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Assessing agricultural risk management using historic crop insurance loss data over the Ogallala Aquifer

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Assessing agricultural risk management using historic crop insurance loss data over the ogallala aquifer

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ABSTRACT

Much of the agricultural production in the Ogallala Aquifer region relies on groundwater for irrigation. In addition to declining water levels, weather and climate-driven events affect crop yields and revenues. Crop insurance serves as a risk management tool to mitigate these perils. Here, we seek to understand what long-term crop insurance loss data can tell us about agricultural risk management in the Ogallala. We assess patterns and trends in crop insurance loss data from the U.S. Department of Agriculture Risk Management Agency. Indemnities, or insurance payments, totaled \$22 billion from 1989–2017 for the 161 counties that overlie the Ogallala Aquifer. We focused on the top ten weather and climate-driven causes of crop loss for the Ogallala, which comprised at least 92% of total indemnities. Drought, hail, and heat were the leading causes of crop loss for the region, and varied over space and time. For example, drought is a significant cause of loss across all seasons, while hail is more prevalent in the spring and summer. Spatially heterogeneous patterns emerged showing larger hail indemnities in the northern Ogallala versus larger drought indemnities in the southern portion. We performed a Mann-Kendall trend analysis of county-level annual loss cost values (the ratio of indemnities to liabilities). Drought and excess moisture showed significant increasing loss cost trends in the western counties of the Ogallala. In contrast, hail showed significant decreasing trends in the northern and eastern portions. These results suggest the northern counties of the Ogallala may perceive hail as a greater risk, and may be better equipped to handle drought losses as compared with the southern Ogallala. Crop insurance loss data play a role in integrating long-term trends with near-term management practices, and providing relevant risk information in producers' operational to tactical decision making processes.

1. Introduction

Irrigation for agricultural production makes up 80% of the United States' water consumption nationwide (Economic Research Service (ERS), 2019). While farms with irrigation only represent 14% of all farm operations, irrigated agriculture contributes over \$152 billion in farm sales to the U.S. economy annually (Economic Research Service (ERS), 2019). Groundwater is a significant source of irrigation, comprising 60% of all sources (Siebert et al., 2010). As the largest aquifer in the U.S., the Ogallala Aquifer underlies more than 450,000 km^2 of the Great Plains with more than 90% of aquifer's water extracted for agricultural purposes (Brauer et al., 2017), supplying water to more than \$35 billion in crops annually (Basso et al., 2013). The Ogallala Aquifer is the lifeblood for this highly productive agricultural region, providing food and fiber security, as well as individual and community livelihoods.

Water availability underpins both the biophysical and economic productivity of major commodity crops in the Ogallala Aquifer region (Cotterman et al., 2018; Araya et al., 2019). Continued use of the Ogallala Aquifer coupled with declining water tables has negatively impacted agricultural production, especially in those areas that are largely reliant on groundwater for irrigation (Foster et al., 2015; Scanlon et al., 2012; Cotterman et al., 2018). Declining water levels and well capacities, decreasing saturated thickness, and negative changes in recoverable water storage have been observed; these hydrologic changes threaten agricultural production and local economies (Foster

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et al., 2015; Steward and Allen, 2016; McGuire, 2017). Moreover, groundwater storage has seen increased rates of depletion in the last 30 years (Scanlon et al., 2012). In the Central High Plains, current groundwater management practices are projected to force a reduction in irrigated corn acreage by 60% and irrigated wheat acreage by half in the next fifty years (Cotterman et al., 2018).

Irrigation management practices and climate-driven events such as drought drive water levels in the Ogallala Aquifer (Haacker et al., 2019). Specifically, increasing drying in the region concomitant with more frequent and intense drought will likely exacerbate diminished agricultural production and aquifer drawdown during water-limited times (Steiner et al., 2017; Haacker et al., 2019). Climate change is expected to result in a net decrease in overall recharge into the Ogallala Aquifer despite differing recharge amounts among the northern, central, and southern High Plains areas (Meixner et al., 2016).

Crop insurance is an important risk management tool used by producers to mitigate negative impacts of crop price declines and weather- and climate-related events. However, federal crop insurance may pose a barrier to water conservation or adaptation - even under declining water levels - due to existing federal irrigation policies (Basso et al., 2013; Deryugina and Konar, 2017). Assessments of historic weather and climate-driven agricultural losses, especially insurance payments, offer producers valuable insight that can be factored into their risk management decisions (Reyes and Elias, 2019). Specifically, changes in causes of crop loss (e.g., drought, hail) over time and space can inform possible risk management strategies for frequent or recurring events, or adaptation strategies based on producers' risk tolerance (e.g., Kistner et al., 2018; Steele et al., 2018; Reyes and Elias, 2019). For example, large indemnities for tart cherries in Utah due to frost and freeze require producers to have access to increasing capital assets given continued production despite large losses (Steele et al., 2018). In southern New Mexico, pecan producers may show lower tolerance to weather events since those with crop insurance may have access to groundwater, and thus report other types of losses unrelated to irrigation supply (Steele et al., 2018). Given the increasing frequency and severity of drought (Cook et al., 2015), and decreasing water availability in the Ogallala Aquifer region, retrospective analyses of crop losses may inform producers' decision making and risk management strategies. Climate change is also expected to increase federally-subsidized insurance premiums and program costs by up to 22%, even with some concurrent adaptation (Crane-Droesch et al., 2019).

Here, we seek to understand what long-term crop insurance loss data can tell us about agricultural risk management in the Ogallala Aquifer region. Our overarching objective is to assess patterns and trends in causes of loss over space and time for the Ogallala Aquifer region to provide agricultural risk management information that is useful to regional agricultural decision makers. First, we visualize regional-scale indemnities, or insurance payments, through time by cause of loss. Second, we aggregate county-level indemnities by state and cause of loss. We also examine causes of loss by month, and top crops at the region and state-levels. Finally, we compare county-level aquifer characteristics with crop loss information, including statistical trend analyses.

Given the importance of agricultural production in this region and declining water levels of the aquifer, historic trends and patterns in crop loss (1) informs risk management decisions and planning related to crop insurance at multiple administrative scales - federal, state, and local, (2) indicates high risk production areas, and (3) strengthens our understanding of the contextual vulnerability of agricultural systems. In using crop insurance as a proxy for agricultural impact from weather and climate-driven causes of loss, this work showcases linkages between biophysical and socio-economic vulnerabilities in agricultural systems (Wallander et al., 2013), and highlights the usefulness of long-term historic trends for informing near-term operational management decision (Brown et al., 2017).

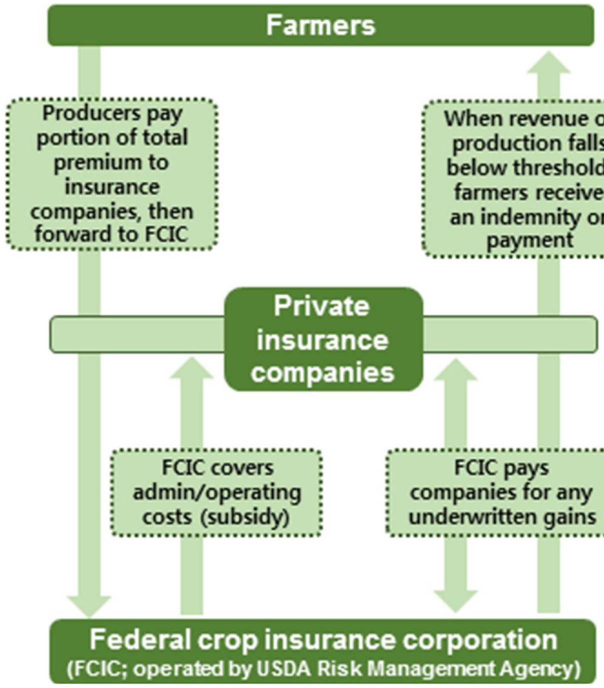

Fig. 1. Overview of the federal crop insurance program. Adapted from Shields (2015) and Reyes and Elias (2019).

2. Crop insurance background

The federal crop insurance program provides a financial safety net to farmers, ranchers, and landowners (Fig. 1). The U.S. Department of Agriculture's Risk Management Agency (RMA) administers the program, offering multiple insurance plans and coverage to mitigate both revenue and yield losses (Shields, 2015). On average, the federal government pays 62% of producers' insurance premium, thereby subsidizing much of their crop insurance (Shields, 2015). The federal government acts as a reinsurer to private companies that offer policies with varying coverage to producers (Fig. 1). During large-scale losses due to drought, for example, the federal government covers private companies' losses (i.e., reinsurance). Since 2000, the number of acres enrolled in federal crop insurance has ranged between 290 and 300 million acres, covering nearly 90% of the 340 million acres of total cultivated acres in the U.S. (Congressional Budget Office (CBO), 2017). Corn, cotton, soybeans, and wheat generally account for over 70% of acres enrolled in crop insurance (Shields, 2015).

Federal crop insurance is available on a "crop-by-crop and county-by-county" basis depending on a variety of factors including risk and producer demand (Shields, 2015). This unit structure can be described in three ways: (1) a basic unit covering land in a single county with a specific tenant/landlord, (2) an optional unit that is a basic unit divided into smaller units using township sections, and (3) an enterprise unit which covers "all land for a single crop in a county for a producer, regardless of tenant/landlord structure" (Shields, 2015). There are three basic types of insurance policies: yield-based, revenue-based, and index-based. Insured crops that experience damage caused by either (1) weather or climate-driven events (e.g., drought, hail), or (2) financial/market disruptions, subsequently trigger insurance payouts given certain thresholds. A producer receives an indemnity, or insurance payment, if their yield or revenue falls below historical or "normal" levels. For example, a $4-10$ year average of a producers' annual crop yield may be used to determine production history and thus thresholds for insurance payouts (Shields, 2015). Index-based loss takes into account the whole farm revenue or area-based yields independent of individual farmers' yields (Shields, 2015). These plans typically use indices of precipitation or vegetation trigger points for payments.

Since 1989, major pieces of legislation that have affected federal crop insurance – programs, processes, and policies – include the Agricultural Risk Protection Act (ARPA; 2000) and Farm Bills (e.g., 1996, 2002, 2008, 2014). Premium subsidies have been increased through legislation four times since 1994 (Congressional Budget Office (CBO), 2018). ARPA allowed RMA to use data mining to review existing policies for anomalous claims (Government Accountability Office (GAO), 2015). Index-based losses began in 2007 as RMA piloted various programs such as the Pasture, Rangeland, and Forage (PRF) program (Motamed et al., 2018). Here we note that our study does not include PRF losses since no explicit cause of crop loss is reported.

3. Methods

3.1. Study area

The High Plains Aquifer, referred to in this paper as the Ogallala Aquifer (its popular name, which is based on the predominant sediment group), is one of the world's largest aquifers spanning an area of over 455,000 km^2 (175,000 mi^2) in the Great Plains of the United States (Qi, 2010) while also underlying a major agricultural production region (McGuire, 2017). Groundwater from the Ogallala supplies almost one-third of all irrigation in the United States, and 98% of water from the Ogallala is used for irrigation (Dennehy et al., 2002). In this study, we include counties with at least 25% of their respective area within the Ogallala Aquifer boundary ($n = 161$) to capture as many counties with agricultural production that may derive water from the Ogallala Aquifer (Fig. 2; Qi, 2010; Haacker et al., 2019). The majority of the selected counties have reported an annual saturated thickness value of at least 9 m sometime between 1989–2017, indicating areas that have the potential to yield sufficient water for irrigation (McGuire, 2017; Haacker et al., 2019), although not all areas with sufficient aquifer saturated thickness are used for irrigated agriculture. However, we note that there are places with abundant water and low irrigation – including the Sand Hills area; Lea County, New Mexico; and the Rosebud Reservation in South Dakota – where factors such as local regulation, soil quality, and non-agricultural land use limit irrigation. Additionally, we acknowledge that although previous research has shown that at least 9 m of saturated thickness is an indicator of the aquifer's ability to provide enough water for irrigation given predominant hydraulic conductivity in the High Plains (Hecox et al., 2002), other factors may influence well yields and the capacity for wells in areas of sufficient saturated thickness to effectively irrigate crops.

3.2. Data

3.2.1. Crop loss data

We obtained crop insurance loss data from the U.S. Department of Agriculture Risk Management Agency (RMA). These contain information on the cause of crop loss (e.g., drought, hail, etc.), crop affected, amount paid to the producer (indemnity), value of the crops insured (liability), and insurance premium. The spatio-temporal resolution of the data are at county-level and monthly time step. The time period of analysis is from 1989–2017.

We primarily focus on weather and climate-driven causes of loss since they have a biophysical meaning for crop damage, and are explicitly reported as such (Reyes and Elias, 2019). We are interested in biophysical manifestations of environmental impacts and require an explicit cause for crop loss, and thus exclude revenue- and index-based insurance in our analyses. We include most major commodities; however, these data do not necessarily represent all agricultural production, but rather those insured under federal crop insurance and which have experienced losses. Moreover, we do not distinguish between irrigated and non-irrigated acreage for different causes of loss; however, specific RMA policies for irrigated land with losses are reported as such (i.e., "failure of irrigation supply"). While there are programmatic and policy changes that influence long-term trend analysis, we minimize these by calculating annual county-level loss cost (see Section 3.3; Reyes and Elias, 2019). The scope of this study is on retrospective analyses of crop insurance loss data, rather than forecasting indemnities. Drawbacks to such forecasts linking indemnities with environmental conditions include predicting future management decisions, use of probabilistic climate forecasts, and uncertain policy changes (Carriquiry and Osgood, 2012).

3.2.2. Aquifer characteristics and water use data

We obtained water table elevation and saturated thickness data for the Ogallala Aquifer. These were calculated as mean values by county according to Haacker et al. (2016). Irrigation water use data were aggregated from 1990 to 2015 from the U.S. Geological Survey, which has collected county-level water use data every five years across multiple sectors (Dieter et al., 2017). We calculated the change in total irrigation water use between 1990 and 2015 since this time period best matches the range of the crop loss data (1989–2017).

3.3. Data analysis

We follow the methods of Reyes and Elias (2019) to present and transform data for visualization and analysis. The *relative fraction* of indemnities is the relative contribution of different causes of loss to overall indemnities. It is determined by dividing nominal indemnities for a specific cause of loss and dividing by the total indemnities for a given time period (e.g., 1989–2017) and spatial aggregation unit (e.g., county). The relative fraction of indemnities by cause of loss is also calculated for the top crops in the region, and for each month.

We use the *loss cost* to examine how indemnities have changed over time, and also note that we do not explicitly evaluate how crop prices change over time and how those changes affect decision making related to crop choice or purchasing crop insurance. Loss cost is calculated as $\left(\frac{indemnities}{liabilities}\right) \times \$100$ for the appropriate spatio-temporal resolution and cause of loss (e.g., drought, hail, etc.), and is expressed in dollars. To assess trends over time for indemnities, it is necessary to normalize losses (e.g., Changnon and Hewings, 2001; Smith and Katz, 2013; Reyes and Elias, 2019). Loss cost accounts for inter-annual changes in specific commodity prices, RMA program policies, and various socio-economic conditions (Changnon and Hewings, 2001; Barthel and Neumayer, 2012). Moreover, loss cost integrates across these socio-economic and management conditions since we aggregate data at the monthly and annual time scale, and use the loss cost for trend analyses rather than nominal indemnities (e.g., Smith and Katz, 2013; Reyes and Elias, 2019). Finally, loss cost has been used extensively when examining crop insurance loss data including actuarial assessments of the RMA program (e.g., Knight and Coble, 1999; Woodard et al., 2011), trends of hail losses over time (e.g., Chagnon and Changnon, 1990, 1997), and regional trend analyses of causes of crop losses (e.g., Reyes and Elias, 2019).

Previous studies have used loss cost to analyze annual trends over time (e.g., Reyes and Elias, 2019). We use the Mann-Kendall statistical test (Helsel and Hirsch, 2002) to assess monotonic trends on annual loss cost values. The test is non-parametric and indicates whether values tend to increase or decrease, either linearly or nonlinearly, with time (i.e., monotonic change; Helsel and Hirsch, 2002). Loss cost is appropriate for time-series analysis because it accounts for current year value of crops insured (Reyes and Elias, 2019). We perform the Mann-Kendall test on county-level annual loss cost values from 1989–2017 for the top ten biophysical causes of loss for the Ogallala Aquifer region (see Section 3.2). The Mann-Kendall Tau represents strength and direction of monotonic trend (-1 for very negative trends, 1 for very positive trends). We report Tau values having a standard deviation greater than zero, and having at least nine years of values from 1989–2017 (e.g.,

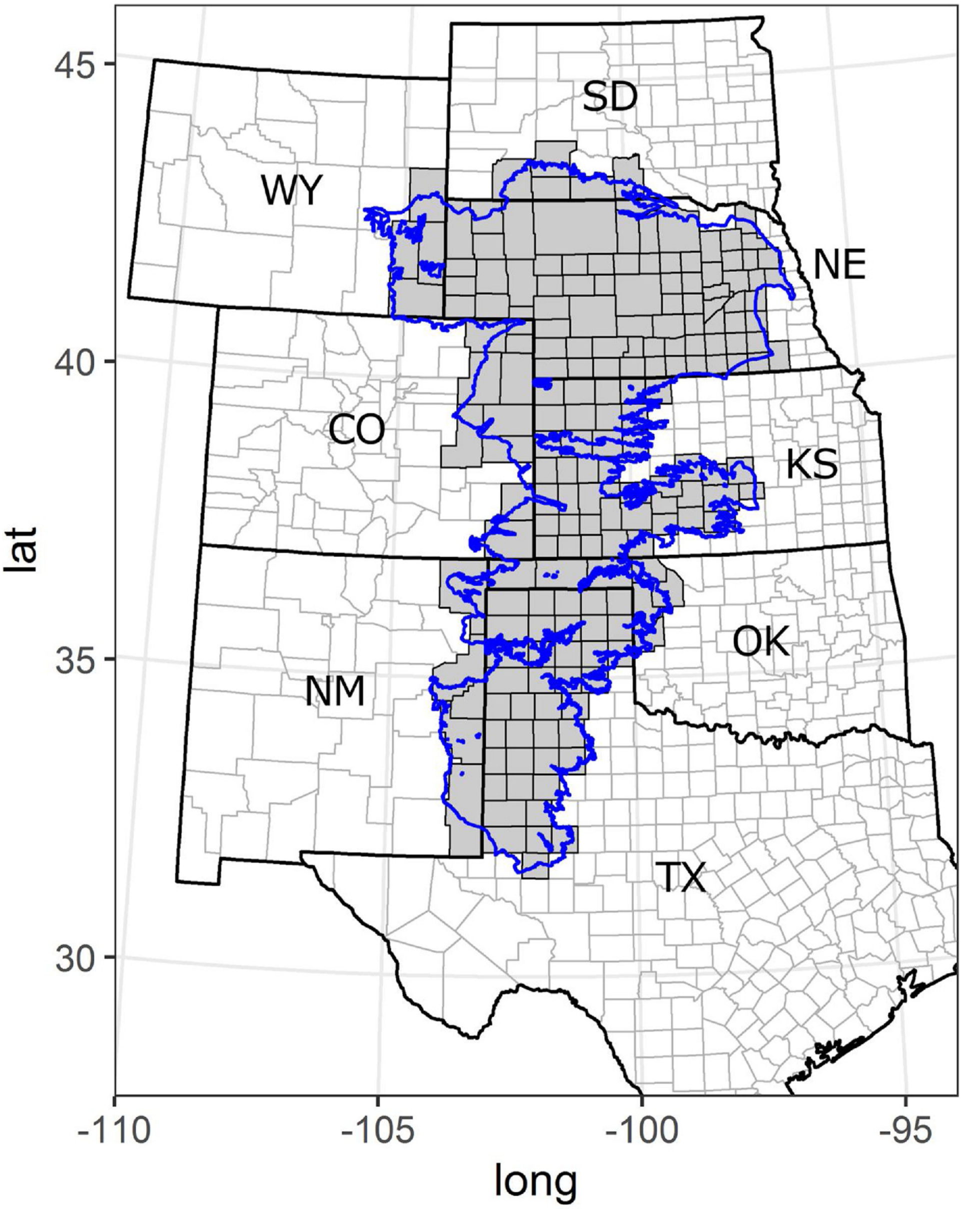

Fig. 2. Ogallala Aquifer region and constituent states. The boundary of the Ogallala Aquifer is delineated (blue) and overlaid with counties (gray) comprising at least 25% of their respective area within the aquifer boundary. These counties are used for subsequent analyses in this paper. The eight states with portions in the Ogallala aquifer are: Wyoming, Colorado, South Dakota, Nebraska, Kansas, Oklahoma, New Mexico, and Texas. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

Reyes and Elias, 2019). Significant county-level loss cost trends are based on a p-value threshold of 0.05 following Reyes and Elias (2019).

4. Results

4.1. Crop losses through time

Total indemnities for the top ten weather and climate-driven causes of crop loss in the region were $20.47 billion from 1989–2017. Annual indemnities and liabilities typically feature drought, hail, and heat as top causes (Fig. 3). The top cause of loss in a given year alternates between drought and hail. However, indemnities and liabilities post-1999 have larger proportions of crop loss due to drought than pre-1999 losses. Drought comprises more than half of indemnities and liabilities in 2002, 2003, and 2005. More recently, there was a threefold increase in indemnities and almost 8-fold increase in liabilities from 2011 to 2013 compared to any other year. Between 2011–2013 drought was the primary contribution to both indemnities and liabilities; however, between 2014 and 2017, hail has generally been on par or greater than drought with respect to relative fraction of annual indemnities and liabilities.

Over time, most major causes of loss in the Ogallala display consistent annual loss cost with slight variations due to weather and climate-driven events (Fig. 3). Most notable is a steady increase in lost cost due to failure in irrigation supply except for 2011, which also saw decreases in loss cost across other causes. Decreases in loss cost are due to either (1) decreasing indemnities relative to liabilities, or (2) increasing liabilities relative to indemnities. We also note that drought is considered a “lack of water” causing dry conditions that decrease soil moisture and thus plant water uptake. Crop losses due to drought are distinguished from those irrigated crops that do not receive sufficient water, which are losses reported as *failure of irrigation supply*. Failure of irrigation supply refers to the lack of physical water availability and contrasts with failure of irrigation equipment which corresponds to

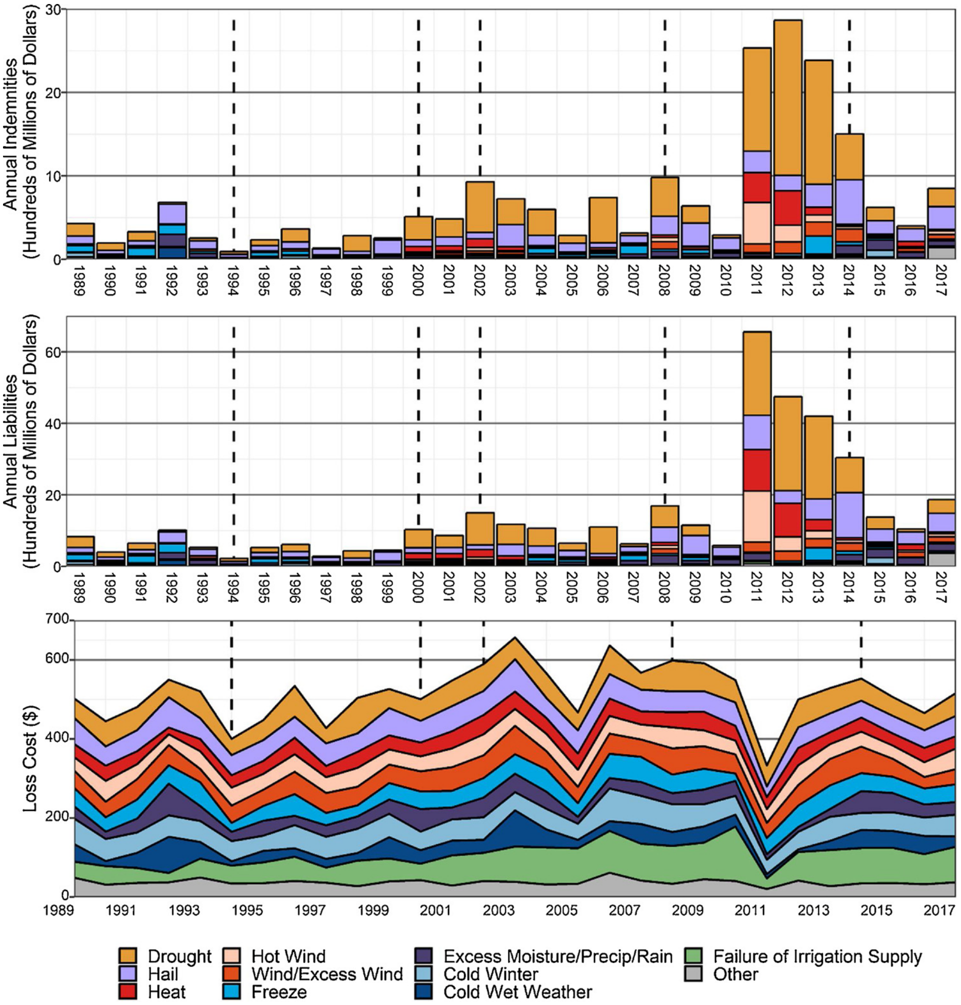

Fig. 3. Annual values for nominal indemnities, nominal liabilities, and loss cost by top causes of loss for the Ogallala Aquifer region. Loss cost is defined as indemnities divided by liabilities multiplied by $100. Nominal values provide a sense of how loss cost is calculated. Stacked bars for indemnities and liabilities show the individual contribution of each cause of loss relative to overall annual damages. Vertical dashed lines represent major policy changes via Congressional bills that have significantly affected crop insurance programs (as described in Section 2). Note scale differences for indemnities and liabilities.

crop losses due to irrigation hardware, efficiency, and conveyance losses.

4.2. Causes of loss by region and state

4.2.1. By region and state

The top ten causes of loss aggregated over all counties in the Ogallala Aquifer region from 1989–2017 were: drought, hail, heat, hot wind, wind/excess wind, freeze, excess moisture/precipitation, cold winter, cold wet weather, and failure of irrigation supply (Fig. 4).

Drought and hail are the largest causes of loss over the Ogallala comprising 67% of all indemnities between 1989-2017. The remaining 8 of the top 10 causes of loss individually account for 7% or less of the total indemnities across the region. A state-by-state view highlights regional differences. For example, hail replaces drought at the leading cause of loss in Wyoming. Drought is a prominent cause of loss across the Ogallala Aquifer states, and makes up more than half of indemnities in South Dakota, Kansas, and Oklahoma. Hail is generally the second leading cause of loss across Ogallala-constituent states. Separately, wind and hot wind account for 5% of the total indemnities across the region. Wind/excess wind ranges from 2% in South Dakota and Kansas to 11% in Wyoming. For hot wind, South Dakota shows the lowest relative fraction (1%) while Texas features the largest percentage of indemnities due to this cause (9%). Cold-related causes of loss such as cold winter and freeze feature prominently in separate states such as in Wyoming (11% for freeze), South Dakota (11% for cold winter), and Oklahoma (9% for freeze). Failure of irrigation supply was a small portion of the total indemnities from 1989 to 2017 accounting for 1% of the total over the region, and 0-4% on a statewide basis.

4.2.2. By month

The top three monthly causes of loss reflect seasonal and spatial differences in agricultural vulnerabilities over the Ogallala region and constituent states (Fig. 5). Drought represents the largest annual cause of loss by indemnity across the Ogallala region, accounting for more than 50% of regional monthly indemnities except for the months of May, June, September, and October. Drought is a top three monthly cause of loss in all Ogallala states and months. In the warm-season months, drought makes up at least half of monthly indemnities in most states especially in April, June, July, and August. Throughout the cold-season months, drought is the leading monthly cause of loss especially for Kansas, Oklahoma, New Mexico, and Texas. Drought makes up greater than 75% of state-level indemnities in the month of December for Kansas and Oklahoma. In contrast, hail is generally prevalent during the warm-season months especially in June and July. Northern Ogallala states such as Wyoming, Colorado, and Nebraska show hail comprising over half of indemnities for the month of June. Only in Wyoming is hail a leading annual cause of loss. Hail is also a top three cause of loss in all

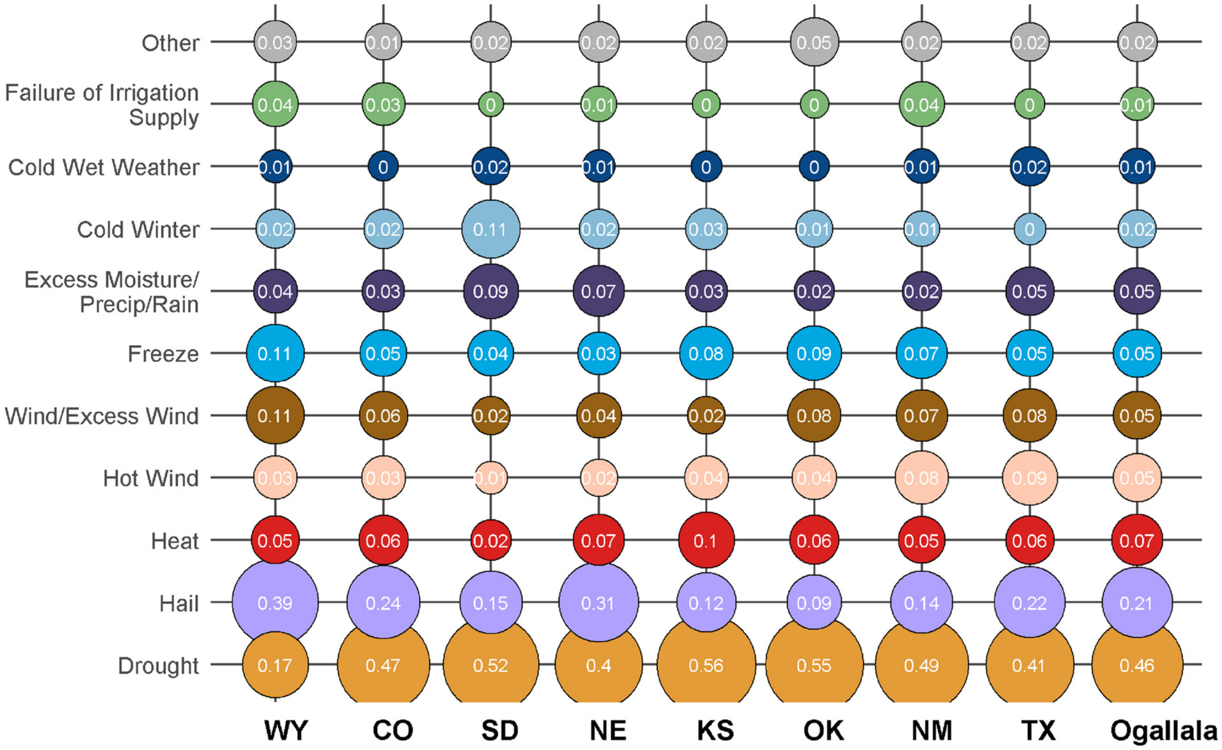

Fig. 4. Relative fraction of aggregated indemnities by top ten regional causes of loss from 1989–2017. Size of individual bubbles represent the contribution of specific causes of crop loss by state and for the Ogallala region. Index-based losses and price-related losses are excluded in this analysis.

Ogallala states during the month of June. We note that crop loss due to hail does not mean there is more hail during this time but that crops might be more at a more vulnerable stage.

Warm-season causes of loss, such as hail and heat, reflect crop growth cycles and seasonal vulnerabilities especially during the months of June, July, and August. Heat is a top cause of loss in July and August across the region, comprising a larger proportion of loss in Kansas, Texas, and Oklahoma. Hot wind appears a top three cause of monthly loss for the southern Ogallala states of Oklahoma, New Mexico, and Texas during the warm-season months. Wind/excess wind is a top three cause of loss across states during the cool-season months and April. Cold winter makes up over half of monthly aggregated indemnities especially in January and February for South Dakota and Nebraska, high-latitude states that grow winter wheat. In contrast, freeze is most prevalent as a top three monthly cause of loss during the shoulder seasons, or transitions from warm to cool seasons (April, September, and October).

We include frost and Mycotoxin because of their importance as a top monthly cause of loss despite these two causes not being in the top ten regional causes of loss (Fig. 4). Frost is only a top three monthly cause in Wyoming during September. Mycotoxin emerges as a top cause in isolated months and locations: October in Kansas, September/October in Oklahoma, and September in New Mexico.

4.2.3. By crop

The top three crops reporting losses and subsequent insurance payments between 1989–2017 for the Ogallala Aquifer were cotton, wheat, and corn (Fig. 6). These three crops comprised 82% of indemnities for the time period of analysis. In some states, the relative importance of various crops is significantly larger as compared to the Ogallala-wide relative fraction. Cotton makes up 29% of Ogallala-wide indemnities, but is more than twice the relative indemnities by crop for Texas (71%). Similarly, wheat comprises 27% of regional-scale indemnities, but is 2.7 times larger for state-level indemnities for Oklahoma (73%). Other states with larger relative fraction of indemnities for wheat compared to Ogallala-wide fraction include all states except Nebraska and Texas

Other crops important to the region include grain sorghum and soybeans. Some crops only report 1% or less of regional indemnities; however, their relative contribution to indemnities by state indicates their importance at that spatial unit. For example, while dry beans make up 1% of regional Ogallala indemnities, they make up 12% of aggregated indemnities for Wyoming, 2% for Colorado, and 3% for Nebraska. Similarly, sunflowers comprise 1% of regional indemnities yet 7% of state-indemnities for Wyoming. Peanuts make up 1% for the Ogallala, as well as 1% of state indemnities in New Mexico and Texas. Potatoes comprised 2% of aggregated indemnities in New Mexico.

4.3. Causes of loss by county

4.3.1. Crop loss and aquifer characteristics

There is a wide range of county-level indemnities (1989–2017) across the Ogallala Aquifer with some two orders of magnitude larger than the smallest amount (Fig. 7a). In general, indemnities increase from north to south with highest county indemnities in the southern Texas High Plains. The leading causes of crop loss at the county-level are mostly limited to drought and hail (Figs. 7b and c). Other top causes include heat, wind, excess moisture, and failure of irrigation supply (not shown). The largest percent of drought indemnities occur in central and southern areas of the Ogallala Aquifer region including the far eastern counties of the region (Fig. 7b). In contrast, the northern reaches of the Ogallala Aquifer region feature major portion of county indemnities as hail, especially in Nebraska and the Texas Llano Estacado (Fig. 7c).

Most changes in water table elevation between 1989 and 2016 are negative (Fig. 7d). Significant decreases in water table elevation are located in the central and southern portions of the Ogallala including southwest Kansas, the Oklahoma Panhandle, and the northern Texas Panhandle. The counties that have reported a mean saturated thickness value of 9 m or more (bolded county boundaries; Fig. 7d) indicate the

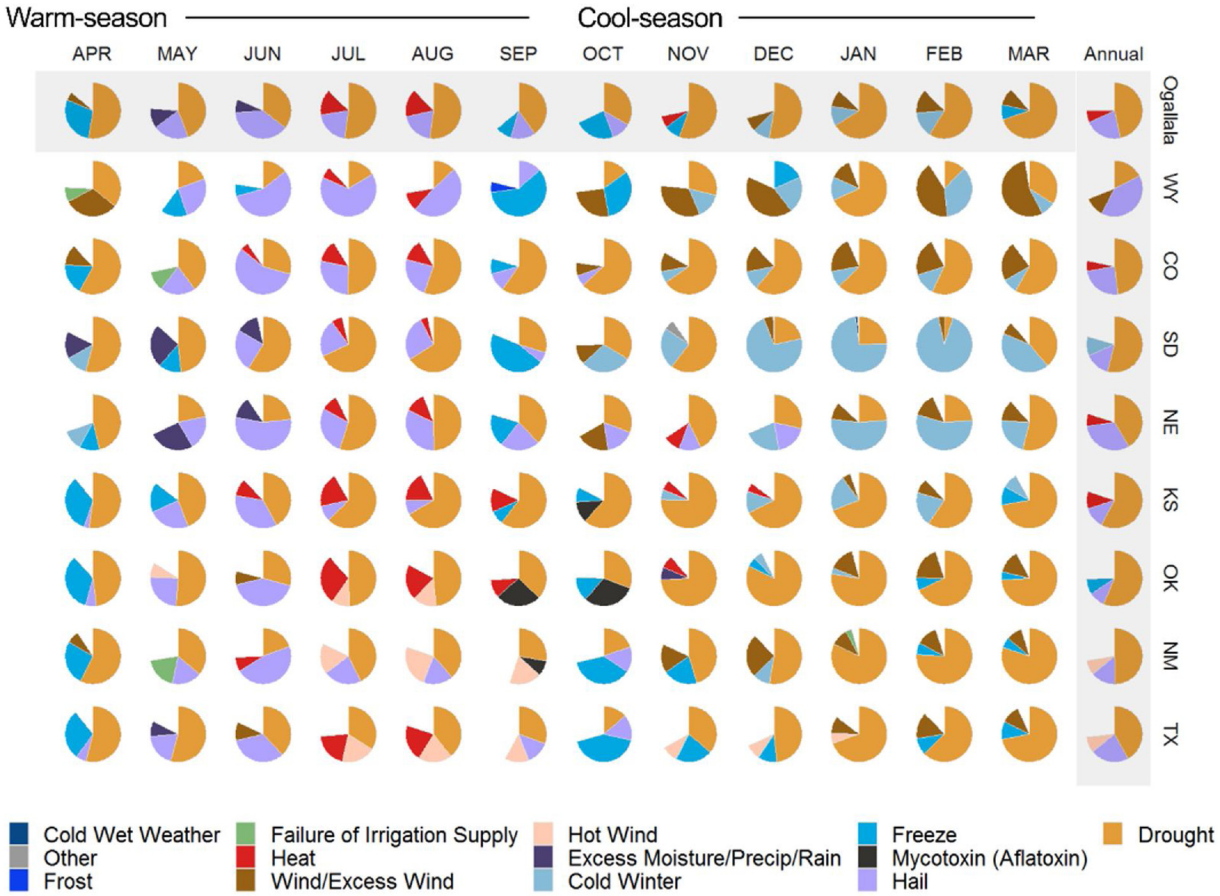

Fig. 5. Top three leading causes of loss for different time periods and regions using aggregated indemnities from 1989–2017. Columns show aggregated indemnities broken out by month from 1989–2017, and also for the entire time period ("Annual", right-most grayed column). Rows indicate indemnities aggregated by different states and the whole Ogallala Aquifer region ("Ogallala", top-most grayed row). The top right pie chart represents the top three leading causes of crop loss for the entire Ogallala Aquifer region from 1989–2017.

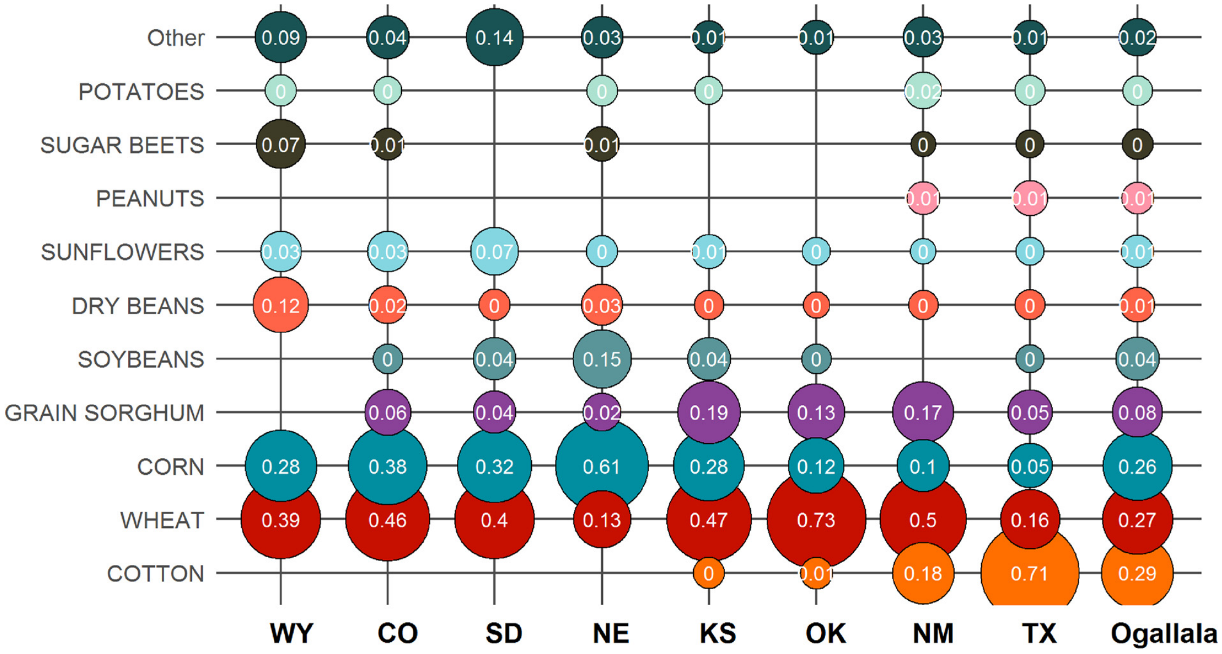

Fig. 6. Relative fraction of indemnities by crop from 1989–2017. Size of individual bubbles represents the relative contribution of crops by indemnities by state and for the Ogallala region. These data represent damage by most causes of loss excluding revenue-based and index-based losses.

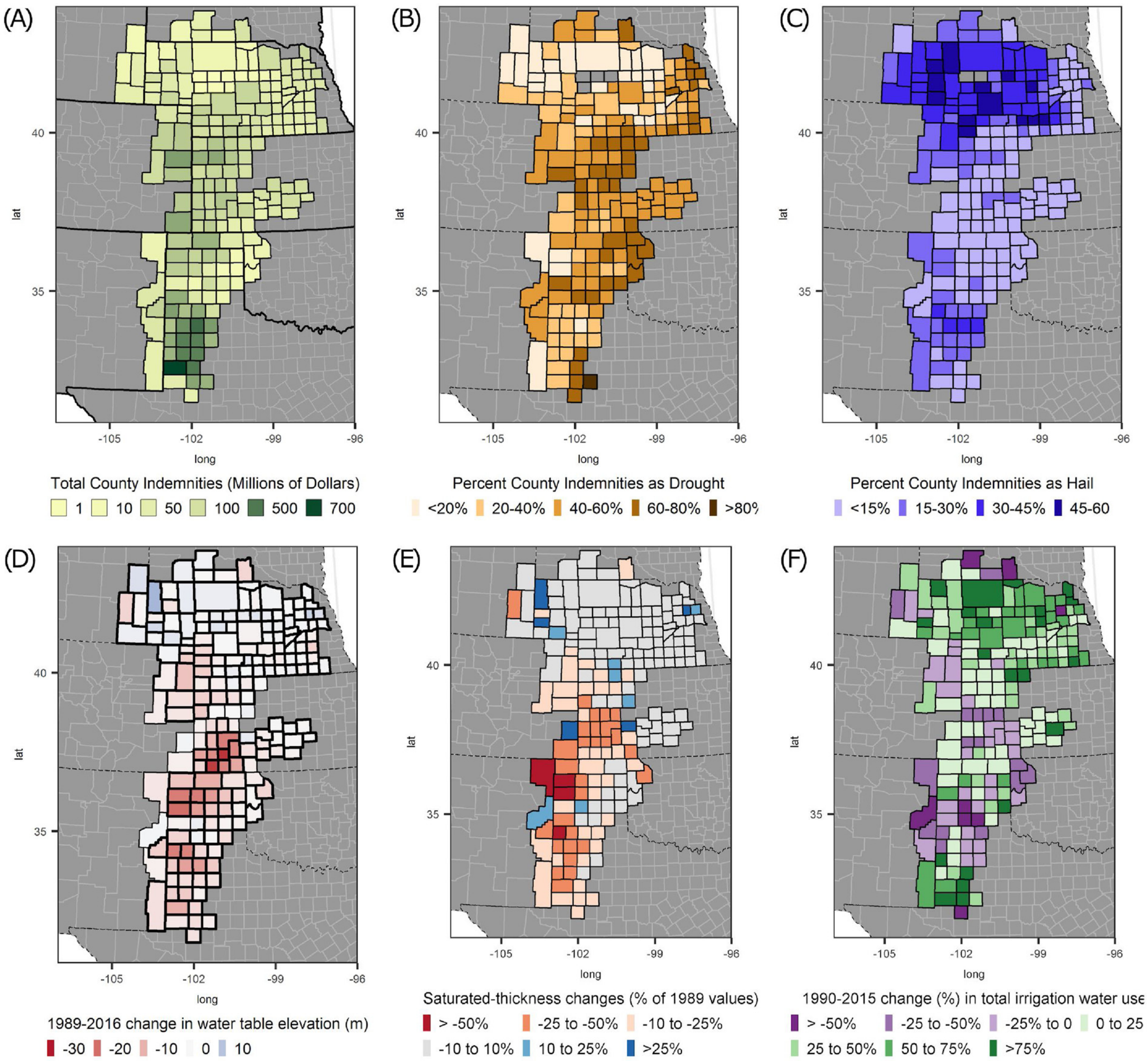

Fig. 7. County-level crop insurance losses, biophysical characteristics, and irrigation water use of the Ogallala Aquifer. Total county indemnities summed from 1989–2017 are presented (A) along with the proportion of crop loss attributed to drought (B) and hail (C). Biophysical data by county on the Ogallala Aquifer were calculated values using the data and procedures of Haacker et al. (2016). We show the change in water table elevation (meters) between 1989 and 2016 (D) and indicate counties with a saturated thickness value of 9 m for one year between 1989 and 2016. Saturated thickness changes between 2016 and 1989 (E; as a % of 1989 values) are shown. Change in total irrigation water use between 1990 and 2015 (F) is calculated from U.S. Geological Survey data.

potential to yield sufficient water for irrigation (see Section 3.1). These counties are mainly located in the central Ogallala (Colorado and Kansas), and eastern New Mexico. We also present changes in saturated thickness, a hydrogeological measure of vertical thickness of saturated materials (i.e., water-filled pores, and thus groundwater availability; Fig. 7e). As a percent of 1989 values, 2016 values show mainly saturated thickness decreases in the southern half of the Ogallala Aquifer: southwest Kansas, northeast New Mexico, and Texas. There are slight decreases in eastern Colorado and adjacent counties in northwestern Kansas. Total change in irrigation water shows a mix of both increases and decreases across the Ogallala Aquifer (Fig. 7f). However, the majority of increases occur in the northern reaches of the aquifer in Nebraska, and some portions of eastern Kansas and the Llano Estacado in Texas.

4.3.2. Trend analysis

4.3.2.1. Overview. We present county-level trends of annual loss cost values from 1989–2017 by the top ten causes of loss for the Ogallala (Fig. 8). In general, hot/dry causes (drought, heat, failure of irrigation supply, hot wind) show a greater number of significant increasing trends rather than decreasing trends across the Ogallala counties. Hail, cold winter, cold wet weather, and wind/excess wind show more significant decreasing trends than increasing ones. The greatest number of significant county-level trends occurs with hail (36) followed by excess moisture (29).

4.3.2.2. Hot/dry. The majority of county-level trends for *drought* show increasing loss cost values. Significant increasing trends of loss cost are located in the western portions of the region, while significant decreasing trends are located in the eastern portions of the Ogallala. There are also four times as many significant increasing trends (16) as there are decreasing ones (4). *Heat*, as compared to drought, shows more balance between significant increasing (10) and decreasing (9) trends. In general, significant increasing loss cost trends in heat are observed in the north and northwestern counties, and far southern (Texas) counties of the Ogallala, while significant decreasing trends are located throughout the Ogallala with a concentration in the eastern fringes of the region (eastern Nebraska and Kansas).

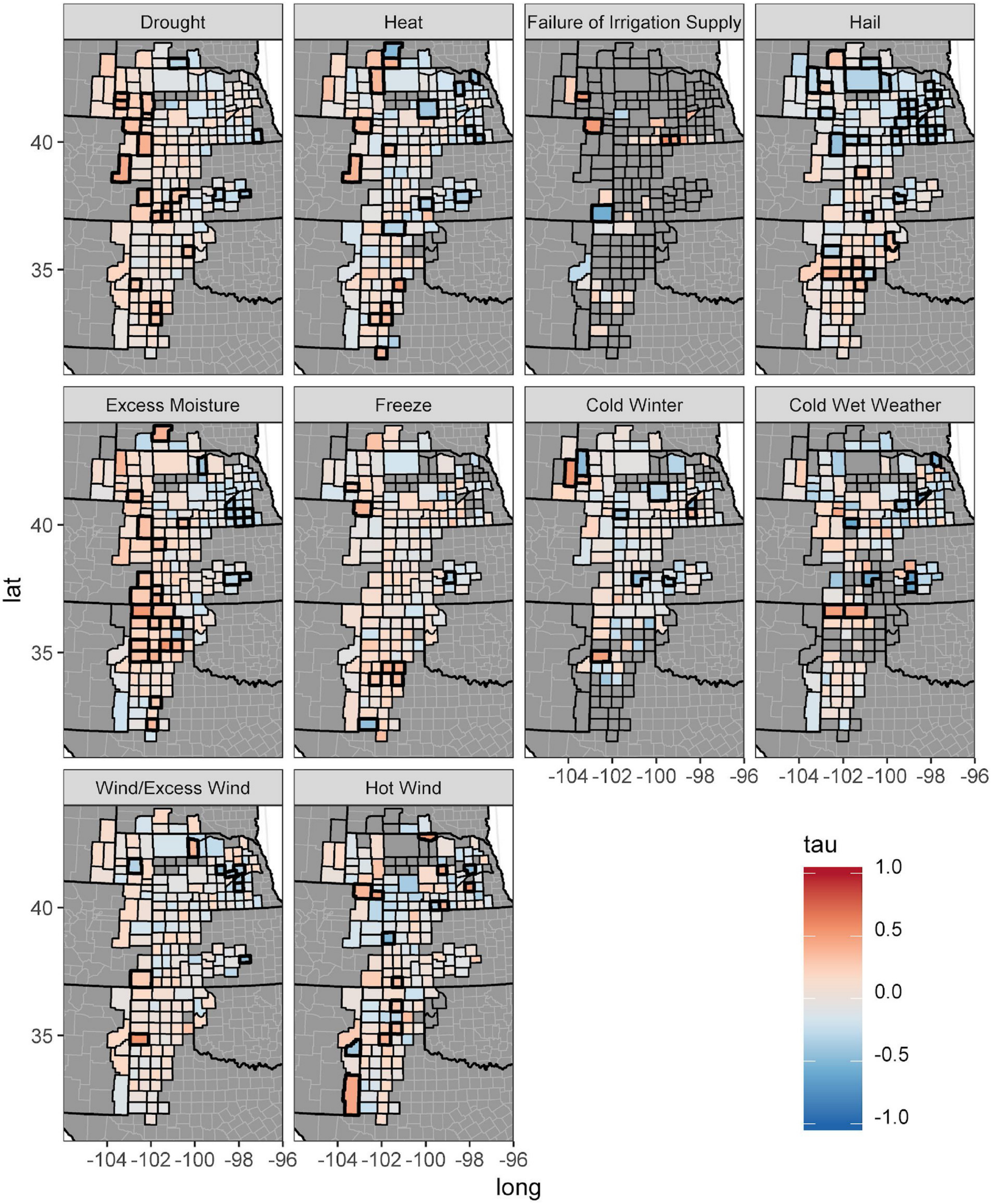

Fig. 8. Trends in county-level loss cost by causes of loss. Mann-Kendall trend analysis is performed on annual county-level loss cost from 1989–2017. Tau values are reported with positive numbers indicating increases in loss cost, and negative values indicating decreases. Bolded counties indicate significant trends ($p < 0.05$).

4.3.2.3. Failure of irrigation supply. The fewest county-level trends are reported by *failure of irrigation supply*. Despite very few trends, there are quite a number of significant ones showing increasing loss cost values (4). Moreover, the percentage of counties with significant trends compared to all counties showing trends (non-significant and significant) is the largest of all the causes of loss.

4.3.2.4. Hail. Hail features the most significant trends across Ogallala counties (36) with more than 75% of them decreasing trends, with most of those in Nebraska (22/28). Of the eight counties that show significant increasing trends, five are located in the Llano Estacado of Texas.

4.3.2.5. Excess moisture. Significant trends in excess moisture are the 2nd leading number across Ogallala counties with the majority (70%) increasing trends located mostly in the western counties of the region.

Increasing and significant loss cost trends of excess moisture are prevalent across counties along the western and southern reaches of the

Ogallala Aquifer region including western Nebraska, eastern Colorado, western Kansas, the Oklahoma Panhandle, and northern Texas. Nine of the 20 counties with increasing significant trends are in Texas. Significant decreasing trends due to excess moisture are primarily located in the eastern portions of the Ogallala and in the states of Nebraska (8) and Kansas (1).

4.3.2.6. Cold/wet. There are eight significant loss cost trends for *freeze* with six increasing and two decreasing trends. *Cold winter* features ten significant loss trends with four increasing and six decreasing trends. The latter are located in Nebraska (4) and Kansas (2). There are nine significant trends for *cold wet weather* with two increasing trends and six decreasing ones. The former are located in Oklahoma (Cimarron and Texas counties), and the latter located in Nebraska and Kansas.

4.3.2.7. Wind-related. There are almost three times as many significant increasing trends (11) as compared with decreasing trends (4) for *hot wind*. In contrast, there are twice as many counties showing decreasing trends than increasing ones for *wind/excess wind*. The majority of significant decreasing trends occur in eastern Nebraska.

5. Discussion

5.1. Drought, water scarcity and irrigation in agricultural risk

Drought as the leading cause of crop loss annually, and as a percentage of aggregated losses from 1989–2017, closely mirrors nationwide trends (Wallander et al., 2013; Reyes and Elias, 2019). The significant increases in annual indemnities (Objective 1) and contributions of hot and dry causes of crop loss between 2011 and 2014 can be attributed to the 2012 Great Plains drought (Fig. 6;Hoerling et al., 2013). This relationship was particularly notable during 2011 and 2012 when more than 75% of indemnities were due to drought, heat, or hot wind (Fig. 6). The decrease in loss cost in 2011 may indicate higher production risk illustrated by the much larger liabilities relative to indemnities. In contrast, decreases in loss cost can also suggest more hedging against certain disasters and crop loss due to larger liabilities (Reyes and Elias, 2019). These historic changes in indemnities and loss cost related to the 2012 drought has informed producer decision-making around current and future drought conditions, programmatic outreach related to crop insurance signup deadlines, and future programmatic costs the federal government may encounter given more frequent and intense drought in this region (Coble et al., 2000; Cook et al., 2015).

Failure of irrigation supply only makes up 1% of regional, aggregated indemnities from 1989–2017 (Fig. 4), yet shows the largest increases in annual loss cost over time, suggesting higher indemnities relative to liabilities over time, or relatively flat indemnities with decreasing liabilities (Fig. 3). Even if crops fail, farmers may continue to water their crops to satisfy insurance payout requirements resulting in increased irrigation use, notwithstanding drought conditions or actual plant water uptake (Deryugina and Konar, 2017). Producers who purchase crop insurance have also been shown to use more water due to increasing acreage planted and/or because of making shifts in crop mixes and rotations (Deryugina and Konar, 2017; Claassen et al., 2017). In this region, farmers anecdotally refer to the cost of pumping additional acre-inches of water as a kind of "insurance" in terms of how doing so alleviates their constant, justified concern about the potential negative impacts of underwatering (A. Kremen, personal communication, July 26, 2019). This attitude and practice can be reinforced when crop yield and quantity do not appear to suffer due to overwatering (i.e., producing a water surplus; Gibson et al., 2019). In these situations, federal crop insurance may be a maladaptation since management changes in irrigation and/or crop types may be disincentivized (Basso et al., 2013). Subsequently, agricultural production systems are less resilient to future extreme weather events that may decrease water availability (Müller et al., 2017). This has negative impacts on both financial and natural capital, ironically leading to higher vulnerability to weather and climate-driven events such as drought and hail.

Continuous evolution and adaptive management of irrigation systems by producers may limit actual crop failure due to irrigation supply through use of more drought-resistant crops and lower-value practices, for example (Hornbeck and Keskin, 2012). Especially in areas where there is less aquifer drawdown such as in the northern Ogallala, producers may face different management challenges such as district-mandated pumping limits and improving their irrigation scheduling and soil practices to deal with abundant water (i.e., water surplus that can contribute to water quality issues such as nitrogen leaching; Di and Cameron, 2002). There is a tendency for producers to maximize individual profit by using their full water allocation to maximize social benefits (Lauer et al., 2018). Increases in loss cost in counties in eastern Colorado and Nebraska may suggest relatively flat indemnities and with decreasing liabilities given water availability (Fig. 8). In the central and southern portions of the Ogallala, adaptive management strategies may be more prevalent due to higher proportions of indemnities due to drought, less irrigation water available, and a declining water table (Fig. 7; Foster et al., 2014). In Kansas farmers in the state's first Local Enhanced Management Area reduced their water use by 31% over a five-year period without impacting yields, and with a majority reporting higher net profits (Deines et al., 2019). This was achieved by farmers making minor changes, such as shifting production goals from maximizing yields to maximizing profits, shifting to less water-intensive crops, and integrating soil moisture probes, irrigation scheduling and other adaptive management strategies (Deines et al., 2019). In addition, a combination of both drought-tolerant crops and areal-based indices for crop insurance (providing a more complete coverage) may mitigate drought impacts and provide a pathway towards sustainable agriculture in this region (Lybbert and Carter, 2015).

A major limitation of our study is how the landscape is partitioned between irrigated and non-irrigated land. Because our primary focus was on exposing crop insurance loss data over different spatio-temporal scales, and assessing trends using loss cost, we do not explicitly link our results with specific irrigation use. Despite this, our results provide some indication of irrigation use and the resulting crop failure from lack of irrigation (e.g., Fig. 6). Our paper provides a foundation for future directions linking crop insurance loss data with additional management variables, such as irrigation, as well as other landscape variables that may further characterize the relationship between groundwater, management, and insurance use.

5.2. Characterizing 'hot spots' of high production risk areas

Our county-level analyses (Objective 3) serve to effectively determine 'hot spots' of production risk, which we define in this work as areas impacted by multiple stressors related to past weather and climate change (Giorgi, 2006; de Sherbinin, 2014). Using counties as the spatial unit of analysis for 'hot spots' may provide better informed risk management as this geographic scale is more familiar to producers and extension professionals (Elias et al., 2018). Moreover, high resolution analysis (e.g., county-scale, monthly) can show targeted areas for adaptation where consistent types of losses may indicate production areas with greater exposure to specific adverse conditions (Government Accountability Office (GAO), 2015). Agricultural production reliant on groundwater for irrigation may be most at risk in counties that attribute greater than 40% of county-level indemnities to drought (Fig. 7).These hot spots indicate counties that may be most vulnerable under extreme drought conditions and long-term declines in groundwater levels, for example. We note these hot spots experience impacts exacerbated by human activities and that this methodology could be expanded to include populations with limited adaptive ability with physical changes and include both natural and human impacts in identifying hot spots (de Sherbinin, 2014).

Trend analyses of county-level loss cost from 1989 to 2017 reveal spatially-explicit patterns, and may pinpoint hot spots of higher drought risk, such as in the western Ogallala counties (Fig. 8). For example, four counties show increasing loss cost trends in both drought and heat, highlighting the combined impact of increasing temperatures and decreasing water availability in these areas. Most significant trends in failure of irrigation supply are increasing, and located in the northern portion of the Ogallala Aquifer in eastern Colorado and Nebraska suggesting higher production risk areas that may require changes in water management. Large indemnities in counties of the Texas High Plains are primarily attributed to high-value crops such as cotton which comprise more than 70% of Texas' indemnities (Figs. 5, 6a). Significant decreases in aquifer saturated thickness, especially in far eastern New Mexico and the southern portion of the Texas Panhandle (McGuire, 2017), suggest depleted water resources in these cotton-growing areas, but also continued weather and climate-driven losses due to drought, hot wind, and hail (Figs. 5,8). Many of these counties feature significant increasing trends of drought, heat, excess moisture, and hail, many of the climate stressors that impact the very crops grown in this area (Steiner et al., 2018). Interestingly, these areas also correspond with water table decreases and saturated thickness shrinkage (Figs. 6d and e). Results of both changes in aquifer characteristics and trends of indemnities concur with other observational trends of decreases in streamflow and increases in low flow days indicating diminished water availability (Kustu et al., 2010). This information may ultimately aid producers by providing spatially-explicit, county-level information on historic crop vulnerability for future agricultural risk management.

Cimarron and Texas counties in the Oklahoma Panhandle are the 5th and 1 st in Oklahoma, respectively, in agricultural market products sold for many of the primary crops affected by weather and climate-driven events in this state (Fig. 6).These counties feature increasing significant trends of loss cost for both cold wet weather and excess moisture (Fig. 8). This suggests either (1) increasing indemnities due to cold wet weather and excessive rainfall, or (2) increasing liabilities to hedge against these specific losses. Increasing use of center pivot irrigation as an adaptation to drought and less strict groundwater regulation may buffer against dry times (Wenger et al., 2017). Thus, producers anticipate and hedge against other major causes of crop loss such as cold wet weather and excess rainfall. Given the overall increase in loss cost due to failure of irrigation supply over the Ogallala (Fig. 5) and decline of aquifer levels, counties in the Oklahoma Panhandle may be more vulnerable as compared to other areas in the Ogallala region to increasing dry conditions and drought.

The appearance of Mycotoxin as a top cause of crop loss during summer months for Oklahoma supports the importance of spatio-temporal resolution in analyzing cause of loss data (Objective 2; Reyes and Elias, 2019). Almost three-quarters of losses in Oklahoma are from wheat, and the state experiences Mycotoxin as a top cause of loss especially in August and September (Figs. 5,6). This is no surprise given that drought is a modulator of this plant disease especially for cereal crops (Marroquín-Cardona et al., 2014; Medina et al., 2015). Increasing severity and frequency of drought may affect how this disease affects crops not only in Oklahoma but across the Ogallala Aquifer region. Despite its state-level significance, our results present finer-scale information that is more decision-relevant, capturing Mycotoxin's importance at specific months and areal units. We cannot speculate on the actual trends of Mycotoxin over time and space; however, these results suggest the relative importance of this disease as compared to other biophysical causes of crop loss through indemnities. Given that climate change is expected to exacerbate environmental conditions more conductive to Mycotoxin in central North America (Marroquín-Cardona et al., 2014), producers may use this knowledge in their agricultural risk management strategies and data-driven decision-making.

5.3. Spatially heterogeneous regions of risk

County-level crop loss in Nebraska potentially indicates a decreased vulnerability to drought due to (1) relatively larger indemnities from hail and (2) more available water in the northern portions as compared to the southern portions of the Ogallala (Figs. 7d,f). Some parts of Nebraska have experienced a net transfer of water from the surface to groundwater due to surface water use for irrigation. This contributes to a rise in the water table due to continuing irrigation as evidenced by minimal changes in water table and possibly fewer indemnities attributed to drought (Fig. 7). Areas with increases in total irrigation are especially prominent in the Sand Hills area of Nebraska where there is high recharge and water very close to land surface elevation. These counties also coincide with fewer changes in saturated thickness (Fig. 7). Especially in the Platte River Valley, there is less decline of groundwater storage as compared to the southern reaches of the Ogallala Aquifer due to capture of groundwater discharge and increased recharge from surface water irrigation (Scanlon et al., 2012). Due to underlying geology, these areas may be more "buffered" against drought losses given available water for irrigation, and thus show a larger proportion of crop losses to hail (Fig. 3c). While producers in the northern portion of the Ogallala may continue to irrigate during drought, hail is a weather event that cannot easily be mitigated against.

While it is beyond this paper's scope to fully examine past hail events, we note many Nebraska counties feature decreasing loss trends of hail, indicating increasing liabilities due to hail with level indemnities (Fig. 8). This could support the idea that certain areas are insuring more due to perceived risk (Niles et al., 2019) even if losses remain static over time. Moreover, counties in Nebraska report a larger proportion of their indemnities due to hail as compared with other Ogallala counties (Fig. 4). In contrast, some hail events resulting in crop loss may not be reflected in these data due to private insurance coverage and/or less perceived risk of hail damage. More hail is generally experienced in the northern portion of the Ogallala Aquifer region (Cintineo et al., 2012). An increase of crop insurance coverage may be warranted given an upward trend of hail events for the past hundred years, especially in Nebraska (Changnon and Changnon, 2000). Decreasing loss cost trends across Nebraska suggest increasing liabilities over time meaning producers are using crop insurance to hedge against hail damages.

Conversely, areas in the southern Ogallala Aquifer especially the Texas Llano Estacado have experienced a larger proportion of crop losses due to drought (Fig. 7). Large indemnities reported for wheat and cotton in the southern Ogallala also demonstrate increased susceptibility to drought due to how these particular crops are managed in the southern Ogallala states (Fig. 6; Colaizzi et al., 2009). The total percent of crop irrigated is much higher for corn than for either wheat or cotton in the southern Ogallala explaining the former's relatively smaller indemnities (Colaizzi et al., 2009). Moreover, these areas have seen major decreases in water table elevation and saturated thickness changes compounding issues around water availability. While these areas may consistently experience losses due to drought, our trend analysis shows other types of crop loss may become more prevalent (Fig. 8). For example, many Texas counties show increasing loss cost trends of excess moisture potentially indicating larger indemnities with similar liabilities, or similar indemnities and smaller liabilities, over time. It is plausible that these areas are more familiar with drought impacts and may be less prepared for excess moisture events supporting increasing loss cost trends whereby producers may opt to insure the same value of crop but experience more loss over time.

Aggregation of crop loss data affects both visualization and analysis (Reyes and Elias, 2019). For example, the top ten causes of loss for all of the Ogallala counties feature some variation when aggregated by state (Fig. 4). While drought is typically the top cause across Ogallala-states, hail is the number one cause in Wyoming. Beyond the top two causes of loss (drought and hail), cold winter (South Dakota), freeze (Wyoming), wind/excess wind (Wyoming), and heat (Kansas) are some examples of state-level cause of loss contributions that are greater than the regional (Ogallala) relative contribution. We also note that the relative fraction of various loss causes by state is also an artifact of the counties representing each state of the Ogallala (Fig. 2). While the relative fraction of hail for South Dakota and Texas seem similar (~0.2), Texas has 40 counties in the Ogallala versus three for South Dakota. Hail may be relatively important for those three counties in South Dakota given the relative fraction in comparison to other states.

An understanding of both past patterns and trends may assist producers, farm advisors and the farming industry in being prepared for and responsive to weather events leading to crop loss. For example, hail represents a large proportion of total indemnities (30–80 %) in the northern Ogallala Region (Fig. 7c), however trend analysis at the county level reveals a significant decline in hail in many of the northern counties, but drought, heat and failure of irrigation supply have increasing trends in those counties (Fig. 8). Armed with this knowledge, the agricultural community could conceptualize alternate ways of saving water, such as deficit irrigation, drip irrigation and olla irrigation (Lal, 2015). The agricultural support industry could conceive of ways to manage extreme heat including alternate cultivars, shade cloth, misters, and shifting planting dates or seasons. When hail damage occurs, it results in varied levels of defoliation and producers must decide to either remove the damaged stand and replant, or be content with the likely reduced yield. If a producer must replant, then producers will need to rapidly plant an early adapted variety to reach maturity in the shortened growing season before fall frost risk. Having these supplies at-the-ready may aid in rapid adaptation.

5.4. Implications for agricultural risk management

Changes in annual metrics of causes of crop loss (Objective 1) and monthly frequency of top loss events (Objective 2) provide agricultural decision makers insight on expected types of loss, as well as information for risk management strategies. For example, drought and hail are the leading causes of loss for the Ogallala as a region; however, hail as a cause of loss may be more prevalent during the summer months (Fig. 5). Few significant trends for freeze and cold winter (Fig. 8) may be related to asynchronous shifting seasons whereby temperatures may allow for planting and crop growth, but freeze events and timing remain the same (Cleland et al., 2007). Even absent long-term trends in causes of loss (Fig. 8), agricultural advisors and farmers still rely heavily on recent experiences and loss (Marx et al., 2007; Coles and Scott, 2009). Moreover, perceived adaptation and/or farmer needs are positively correlated with weather variability, indicating the usefulness of assessing past crop losses (Niles et al., 2019). Near-term memory of losses due to drought and hail are important to producers in their medium to long-term adaptation and uptake of crop insurance, in addition to other operational and tactical management strategies (Taylor et al., 1988; Prokopy et al., 2013; Brown et al., 2017). Insights on losses are valuable for not only producers, but those who support and serve the farm sector including local Farm Service Agency staff, crop consultants, groundwater management district managers, and extension professionals. Linking producers' past experiences with possible use of climate forecasts remains a major research gap, yet demonstrates how crop insurance loss data can link weather and climate in decision making and decision support (Mase and Prokopy, 2013).

6. Conclusions

Spatio-temporal patterns and trends in the relative contribution of different causes of crop loss provide an integrated assessment of weather and climate-driven impacts on agriculture. Indemnities broken out by causes of loss represent an indicator of both biophysical and socio-economic conditions surrounding agricultural losses, and may be meaningful when considering the contextual vulnerability of these production systems (Steele et al., 2018). For example, large proportions of indemnities due to hail coupled with decreasing loss cost trends may indicate increased hedging (i.e., higher liabilities with similar indemnities over time). Our analysis revealed spatially divergent risks as a function of existing landscape characteristics, climatic factors, weather events, and decision-making processes like management. Specifically, northern producers of the Ogallala may perceive hail as a greater risk due to fewer drought indemnities and increased water availability. In contrast, southern producers report drought as a large proportion of indemnities suggesting continued vulnerability to decreased water availability now and into the future. Crop insurance loss data play a role in integrating long-term trends with near-term management practices, and providing relevant risk information in producers' operational to tactical decision making processes. Examining specific reasons for crop loss contributes to better understanding of effective policy levers and design so that producers can retain profits and enact conservation goals (Lauer et al., 2018). While questions on what policies are acceptable to both Ogallala producers and communities persist, federal crop insurance remains an important safety net.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Dr. Julian Reyes currently serves as an AAAS Science and Technology Policy Fellow in the Office of Global Change at the U.S. Department of State. The view expressed in this article are his own, and not necessarily those of the U.S. government.

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