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To cite this article: Julian J Reyes and Emile Elias 2019 *Environ. Res. Lett.* **14** 074017

IOP Publishing Environ. Res. Lett. 14 (2019) 074017 https://doi.org/10.1088/1748-9326/ab1ac9

Environmental Research Letters

OPEN ACCESS

RECEIVED
14 September 2018

REVISED
16 April 2019

ACCEPTED FOR PUBLICATION
18 April 2019

PUBLISHED
12 July 2019

LETTER

Spatio-temporal variation of crop loss in the United States from 2001 to 2016

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Keywords: crop insurance, agriculture, drought, extreme weather, climate change, vulnerability, adaptation

Supplementary material for this article is available online

Abstract

Crop insurance loss data can illuminate variations in agricultural impacts from exposure to weather and climate-driven events, and can improve our understanding of agricultural vulnerabilities. Here we perform a retrospective analysis of weather and climate-driven reasons for crop loss (i.e. cause of loss) obtained from the Risk Management Agency of the United States Department of Agriculture. The federal crop insurance program has insured over $440 billion in liabilities representing farmers' crops from 2001 to 2016. Specifically, we examine the top ten weather and climate-driven causes of loss from 2001 to 2016 across the nation comprising at least 83% of total indemnities (i.e. insurance payouts provided to farmers after crop loss events). First, we analyzed the relative fraction of indemnities by causes of loss, over different spatial and temporal resolutions. We found that drought and excess precipitation comprised the largest sources of crop loss across the nation. However, these causes varied strongly over space and time. We applied two additional normalization techniques to indemnities using (1) insurance premia and the gross domestic product implicit price deflator, and (2) liabilities to calculate the loss cost. We conducted trend analyses using the Mann–Kendall statistical test on loss cost over time. Differential trends and patterns in loss cost demonstrated the importance of spatio-temporal resolution in assessing causes of loss. The majority of monthly significant trends ($p < 0.05$) showed increasing loss cost (i.e. increasing indemnities or decreasing liabilities) in response to weather events. Finally, we briefly discuss an online portal (AgRisk Viewer) to make these data accessible at multiple spatial scales and sub-annual time steps to support both research and outreach efforts promoting adaptation and resilience in agricultural systems.

1. Introduction

Historically, US agriculture has been able to adapt to, or cope with, short-term changes in climate conditions (Hatfield *et al* 2014). However, future projected warming temperatures and shifts in rainfall could challenge existing crop and livestock production systems compounding pressures on already highly exposed systems (Walthall *et al* 2012, Hatfield *et al* 2014). Agricultural products and yields vary with differences in soil, climate, and management (Walthall *et al* 2012). US agricultural systems are adapted to localized environmental conditions; however, productivity and the environmental effects of agriculture are sensitive to both short-term weather 'shocks' and long-term climatic change (Oram 1989, Walthall *et al* 2012).

Direct effects on agriculture from climate change include shifts in precipitation magnitude, intensity, and frequency, as well as increasing temperatures (Walthall *et al* 2012, Hatfield *et al* 2014). Since rainfall is a major determinant of soil water availability, droughts can cause significant crop damage to non-irrigated production by inhibiting a plant's ability to cope with excess temperatures via evaporative cooling potential. In contrast, excessive moisture, more intense precipitation and hail, and flooding can directly and indirectly

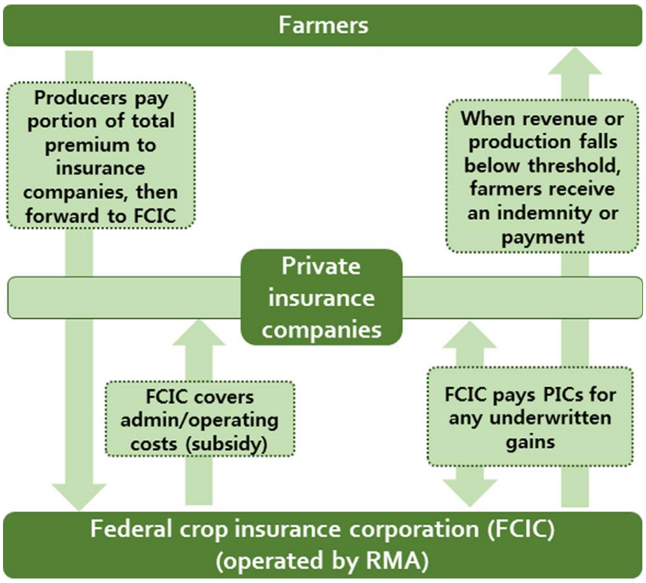

Figure 1. Simplified diagram of the structure and processes of the federal crop insurance program. Adapted from Shields (2015).

damage crops (Walthall *et al* 2012). Increased exposure of cropping systems to higher than normal temperatures and/or prolonged drought conditions can cause shifts in production regions and drive crop losses threatening food security (Schlenker and Roberts 2009, Hatfield *et al* 2014, Elias *et al* 2018a, Kistner *et al* 2018, Steele and Hatfield 2018, Steiner *et al* 2018).

Over $100 billion worth of crops was insured through the federal crop insurance program in 2016 alone (Rosa 2018). Crop insurance, among many risk management options (e.g. crop diversification, farming practices), plays an increasingly important role in producers' decision-making process (Walthall *et al* 2012) and has been used as a weather and climate risk management strategy (Cabrera *et al* 2006, Di Falco *et al* 2014, Annan and Schlenker 2015, Mase *et al* 2017). Historic crop loss data can be used to examine trends over time and assess impacts of past weather and climate-driven events on agricultural production (Changnon *et al* 2000, Rosenzweig *et al* 2002, Lobell *et al* 2011, Smith and Katz 2013, Smith and Matthews 2015, Rohli *et al* 2016). Understanding losses from weather extremes and climate-driven events provides a clear link to societal vulnerability and potential adaptation activities (Changnon *et al* 2000, Mechler and Bouwer 2015).

Here we seek to understand economic vulnerabilities in agricultural systems related to weather events and climate-driven impacts, and to support adaptation efforts via a comprehensive assessment of historic crop loss data. We perform a retrospective analysis of crop loss data, specifically indemnities or insurance payments, to assess causes of loss (COL) (e.g. drought, hail, excess precipitation) over space and time. Our objectives are to (1) illustrate spatio-temporal differences in COL, and (2) examine trends over time at various spatial and temporal resolutions. This analysis (1) increases our knowledge of historic vulnerabilities given indemnities by COL while also highlighting possible adaptation approaches at decision-relevant spatial and temporal scales (Steele and Hatfield 2018), and (2) expands accessibility and discoverability of crop insurance data, via effective visualizations to engage stakeholders and help communicate agricultural production risk (Sheppard 2005). This knowledge base supports data-driven decision-making with the goal of sustaining ecologically resilient and economically viable working lands.

2. Background

The US Department of Agriculture (USDA) Risk Management Agency (RMA) administers the federal crop insurance through the Federal Crop Insurance Corporation (FCIC). The program provides a financial safety net to farmers and ranchers to help mitigate against crop losses due to natural perils or declines in price (Shields 2015). Since 1938, the federal crop insurance program has been enhanced and expanded by Congress to include more crops, encourage greater participation, and increase government support of premia (Shields 2015). The program now covers about 130 crops and about 86% of crop acreage is insured nationally (Shields 2015, Rosa 2018).

There are three major players in the federal crop insurance program: farmers/producers, private insurance companies (PICs), and the FCIC (figure 1). Producers insure crops based on their liabilities, or maximum insured values for a crop representing 'the total insured risk value underwritten by policy' (Smith and Katz 2013). The types of insurance policies available to farmers are typically yield-based or revenue-based meaning either reductions in yield or price will be used as 'triggers' for insurance payouts. The insurance type

Table 1. Overview of normalization methods and characteristics of analyses. See supplementary materials section 4 for background, equations, and summary of each normalization technique.

Normalization technique	Analysis	Temporal resolution	Spatial resolution
Method 1: Relative fraction *Fraction of indemnities attributed to a particular COL for a time period*	Fraction of relative indemnities by COL	Aggregated between 2001–2016, and by *season* between 2001–2016	Nation
Method 2: Adjusted indemnities *Normalized indemnities adjusted for inflation, agricultural value of products, and insurance premia*	Time-series of relative indemnities by COL	Annual	Region
Method 3: Loss cost *Normalized indemnities using liabilities, or insured values*	Trends over time by COL	Annual Monthly	

(e.g. yield- or revenue-based) is not a prerequisite for reported reasons for crop loss whether they are economically-driven (e.g. declines in crop price) or due to natural perils (e.g. drought). In 2014 around 23% of insurance policies that earned a premium were yield-based, while 77% were revenue-based (Shields 2015). A variety of coverage levels exists, and the producer will pay a portion of the premium to the PICs. Importantly, the federal government subsidizes for ~62% of producers' premia (Shields 2015). Federal subsidies are not direct payments, but considered financial benefits to incentivize farmer participation in the crop insurance program. Statutory *premium subsidy rates* are set by Congress and are a certain percent of the policy premium depending on coverage level (i.e. expected yield to be insured; Congressional Budget Office 2017, Rosa 2018). However, *subsidies* change over time as they are a function of subsidy rates, but also crop prices, liabilities (i.e. value of what is insured), overall program participation, and chosen coverage level (Government Accountability Office 2015, Congressional Budget Office 2017).

When crops are damaged or lost due to insurable events or perils, producers receive an indemnity, or payment. These indemnities are based on the insureds' coverage level and liabilities, as well as specific program policies (e.g. irrigated crops; Risk Management Agency 2018). The reasons for crop loss, or COL, can be due to price declines or natural perils. The latter category includes weather and climate-driven COL such as drought, heat, failure of irrigation supply, hail, excess moisture/precipitation/rain, frost, freeze, cold winter, cold wet weather, flood, wind/excess wind, hot wind, tropical cyclones/hurricanes, tornadoes, insects, plant disease, and wildlife (Kistner *et al* 2018, Risk Management Agency 2018). While producers typically establish a specific COL, claims adjusters from either RMA or the PICs verify the COL through on-farm inspection and collection of weather conditions (Risk Management Agency 2018).

3. Material and methods

3.1. Data

We obtained crop insurance and loss data from 2001 to 2016 from the USDA RMA Summary of Business. This particular dataset contains indemnities, liabilities, premia, and associated COL information at the monthly time step at the county-level. Here we focus on biophysical or 'natural' COL, which comprise at least 88% of total indemnities and 76% of liabilities from 2001 to 2016 (supplementary table 1, available online at stacks.iop.org/ERL/14/074017/mmedia). Because we are interested in weather-related and climate-driven COL, we exclude 'price decline' as a COL and area-based COL since there is no explicit reasoning for crop loss. For consistent analysis across regions, we focus on the top ten biophysical COL over the Nation, which are also weather-related and climate-driven (supplementary table 1). Finally, we note that insured crops in the FCIC do not represent all farmers and/or all acreage, and that not all crops have experienced a loss.

We chose the 2001 to 2016 time period to (1) increase temporal resolution to monthly data for analysis, (2) utilize liability and premia data for normalization techniques, (3) ensure consistency of COL over time, and (4) minimize policy changes that substantially change the acreage covered under crop insurance (Shields 2015). Using pre-2001 data constrains our analysis by limiting normalization techniques and reducing temporal resolution for analysis, both of which are important for scientifically robust results. We acknowledge that 16 years of data may not be sufficient to evaluate long-term changes in crop loss and/or discuss *future* vulnerabilities. Additional information on time period selection is available in the supplementary material (see supplementary figures 1 and 2).

3.2. Data transformation

Crop loss data must first be normalized to provide suitable temporal comparison and for trend analysis (Changnon *et al* 2000, 2001, Changnon and Hewings 2001, Barthel and Neumayer 2012, Smith and Katz 2013). Normalization accounts for inter-annual changes in crop prices, RMA crop insurance program policies, and socio-economic conditions like population and employment (Changnon and Hewings 2001, Barthel and Neumayer 2012). Given our objectives, we provide three normalization methods to address temporal bias so that losses can be compared over time

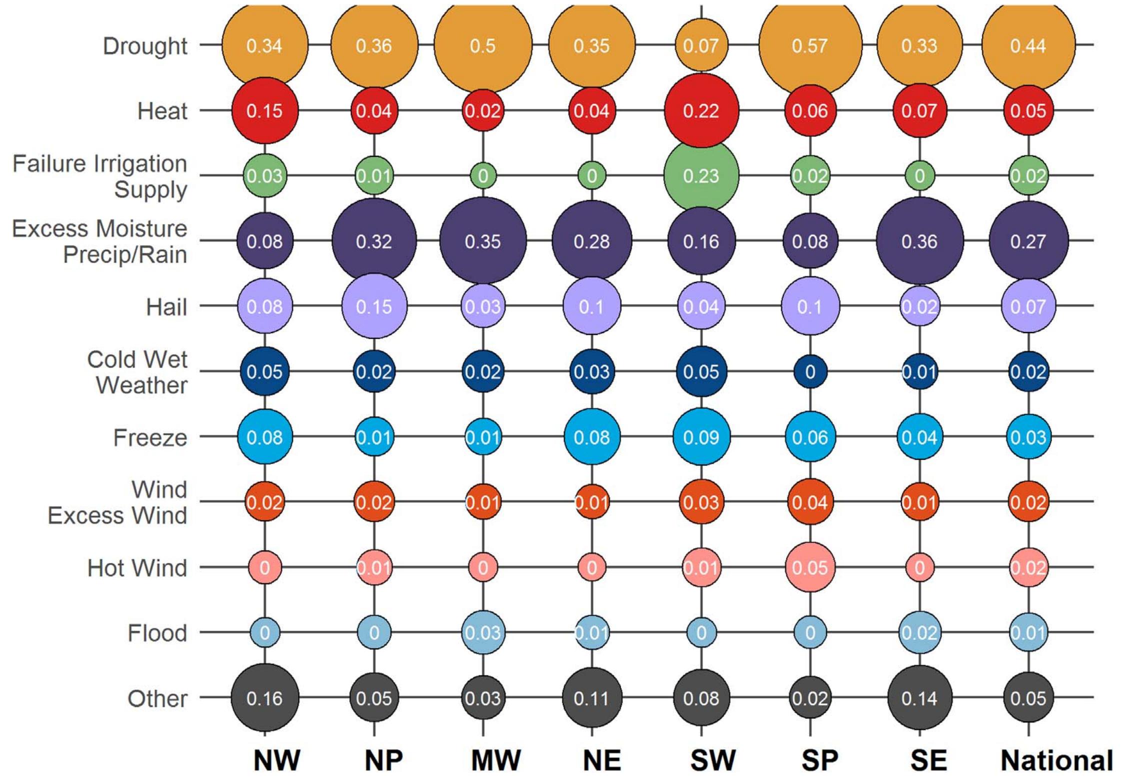

Figure 2. Relative fraction of aggregated absolute indemnities from 2001 to 2016 for the top ten causes of loss (COL) by Climate Hub region and across the nation. Increasing bubble size represents larger contribution of that reported COL out of total indemnities. Values of zero indicate fractional values less than 0.01 (or 1%). Regions are defined as Northwest (NW), Northern Plains (NP), Midwest (MW), Northeast (NE), Southwest (SW), Southern Plains (SP) and Southeast (SE). See supplementary figure 1 for states within each region.

(Gall *et al* 2009). Table 1 briefly describes these techniques with additional details and equations available in the supplementary material section 4.

3.3. Analysis

Table 1 provides a summary of the analyses performed in this study. We analyzed biophysical COL by different spatial aggregations (nation, region) and temporal resolutions (annual, month). For regional analysis, we aggregated COL data using the USDA Climate Hub regions (supplementary figure 1), which have been used in previous agricultural production risk studies (Elias *et al* 2018, Kistner *et al* 2018, Steiner *et al* 2018).

We examined trends in annual and monthly loss cost (Method 3, section 3.3; supplementary material section 4) over time using the Mann–Kendall (MK) test. The non-parametric MK test assesses whether values tend to increase or decrease, either linearly or nonlinearly, with time (i.e. monotonic change) (Helsel and Hirsch 2002). We apply MK using both annual and monthly loss cost values by COL and region. We determined significance (p-value < 0.05) for trends based off comparable p-values reported in the literature that used indemnities, liabilities, or loss cost (Changnon *et al* 2001, Barthel and Neumayer 2012, Smith and Katz 2013). We report trends with a standard deviation >0.

4. Results

4.1. Spatio-temporal analysis of COL

4.1.1. National and regional-scale losses

The top ten biophysical COL from 2001 to 2016 from largest to smallest relative fraction of aggregated indemnities (Method 1, table 1; supplementary material section 4) were: drought, excess moisture, hail, heat, freeze, cold wet weather (CWW), wind/excess wind, failure in irrigation supply (FIS), hot wind, and flood. The top two COL over the nation made up more than 70% of total biophysical-related indemnities from 2001 to 2016: drought (44%) and excess moisture (including precipitation and rain; 27%).

Aggregating indemnities at the regional-scale clearly depicts regional differences in relative fraction of each COL (figure 2). For most regions, the top COL are drought and excess moisture; however, the SW is markedly different from other regions in that FIS and heat are the top two regional COL. FIS comprises <3% of regional indemnities for the other regions. We note that those crops insured under a federal crop insurance irrigated policy, and later affected by a natural peril like drought, must report FIS as a COL even if the underlying cause is drought. This is a stipulation of those policies with an irrigated practice. While other perils like heat and hot wind normally do not occur under an irrigated practice, they may be appropriate COL given environmental conditions. Due to the policy stipulation on irrigated practices, we observe FIS as the leading COL in the SW rather than drought. However, it is important to note that drought is inextricably linked with the rise of FIS-related indemnities since by definition the former COL is defined as 'lack of water.' In addition, FIS is distinctly different from failure of irrigation equipment which is a structural deficiency is conveying water, rather than a natural deficiency of water such as in drought or FIS. Furthermore, an irrigated practice might also reduce the impact of other COL like heat compared to a non-irrigated practice.

Drought accounts for a larger proportion of indemnity payments in the SP than other regions, contributing ~57% of indemnities from 2001 to 2016. Excess moisture is the second ranking COL in the SP, but at ~8% this is less than the national average.

More than 10% of aggregated indemnities feature 'Other' COL indicating regionally-specific COL that are not reflected in the nationwide top ten COL (e.g. NW, NE, and SE). For example, the 16% of aggregated indemnities attributed to 'Other' for the NW represents mostly frost. In the SE, hurricanes and tropical depressions comprise the 'Other' COL category.

4.1.2. National and regional-scale losses—seasonal

Evaluating COL by region and month highlights localized weather and climate-driven events to crop production throughout the year (figure 3). While most regions have experienced drought and excess moisture as the top regional COL over the study time period, the timing of crop losses varies by region. Over the Nation, drought and excess moisture are still in the top three COL by season; however, their contributions to aggregated indemnities from 2001 to 2016 vary seasonally. Drought makes up more than half of indemnities during the summer months, while excess moisture makes up almost half of loss payments during spring months. Besides these two predominant COL, freeze is an important COL during spring and hail appears as a top three seasonal COL during summer.

Drought is responsible for at least half of seasonal indemnities during the summer (NP, MW, SP, SE), and is significant year-round in most regions except the SW and NE. Across regions excess moisture is generally more prevalent during the spring and fall while still appearing as a top three COL in the summer. Excess moisture comprises >50% of aggregated seasonal indemnities in the NP, MW, and SE during spring. Even in the SW, excess moisture is a top COL across all seasons. Specifically, excess moisture is the top COL during fall due to convective storm events related to the monsoon season, especially in the southernmost areas of the arid SW. Hail is most common as a top COL during the summer season in all regions except SW and SE. Heat is a top COL in all seasons for the SW and is occurs most often during the summer months. In addition to heat, FIS is another principal COL in the SW appearing as a top COL in the spring and summer. Freeze is common during winter and spring months, and comprises greater than a quarter of seasonal indemnities in the NE (spring), and SW and SE regions (winter).

4.1.3. National and regional-scale losses over time

Adjusted annual indemnities (Method 2, table 1; supplementary material section 4) depicted both inter-annual variability and regional differences in COL (figure 4). However, the top-ranking regional COL from 2001 to 2016 (figure 2) generally remained the predominant COL when viewed at a more granular time step (figure 4). While drought and excess moisture are realized in most regions, the relative proportion of a specific COL changes annually. The NE had the smallest range of adjusted annual indemnities and is grouped with NW and SW regions. The latter had large increases post-2013 adjusted indemnities attributed to FIS and heat. The NP, SP, and SE shared a similar adjusted indemnities range. NP and SP saw similar patterns in adjusted annual indemnities; however, the composition of annual COL was distinctly different. NP showed drought, excess moisture, and hail play large roles in annual crop losses, while SP displayed drought, hail, and hot wind as top COL. On average, the MW had the highest adjusted indemnities with a peak around \$4.5 billion in 2012. The 2012 drought accounted for more than \$4 billion in adjusted indemnities in the MW alone, a value that is 40 times that of normalized indemnities in the SW for 2012, and more than half of all reported COL and indemnities for that year. That same year, more than 75% of national normalized indemnities were due to drought with substantial amounts for the SP ($> 66\%$), NP ($>75\%$), and MW ($>90\%$). At the national scale, drought and excess moisture COL were present each year, but their relative contributions to regional indemnities fluctuated annually.

4.2. Spatio-temporal trend analysis by COL

Annual and monthly trends of loss cost (Method 3, table 1; supplementary material section 4) reflect changes in COL at the national (figure 5) and regional scale over time (figure 6). Statistical significance is associated with p-values < 0.05. Trends using a threshold of $p < 0.01$ are available in supplementary figures 5 and 6. Actual p-values for both nation and regional analysis are available in supplementary figures 7 and 8.

4.2.1. Annual

At the national scale there were no significant ($p < 0.05$) trends (figure 5). Of the 70 annual trends tested at the regional scale (figure 6), only six were significant with five increasing trends for hail (NW), heat (SE), freeze (SE), and FIS (NW, SP). The only

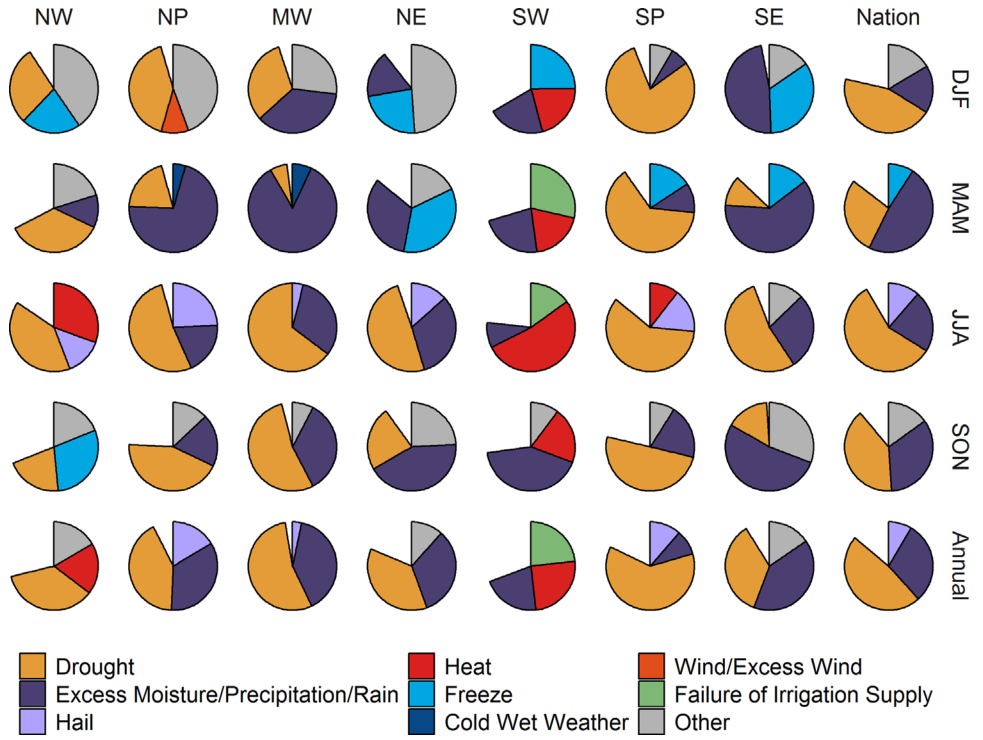

Figure 3. Relative fraction of top three causes of loss (COL) by season (DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November) and region. COL that comprise at least 10% of seasonal regional aggregated indemnities from 2001 to 2016 are shown here for the top ten nationwide losses. Gray slices indicate COL not in the top ten nationwide list but still comprise a significant portion of monthly regional COL. Empty slices indicate top ten COL that are <10% of seasonal regional aggregated indemnities. Hot wind and flood do not comprise >10% of seasonal indemnities or do not make the top three seasonal COL in a given region.

decreasing regional annual trends were excess moisture (NW) and flooding (NE). The SW and NP reported no significant annual trends.

4.2.2. Monthly

Nine monthly trends were significant across the nation with increased freeze, flood, and FIS (almost half of the monthly trends; figure 5). Of the 840 monthly loss cost trends analyzed by region (120 × 7 regions), 52 (~6%) were significant (figure 6). In the SW, monthly significant trends (6 of 120) reflected decreases in CWW (February, August) and hail (March) with increases in heat (November, December) and drought (March). While not significant ($p < 0.05$), we note consistent increasing monthly trends during spring and summer for drought, FIS, and heat COL during spring and early summer. Of the five significant monthly trends in the NW, those increasing typically occur in the summer and fall. The only decreasing monthly trend was in CWW in February; however, there is also an increasing monthly trend in loss cost for CWW in October. The NP contains seven significant monthly trends with consecutive decreasing trends of hail in the fall and increasing trends of drought and hail in the winter. FIS had a significant increase in May match the annual increasing trend for the SP. The MW features eight significant monthly trends with most increases occurring in the late winter and decreases occurring in the fall months. Consecutive monthly increases appear for freeze along with consecutive monthly decreasing trends for hail in the MW. All four monthly trends in the NE show increasing loss cost. Non-significant but important trends with large absolute Tau values occur for hail, flood, and excess moisture. Two-thirds of significant monthly trends in the SE occur during summer and fall months with mostly increases. The SE features the largest number of significant monthly loss cost trends (15 of 120) with consecutive increases in excess moisture (July–November). Of the 15 significant trends, only one shows decreasing monthly trends for CWW.

5. Discussion

5.1. Spatio-temporal resolution matters

Crop insurance data can be aggregated by varying spatio-temporal resolutions, and de-coupled by different COL (figures 2–4). The relative contribution of COL changes over time as a function of weather and climate-driven events; however, those COL are not uniform spatially or temporally (figure 4). Annual indemnities showed marked increases over time for the nation from 1980 to 2011 for the top three crops; however, these trends disappeared when using liabilities to calculate annual loss cost (Smith and Katz 2013). In contrast, our results show trends exist

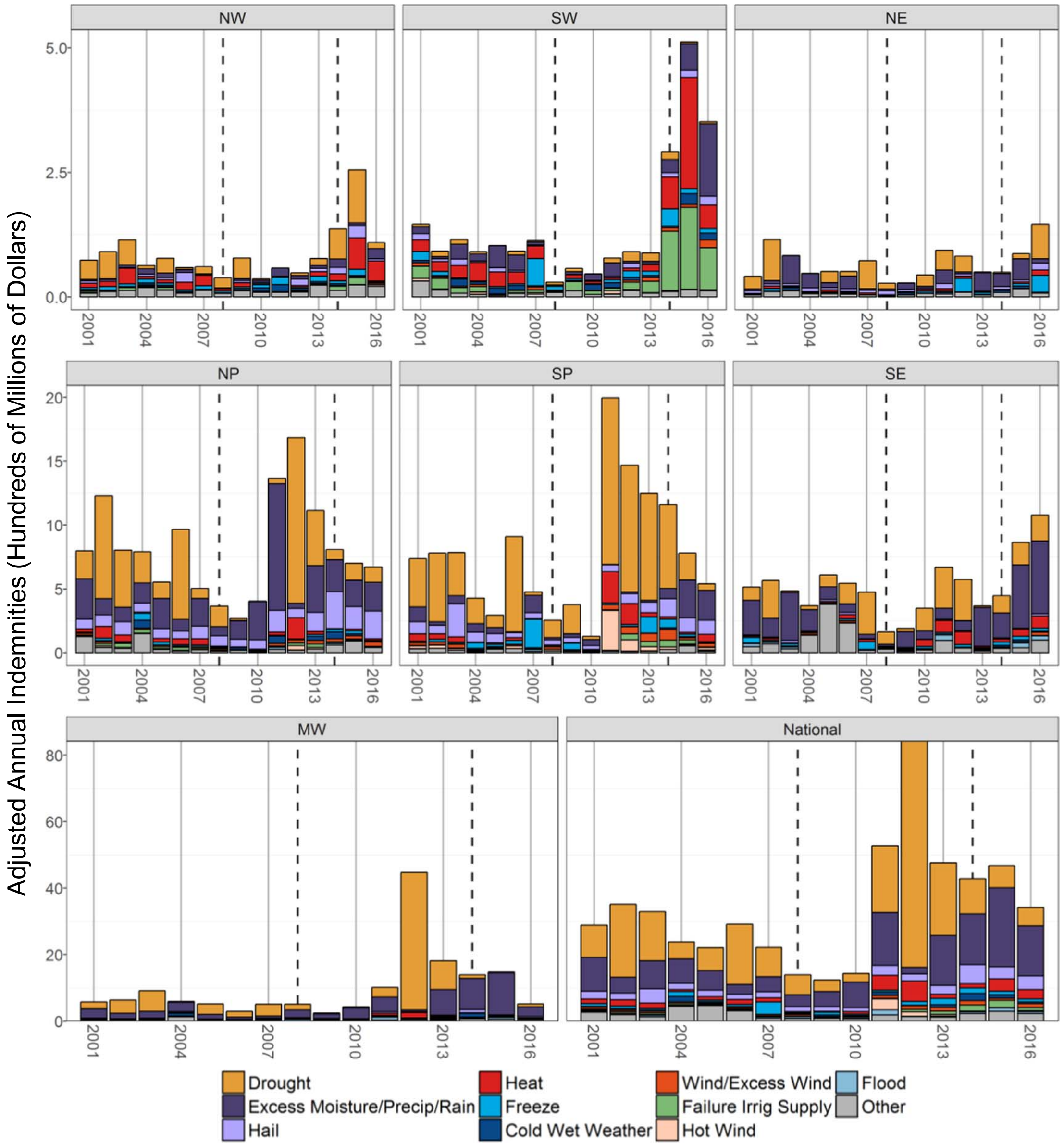

Figure 4. Adjusted annual indemnities (Method 2, section 3.3; supplementary material section 4) accounting for inflation, product output, and premia from 2001 to 2016 for the nation and USDA Climate Hub Regions by causes of loss. Regions are generally organized by similar adjusted annual indemnities. Dashed black lines indicate major policy changes affecting crop insurance including the Food, Conservation, and Energy Act of 2008 (i.e. '2008 Farm Bill'), and the Agricultural Act of 2014 (i.e. '2014 Farm Bill').

from 2001 to 2016 but are highly dependent on the COL and spatio-temporal resolution of aggregation (figures 5 and 6). For example, increasing loss cost trends mostly occur in the summer months for the SE, while show up in the winter months for the MW (figure 6). FIS shows increasing trends in the summer months for the SW, while excess moisture shows increasing trends in the fall months for the SE. Multi-scale complexities of both biophysical (e.g. crop physiologies, soil textures) and socio-economic (e.g. policies, incentives, institutions) conditions require varying methodologies and spatio-temporal scales to analyze system-wide impacts from weather and climate-driven events (Elias *et al* 2018a, Steele *et al* 2018).

Differential trends in loss cost further substantiate the importance of spatio-temporal resolution (figures 5 and 6), and suggest more complex and nuanced analysis is necessary when using crop loss data in climate impact or agricultural research. In general, there are time-varying patterns of major COL related to water scarcity (e.g. drought) and water abundance (e.g. excess moisture) that exist regionally, but differ in relative contribution to overall indemnities (figures 2 and 4). Alternating hot/dry and cold/wet COL is evident in aggregated seasonal COL by region (figure 3). Moreover, monthly trend analyses show potential seasonal shifts such as in the NW with increasing CWW trends early autumn followed by decreasing CWW trends during the late winter (figure 6). Monthly trends (significant and non-significant) that vary by Climate Hub region also corroborate spatial scale as an important factor in climate

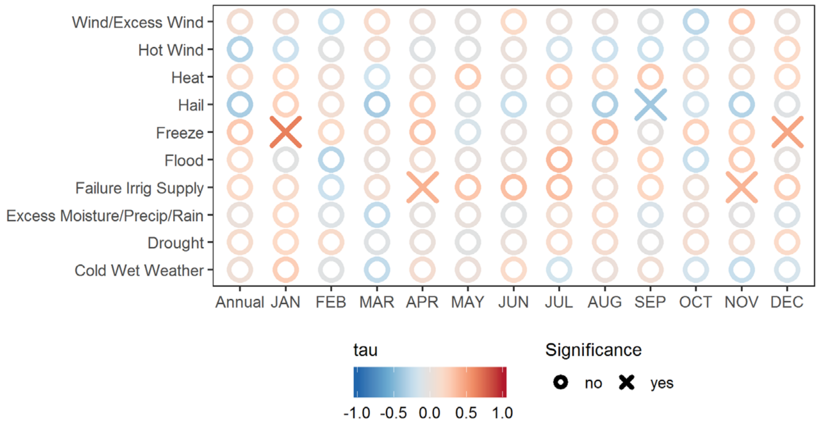

Figure 5. Annual and monthly Mann–Kendall trends of loss cost by cause of loss over the nation. Significance is associated with p-values less than 0.05 for the Mann–Kendall test. Tau values represent strength of the monotonic trend with more positive values (red) indicate increasing trends in loss cost, and more negative values (blue) indicating decreasing trends.

impact studies in the agricultural sector (Barrow and Semenov 1995, Mearns *et al* 2001, Moss *et al* 2010). By resolving data at the regional scale, we find that FIS is the top COL in the SW rather than drought because of the large amount of irrigated cropland, which is a function of the underlying dry conditions, management decisions to cultivate crops in this semi-arid region, and program policies of the FCIC (Elias *et al* 2018a, Risk Management Agency 2018). Since Climate Hub regions exhibit fairly similar crop production and practices across their component states, future research could consider natural geographic units including Major Land Resources Areas or ecoregions, which have also been applied in agricultural settings (Antle and Capalbo 2001, Ricketts and Imhoff 2003).

Policies (e.g. Farm Bills of 2008, 2014) affect patterns and trends of indemnities due to changes in commodity coverage, and types of insurance, all of which will impact insurance participation rate and total payout (Congressional Budget Office 2017, Rosa 2018). First, we sought to minimize the effects of policies by starting our analysis after the 2000 ARMA act, which was the last time legislation increased statutory premium subsidy rates (Rosa 2018). Second, we also reduced impacts of on-farm management activities by aggregating at the county-level, an operational scale used by extension specialists, crop advisors, and farmers. Third, we normalized indemnities by liabilities to control for changes in commodity prices allowing us to conduct inter-annual comparisons. Our results provide larger-scale patterns by aggregating data at the regional to national level subsequently limiting the influence of a single producer's management decision, of which data would be difficult to match with the COL data due to privacy issues.

5.2. Regional-scale vulnerabilities

We found differential impacts of COL by region and season using a sub-nation footprint (e.g. Chiang *et al* 2018) showing increased vulnerabilities to crop losses by weather and climate-driven events (figure 3). Consistently increasing and significant monthly trends in excess moisture in the SE correspond to an intensification of the hydrologic cycle in the region (figure 6), and indicate continued crop losses due to water abundance (Carter *et al* 2018). In the SP region, the fraction of aggregated indemnities for hail is larger than excess moisture indicating the intensity of precipitation rather than sheer amount is important in this area. The SP reported both monthly increases and decreases loss cost due to hail likely minimizing annual trends, but still remaining an important COL affecting high value, hail-sensitive specialty crops in the area (Steiner *et al* 2018).

Water often drives agricultural production patterns given that drought (44%) and excess moisture (27%) represent the highest indemnities nationally (figure 2). In addition, the increasing monthly trends for drought and FIS over multiple regions (SP, SW) with semi-arid to arid climates reflect increasing crop loss due to lack of water (figures 5 and 6). For example, increasing trends during the late spring and early summer months in the SW for drought, heat and FIS (figure 6) correspond with prolonged and hotter droughts in the region, warmer temperatures, and increasing water scarcity in the SW (Cayan *et al* 2010, Cook *et al* 2015). These have negative impacts on agriculture since most of the crops in the SW are irrigated. Significant monthly trends of FIS pinpoint months of observed or projected water stress and/or particular counties/crops which may be most vulnerable. Specifically, FIS as a top COL in the SW reflects the water scarcity in this region, on-going historic drought, and potential for future crop declines due to lack of water from underlying causes like drought and heat (Elias *et al* 2018b).

Increasing rainfall during the growing season has been observed over the past 30 years, and has had a significant impact on agriculture in the MW (Angel *et al* 2018, Kistner *et al* 2018). Mostly weak and decreasing

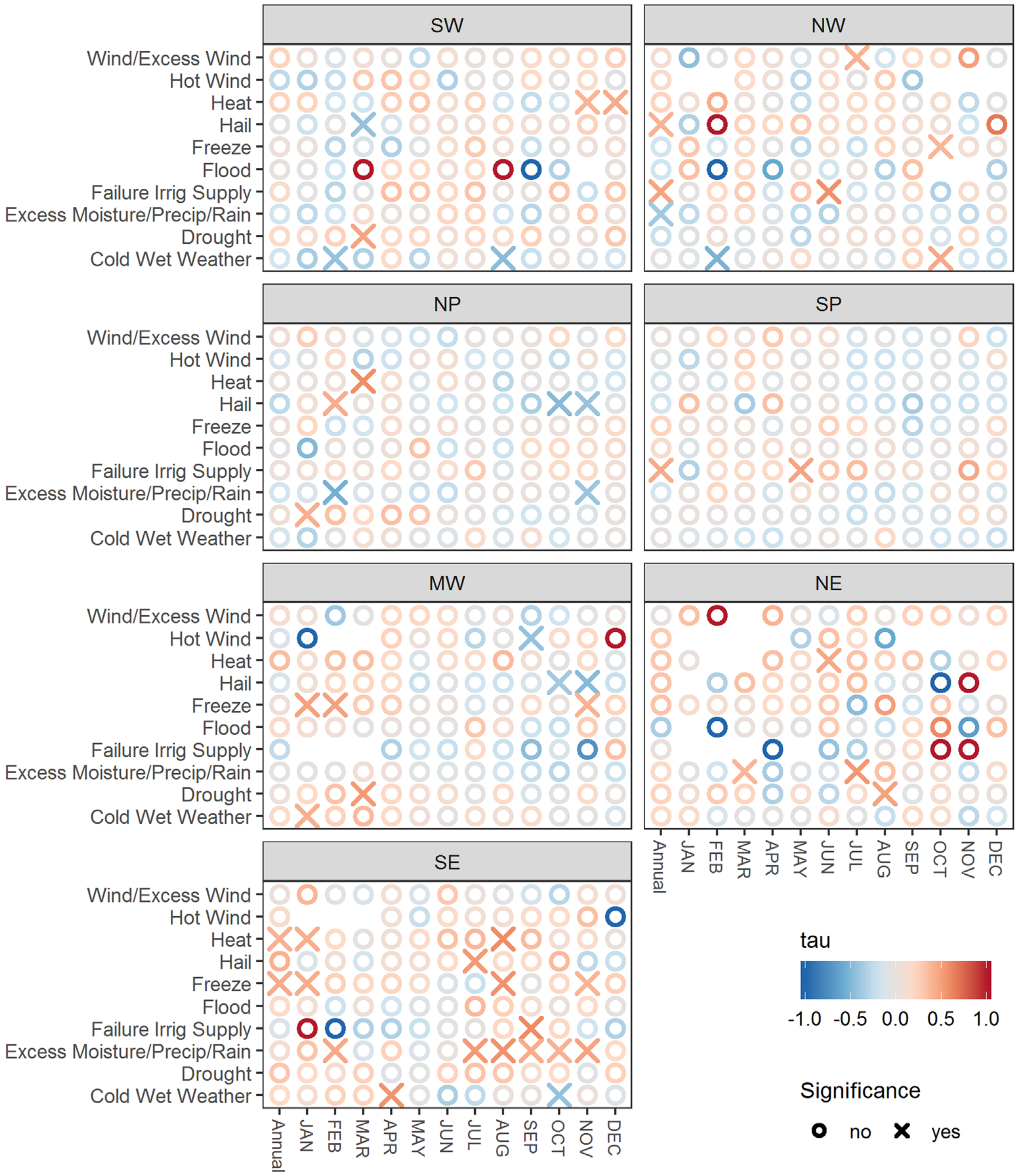

Figure 6. Annual and monthly Mann–Kendall trends of loss cost by cause of loss (COL) by USDA Climate Hub Region. Significance is associated with p-values less than 0.05 for the Mann–Kendall test. Tau values represent strength of the monotonic trend with more positive values (red) indicate increasing trends in loss cost, and more negative values (blue) indicating decreasing trends. Blank entries represent COL that were non-existent for that region-month combination, or lack of data points for any apparent trends (standard deviation >0).

loss cost trends in excess moisture signal rising indemnities and stabilizing liabilities (supplementary figure 4), and indicate crop insurance being used as an adaptation tool against excess precipitation (figure 6). A mix of weak increases and decreases in loss cost for drought suggests fewer large-scale crop losses, and supports an overall trend in reduced exceptional drought in the MW (Mishra *et al* 2010). Increases in monthly trends for CWW, freeze, and heat during winter months reflect large-scale swings in hot/dry and wet/cold COL impacts on crops in the MW (figure 6; Mishra *et al* 2010). The regional timing of such COL modulation is in line with expected future impacts of increasing winter/spring precipitation and warmer temperatures (Angel *et al* 2018).

Warming temperatures and declining snowpack in the NW may be reflected in the significant increasing annual trend of FIS (May *et al* 2018; figure 6). Given that NW agriculture is dependent on irrigation in low precipitation areas, increasing loss cost trends indicate that FIS (i.e. lack of water) is a constraint for additional agricultural production. In contrast, a significant decreasing annual trend for excess moisture for the NW may simply indicate low rainfall amounts as a less significant COL versus FIS. Most likely increases in loss cost related to FIS may show increasing indemnities rather than changes in liabilities. It is important to note that decreasing trends in loss cost could signify decreasing or similar indemnities with increasing liabilities over time. In these cases, producers may be hedging against COL like excess moisture and CWW with higher premia paid for insurance given past events, even if indemnities remain similar or less over time.

5.3. Risk management implications

We acknowledge the difficulty of using 16 years of either annual or monthly data to identify long-term trends. Longer time periods increase the power and rigor of trend analyses such as MK, but we were unable to obtain monthly COL data with both liabilities and indemnities (to calculate loss cost) prior to 2001 (see section 3.1). Even with 16 years of data, farmers and ranchers may find historic patterns of crop loss valuable especially for more operational (this year), tactical (5 years), and strategic (10 years) decision-making time frames (Brown *et al* 2017). Moreover, there is value in assessing contemporary trends (<20 years data) of crop loss data in order to evaluate weather impacts on agricultural production (e.g. Lobell *et al* 2011, Barthel and Neumayer 2012, Kistner *et al* 2018, Wolfe *et al* 2018). Nonetheless, our results show that crop loss is important in providing a broader view of agricultural vulnerability from both a biophysical and socio-economic perspective (Rosenzweig *et al* 2002, O'Brien *et al* 2007, Elias *et al* 2018a, Steele *et al* 2018).

Farmers and ranchers still rely heavily on near-term memory and recent experiences rather than long-term changes in historic loss (or future climatic projections) for decision making (Marx *et al* 2007, Coles and Scott 2009, Steele *et al* 2018). Therefore, patterns in cumulative indemnities by COL over time (2001–2016; figure 2), or by season (figure 3) may inform producers on (1) additional risk management strategies based on frequently occurring natural perils, or (2) on-farm adaptation strategies to adapt to decreasing, increasing, or similar types of weather-induced losses given their level of risk tolerance (e.g. Kistner *et al* 2018, Steele *et al* 2018). Even among agricultural advisors or extension professionals who work closely with farmers, perceived weather variability is positively correlated with crop loss, while perceptions for adaptation and future farmers' needs are consistently correlated with weather variability perceptions (Niles *et al* 2019). Therefore, more recent and significant crop losses and their associated COL may be most salient to farmers in influencing management changes (Niles *et al* 2019). Using this knowledge, producers may elect to reduce their risk by shifting production systems, increasing crop insurance coverage, changing varieties of crops (e.g. drought-tolerant or heat-adapted), and/or management.

Areas with consistently high indemnities or increasing loss cost trends indicate high production risk areas, and may inform planning and adaptation options (Government Accountability Office 2015). In such locations, higher costs represent higher production risk from various COL (e.g. drought), and programs and policies may not cover actual losses through premia (Government Accountability Office 2015). For example, warming temperatures were found to decrease yield, increase yield risk, and increase premiums and subsidies resulting in larger government costs and taxpayer burden (Tack *et al* 2018). Our results do not focus on future changes; however, annual or monthly trends in heat as a COL may suggest areas (e.g. NE and SW regions; figure 6) of higher risk due to historic heat losses. These areas may also highlight where farmers participate in 'riskier' practices or more environmentally-detrimental activities (Woodard and Marlow 2017).

Crop insurance may provide disincentives (i.e. moral hazard) for adapting to future climatic conditions if federally-subsidized premia is economically advantageous versus structural or management changes (McLeman and Smit 2006; Annan and Schlenker 2015, Mase *et al* 2017, Tack *et al* 2018). However, the financial stability of crop insurance may also provide opportunities for farmers to make long-term investments to adapt to changing agronomic conditions (Mieno *et al* 2018). While we focus on explicitly-reported COL ('indemnity insurance with physical inspection', Vroege *et al* 2019), there are opportunities for multi-scale loss assessment including weather-index and/or area-yield insurance types using remotely-sensed data (Vroege *et al* 2019). Satellite data of phenology can be used to improve index-based insurance program implementation and reduce asymmetric information problems (e.g. density of weather station in a given space or proximity to weather station; Dalhaus *et al* 2018, Vroege *et al* 2019). These advances may help address the spatio-temporal challenges in assessing agricultural losses as we have identified through differential trends in COL by region and season.

We find the value chain of 'big data' to be relevant in this study, and offers a framework for our research during the data exploitation stage: analyze, visualize, and make decisions (Miller and Mork 2013). Visualization of historic crop loss data and assessment of trends prompts consideration of decision-making processes (e.g. crop selection, management, insurance participation, acreage insured) in vulnerability assessments (e.g. Steele *et al* 2018). Moreover, these past crop losses due to specific weather-induced events provides producers multiple decision time frames for determining their financial risk management tools, crop insurance coverage, and other management factors (Brown *et al* 2017, Kistner *et al* 2018). Because of this, we also developed a web portal to enable easy access, viewing, and on-the-fly analysis of RMA COL data (AgRisk Viewer;

https://swclimatehub.info/rma/). These data can be used to understand county-level crop impacts over time, anticipate future weather-related pressures, and conceive scale-appropriate adaptation solutions (Elias *et al* 2018b). This tool supports an understanding of which crops have been most impacted by specific weather and climate-driven events for targeted climate adaptation and thoughtful planning to sustainably build resilient agriculture. Static representations of USDA RMA data on the web may not enable farmers and ranchers to enhance their decision making with crop loss data (Government Accountability Office 2015); however, as shown here, data transformation, analytics, and visualization (e.g. AgRisk Viewer) can provide meaningful interpretation to producers in management operations and financial risk assessment.

6. Conclusions

Crop insurance is an important risk management strategy for producers during weather and climate-driven events such as hail and drought. Historical data on indemnities and COL can offer insights on both the biophysical and socio-economic vulnerabilities of agricultural systems. Given the economic importance of both water scarcity and abundance at the national scale, efforts should be prioritized to address the challenges of drought and excess precipitation, especially on crop-related losses, now and into the future. Spatio-temporal resolution matters when analyzing these data and considering vulnerabilities, such as finding the importance of FIS in the SW. While crop insurance can mitigate the impacts of weather and climate on producers, food provisioning and security require crop production in suitable environments, which can be informed by crop loss analyses at varying scales.

Acknowledgments

This work is a contribution of the United States Department of Agriculture (USDA) Southwest Climate Hub. Manuscript development was supported by USDA, Agricultural Research Service, Jornada Experimental Range (CRIS Project # 3050-11210-24 007D). Thanks to Danielle Shannon (Northern Forests Climate Hub) for providing the National Climate Hub map. We thank Jeb Williamson for his creative development of the AgRisk Viewer and continued engagement with the Southwest Climate Hub team. We thank Andrew Eischens and Mark Shilts for their feedback on the RMA data. We also thank Caiti Steele, Rachel Steele, and Brandon Bestelmeyer for constructive feedback and review on this manuscript.

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