. 2012). However, earlier spring onset can increase vegetation frost damage risk (Kim et al. 2014) or lead to decreased yield from reduced day length. Simply shifting planting dates to accommodate warming trends may not be a consistently viable adaptation. Growers may select drought tolerant cultivars or, where possible, practice deficit irrigation to ensure enough available water during critical periods like flowering. The effects of diminished water supply increased heat stress and crop yield reduction compound vulnerabilities for regional crop production.

These spatially explicit findings on temperature enable prioritization of regions for examination of adaptation scenarios, especially if overlaid with existing and projected water resources. These scenarios should include biophysical, agricultural, and socioeconomic factors among the current suite of indicators assessed here to build resilient production systems (Steenwerth et al. 2014). Climate change impacts (for example, higher temperatures and CO_2 concentrations, increased drought and flooding) may be somewhat ameliorated by advances in crop physiology and genetics. However, there are social controversies surrounding genetic engineering. Since adaptations often come at a physiological cost, the trade-offs in introducing new plant traits must be considered (Steenwerth et al. 2014). In addition, development of transgenic crops has been slow (Mittler and Blumwald 2010). Identification of representative target environments under future temperature regimes informs establishment of regional crop networks, where germplasm with increased heat and drought tolerance and agricultural practices that mitigate elevated temperatures can be developed.

4.4 Beyond temperature

Other factors besides increasing temperature will affect crop production. Changes to components of the hydrologic cycle, trending towards more arid conditions (Jones and Gutzler 2016), will ultimately reduce total water availability. Social and economic factors such as competition for dwindling water resources between varied sectors could reduce water supplied to crop production. Increasing CO_2 concentrations can provide benefits for some plants, but projected changes in temperature and precipitation may outweigh any benefits associated with CO_2 (Walthall et al. 2012). Also, impacts of such changes on pollination, weeds, pathogens, and pests will undoubtedly influence crop production.

4.5 Conclusions

County-level analyses of midcentury climate impacts (absolute and relative) on FC indicate particular vulnerability to increasing temperatures within California's southern Central Valley and the southern California/Arizona border. Imperial County's (CA) high vulnerability is due to extensive cultivation of highly sensitive FC therein. Depending upon the coincidence of extreme heat events with certain plant growth phases, more temperature-related crop failure is likely. For historic and midcentury analyses, July had the most days > 35 °C across the greatest spatial extent. By midcentury, nearly all cotton and rice areas will have > 15 days > 35 °C in July. Maize (12%) and alfalfa (14%) areas will shift outside normal summer maximum TR, while TR for cotton nearly doubles by midcentury. FC production is already limited by temperature impacts on yield potential in the SW USA. The historic range for maize and cotton already suffers yield reductions of 18 and 26%, respectively, as compared with yield potential. We expect further reduced yields by midcentury compared to historic yields, such as a 15.4% yield reduction in cotton in its current locations. Relatively lower yield reductions in maize are anticipated as it covers a greater spatial extent and thus broader temperature conditions. Decision-making to adapt to climate change must integrate vulnerability of total regional crop acreage and its composition to future temperatures. This work demonstrates that viable locations where these FC might be established under future TR are presently occupied by high value specialty crops and other land uses, suggesting that the SW region will continue to grapple with the tensions among agriculture, conservation, and other land management goals and reflecting the situations encountered in many global regions as resources become impacted in our changing climate.

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