Agricultural Perspectives on Hailstorm Severity, Vulnerability, and Risk Messaging in Eastern Colorado

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ABSTRACT: Eastern Colorado is one of the most active hail regions in the United States, and individual hailstorms routinely surpass millions of dollars in crop loss and physical damage. Fifteen semistructured interviews with eastern Colorado farmers and ranchers were conducted in the summer of 2019 to gauge perceptions of the severity and vulnerability associated with hailstorms, as well as to understand how forecasts and warnings for severe hail are received and acted upon by the agricultural community. Results reveal a correspondence between perceived and observed frequency of hailstorms in eastern Colorado and highlight financial losses from crop destruction as the greatest threat from hailstorms. In contrast to the National Weather Service defining severe hail as at least 1.0 in. (25.4 mm) in diameter, the agricultural community conceptualizes hail severity according to impacts and damage. Small hail in large volumes or driven by a strong wind are the most worrisome scenarios for farmers, because small hail can most easily strip crop heads and stalks. Larger hailstones are perceived to pose less of a threat to crops but can produce significant damage to physical equipment and injure livestock. Eastern Colorado farmers and ranchers are avid weather watchers and associate environmental cues with hailstorms in addition to receiving warning messages, primarily via alerts on mobile telephones. Hailstorms elicit feelings of dejection and anxiety in some respondents, whereas others accept hailstorms as part of the job. Increasing awareness of the agricultural perceptions of hailstorms can help the meteorological community direct hail prediction research efforts and improve risk communication to the agricultural sector.

SIGNIFICANCE STATEMENT: Farmers and ranchers across eastern Colorado routinely face the impacts of hailstorms, and this study is the first to specifically gauge how these agriculturalists perceive vulnerability toward hailstorms, as well as how they receive and respond to warning messages. Although the current NWS threshold for severe hail is 25.4 mm, farmers and ranchers perceive smaller hail, either in large volume or driven by strong winds, as most detrimental to crops. Many farmers express anxiety or dejection toward hailstorms, because their pride in providing a quality product to consumers is damaged. Understanding farmers' perspectives of hailstorms can help to forge stronger partnerships and improve risk communication between forecasters and the farming community and motivate further research into hailstorm predictability. The methods of this study can be applied to other hail-prone regions of the country to assess perceptions from farmers who live in different meteorological and agricultural environments.

KEYWORDS: Social Science; Hail; Agriculture; Communications/decision making; Regional effects; Societal impacts

1. Introduction

Hailstorms are a ubiquitous warm-season feature across the midsection of the United States and are responsible for property damage, crop loss, and, in rare cases, human injury. Economic impact from U.S. hailstorms continues to rise and now commonly exceeds tens of billions of dollars annually; in some cases, a single hailstorm can be a billion-dollar disaster if it strikes a major metropolitan area (Prein and Holland 2018; Rocky Mountain Insurance Information Agency 2019). The environments supportive of hailstorms are relatively well-known, as are climatological statistics such as frequency, seasonality, and spatial distribution (Changnon 1977; Changnon and Changnon 2000; Allen and Tippett 2015; Allen et al. 2015; Lepore et al. 2018; Allen et al. 2020). Less understood are the human perceptions of and responses to hailstorms and their associated impacts. For example, there has been no formal analysis of what people view as the greatest risk from hailstorms, how hailstorm severity is conceptualized, whether exposure and sensitivity to hailstorms are perceived to be changing over time, and how warning messages for hail are received and interpreted. Gaining an understanding of these questions and others can lead to more effective risk communication, endeavors to support the most vulnerable, and future research pathways to study hailstorm characteristics. This study is the first to specifically investigate hailstorm perceptions through the lens of the agricultural sector, arguably the sector most affected by natural hazards in day-to-day operations. As such, 15 semistructured interviews were conducted with farmers and ranchers who live and work in eastern Colorado.

Hailstorms generally occur east of the Rocky Mountains, with a corridor of maximum activity in the Great Plains, from

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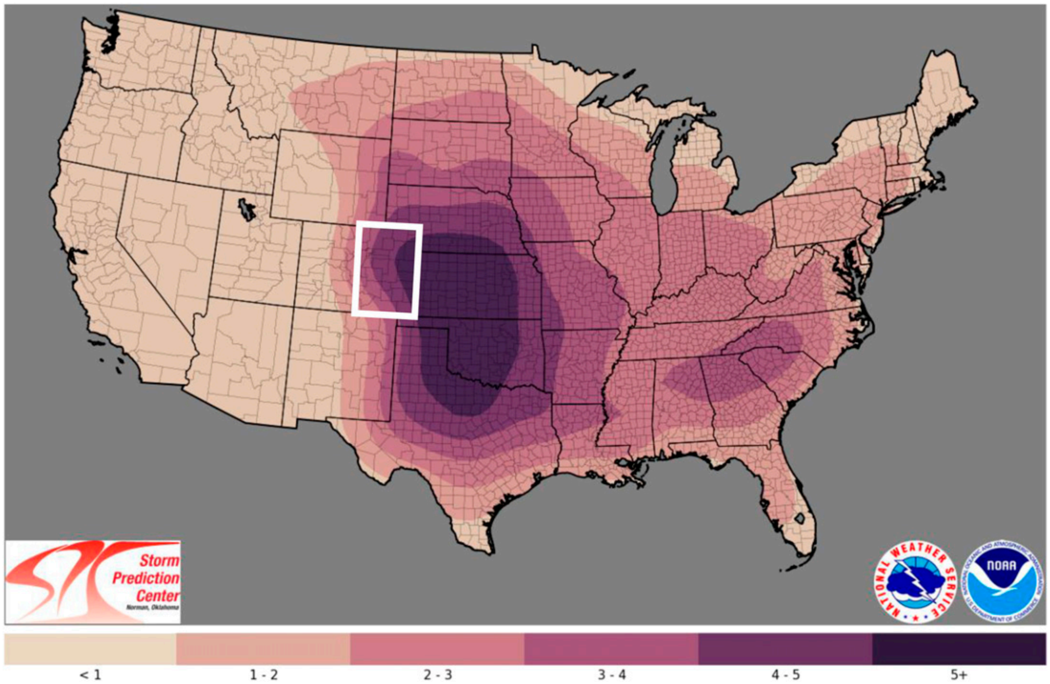

FIG. 1. Mean number of 1.0+-in. (25.4+ mm) hail days per year within 25 mi. (40 km) of a point for the period 1986–2015, produced by SPC (https://www.spc.noaa.gov/wcm/). Data are taken from the SPC local storm report archives.

Texas northward through Nebraska (Fig. 1; Allen and Tippett 2015). Within this area of enhanced hail activity, eastern Colorado has experienced some particularly damaging hailstorms in recent years. The 8 May 2017 Denver event became the second costliest hailstorm in U.S. history with an estimated $2.3 billion in damage; a 6 August 2018 hailstorm killed five animals and injured close to a dozen people at the Cheyenne Mountain Zoo in Colorado Springs (Childs and Schumacher 2018b); and on 13 August 2019, the largest hailstone in state history was measured at 4.83 in. (122.6 mm) in Kit Carson County in far eastern Colorado. According to the Rocky Mountain Insurance Information Association, Colorado trailed only Texas in the most hail claims for the period 2003–15, and in 2018 Colorado was the state with the most automobile and homeowners insurance claims for hail, with over $598 million (State Farm 2019). While large hailstones [e.g., those in excess of 1.0 in. (25.4 mm)] tend to lead to the most physical damage, so-called plowable hailstorms, in which hail accumulates to appreciable depths and requires snow plows for its removal, can also cause substantial damage and travel interruptions across Colorado (Kalina et al. 2016; Friedrich et al. 2019). The eastern half of Colorado has seen an increasing trend in hail reports at all size thresholds since 1997 (Childs and Schumacher 2019), an era in which severe weather data are more reliable because of standardized reporting practices and implementation of Doppler radar (Agee and Childs 2014; Allen and Tippett 2015). This increasing trend is in contrast to national-level hail trends, which were essentially flat over the period 1997–2014 (Allen and Tippett 2015). There also exists an increasing proportion of 2.0+-in. (50.8+-mm) and 3.0+-in. (76.2+-mm) hail reports relative to all *severe* (1.0+-in.; 25.4+-mm) hail reports across eastern Colorado since 1997; in 2018, one-fifth of all severe hail reports in this region were at least 50.8 mm in diameter (Childs and Schumacher 2019).

Eastern Colorado is also unique in its mix of urban centers along the Front Range adjacent to a vast area of sparsely populated agricultural land that makes up the eastern plains. This dichotomy showcases the population bias inherent within hail data. For a hailstone report to be tallied, a trained spotter, storm chaser, or member of the public must collect the hail, measure its size, and send the information to their local National Weather Service (NWS) office, often with a photograph. This requires that people be in close proximity to where hail is falling, which lends itself to more populated areas. This leads to a disproportionate amount of hail reports in cities and along major roadways, while many hailstones that fall in rural areas go unreported for lack of population (Fig. 2). The eastern plains of Colorado also feature a relatively small gridded network of paved roads, evidenced in Fig. 2 as north–south and east–west lines of hail reports.

Hailstorms that affect rural areas also tend to lag those in metropolitan areas in garnering media attention despite their significant agricultural impact. One hailstorm has the potential to wipe out an entire field, leading to sizable losses both financially and in crop yield (Lemons 1942; Changnon 1971; Shapiro et al. 1986; Lollato et al. 2017; Battaglia et al. 2019). Crop damage is not restricted by hailstone size, as smaller, subsevere hail can be even more detrimental on a field of crops than larger hail (Changnon 1977; Sánchez et al. 1996; Doswell 2001). In the European Severe Weather Database, which includes descriptions of hail damage, crop damage reports far exceed reports of damage to physical structures and is most frequently associated with hail less than 30 mm (Púčik et al. 2019). In addition,

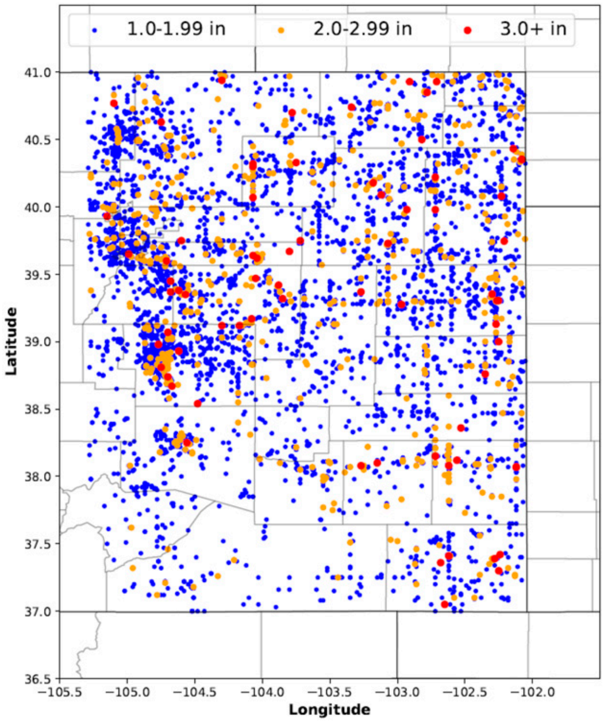

FIG. 2. Distribution of all 25.4+-mm hail reported across eastern Colorado over the period 1997–2018, according to SPC local storm reports. Adapted from Childs and Schumacher (2019).

rural agricultural areas often face higher vulnerabilities and reduced capacity for resilience to climate and weather hazards (Kapucu et al. 2013; Cox and Hamlen 2015). With agricultural output contributing $41 billion to Colorado's economy each year (Davies et al. 2012), and some 90% of Coloradoans reporting that their quality of life is improved because of agriculture (Chriestenson et al. 2016), any hindrance to achieving maximum yield can result in local economic instability.

In recent years, the U.S. agricultural sector has been the subject of much research investigating perceptions of climate change and its impacts on applicable natural hazards. A slight majority of farmers believe that climate change is occurring (Arbuckle et al. 2013; Prokopy et al. 2015b), although mixed perceptions exist among farmers as to whether the main driver of climate change is anthropogenic (Arbuckle et al. 2014; Prokopy et al. 2015b), and Prokopy et al. (2015a) found that climate and agricultural scientists are nearly 4 times more likely to believe in anthropogenically caused climate change than are farmers. Interestingly, despite a general concern for climate change impacts on weather patterns that affect crop yields, the majority of U.S. farmers agree that adaptation strategies can overcome adverse effects (Arbuckle et al. 2013; Prokopy et al. 2015b). At the local scale, Lane et al. (2018) held focus groups of farmers in New York and Pennsylvania and revealed a concern that a new normal is emerging in which extreme events—specifically drought and heavy rainfall—are becoming more frequent. Similarly, Vermont farmers are concerned about climate change intensifying existing risks, specifically citing floods (Schattman et al. 2016). The samples in these two studies also felt concern for secondary effects such as soil erosion and market stress. Moreover, in a survey of midwestern U.S. farmers, the majority of respondents cited an increase in variable and unusual weather patterns in the past five years, with the greatest concerns being extended drought and heat stress (Mase et al. 2017). Unlike the hazards of drought, extreme heat, and to some degree flooding, which exacerbate slowly over a growing season or several growing seasons, a hailstorm is an isolated event that can produce the same end result (i.e., a destroyed crop) in a matter of minutes. This means that any changes in frequency or severity will be felt more tangibly on an annual basis by farmers. Hailstorms are also unique in their ability to not only impact crops, but also damage equipment and present risks to people working in the fields. Despite these distinctive attributes, research is lacking on agricultural perceptions of the hailstorm hazard and associated vulnerabilities and mitigation strategies. Some studies outside of the United States have measured how farmers perceive and adapt to hailstorms, including in China (Zheng and Byg 2014), India, Nepal (Choudhary et al. 2012; Paudel et al. 2014; Shukla et al. 2016), and Italy (Menapace et al. 2015), but this is the first modern study to specifically measure hailstorm perceptions in a region of the United States within the farming industry.

In the United States, "severe" hail is formally defined as being at least 25.4 mm in diameter. This threshold was adjusted upward from 19.1 mm in 2010 after media and stakeholders suggested that appreciable property damage does not occur until hail is at least 25.4 mm (NCEI 2009; NWS 2010). There currently does not exist a severe hail warning issued by the NWS; rather, when severe hail is indicated via radar or trained spotters, a severe thunderstorm warning (SVR) bulletin will be issued. These warnings always include the anticipated hailstone size and sometimes include a special tag demanding action steps if significant impacts are expected. A note about subsevere hail is sometimes included in an SVR for wind, but never is an SVR issued for hail alone that is less than the 25.4-mm threshold. To our knowledge, there has not been a formal investigation of users' perceptions of this severe hail threshold used in warning messages, or the evaluation of how SVR for hail are received and acted upon. In fact, much of the existing literature on public warning reception has focused on tornado warnings (e.g., Donner 2007; Brotzge and Donner 2013; Ripberger et al. 2015, 2020). In an effort to make weather warnings more conducive to taking action, in 2014 the NWS implemented "impact-based warnings" (IBWs), wherein SVR and tornado warnings can include a tag detailing expected impacts to people and/or property. Experiments are also ongoing to incorporate probabilistic hazard information (PHI) to weather warnings, which will provide via both text and color scales the likelihood of receiving serious impacts. Research is showing that including IBWs increase one's probability of taking actions such as sheltering in place or seeking safer shelter (Ripberger et al. 2015; Casteel 2016), but again, no study exists that isolates severe hail. The work presented here solicits feedback of farmers' and ranchers' needs and desires in hail warning messages, which can motivate experiments within

NWS to make SVR and PHI language for hail more effective and meaningful to the public.

To review, this study is innovative for its emphasis on hailstorm perceptions within the agricultural sector. While we seek a broad spectrum of information, two main research questions can be established: 1) How do farmers and ranchers perceive the severity of hailstorms and their vulnerability toward them, and what factors drive these perceptions? 2) How do farmers and ranchers receive and respond to warning messages for severe hail? By focusing on the small domain of eastern Colorado, local forecasters and other decision-makers can better understand the needs of the agricultural communities they serve, and thus foster stronger relationships, as opposed to assuming that more general perceptions apply in their locale. Moreover, this study paves the way for future work employing similar methods with farmers in other hail-prone parts of the country who raise different kinds of crops to see if similar themes emerge.

2. Theoretical foundations

The semistructured interviews were developed in such a way as to elicit the mental models of the agricultural stakeholders associated with hailstorms through the framework of the Protective Action Decision Model (PADM; Lindell and Perry 2012). A mental model can be thought of as a set of relevant beliefs and inferences that someone has regarding a risk that in turn guides his or her conclusions and responses (Bostrom et al. 1992; Morgan et al. 1992, 2002). The mental models approach in qualitative research has been utilized in numerous disciplines for decades (Morgan et al. 2002 and references therein) and can be particularly insightful in deciphering natural hazards risks. For example, the mental models approach has been used to gauge public perceptions of natural hazard risks, including flash floods (Wagner 2007; Morss et al. 2015; Lazrus et al. 2016), hurricanes (Bostrom et al. 2016), heat waves (Chowdhury et al. 2012), wildland fires (Zaksek and Arvai 2004), and climate change in general (Bostrom et al. 1994; Otto-Banaszak et al. 2011).

The process of eliciting mental models, and indeed the mental models themselves, can be manifested in a variety of frameworks, including protective-action decision-making. The interview protocol designed here specifically draws upon the PADM. Developed by Lindell and Perry (1992, 2004) and later revised (Lindell and Perry 2012), the PADM represents an information processing pathway by which environmental cues and direct messages about a hazard are received, interpreted, and acted upon by a person. The revised PADM consists of three predecisional processes (exposure, attention, and comprehension) and three perceptions (threat, protective action, and stakeholder) that inform the decision itself, followed by the behavioral response to that decision, with consideration of situational factors (Lindell and Perry 2012). Accordingly, the PADM provides a structure for conceptualizing how a person perceives, interprets, and responds to a hailstorm threat, which is inevitably influenced by his or her mental models.

Terminology within natural hazards literature can be defined in many ways (Cutter et al. 2008; Cutter and Finch 2008; Paul 2011), and their relationships to each other can also take on a number of mathematical and conceptual forms depending on the research objectives and field of study (Wisner et al. 2012; Turner et al. 2003; Zarafshani et al. 2016). Here, we elect to follow Wisner et al. (2012) in defining overall hailstorm *risk* as the intersection of *hazard* and *vulnerability*. In this framework, the hazard (i.e., a hailstorm) can refer to one or more of the characteristics of the phenomenon. We will specifically focus on the magnitude or *severity*, which we define as the degree of negative impacts (as opposed to a specific hailstone size), as a measure of hazard. Vulnerability can be partitioned into components of *exposure* (i.e., a person experiencing hailstorms on his or her property) and *sensitivity* (i.e., the social, economic, and demographic characteristics that influence one's ability to prepare for, respond to, and cope with the impacts from a hailstorm Cutter 1996; Cutter et al. 2000; Smit and Wandel 2006; Turner et al. 2003). Also, the realization of risk produces natural and human *impacts*, defined here as negative effects wrought by a hailstorm.

In addition to the construct of risk itself, the interview protocol is concerned with risk perception, which can be defined broadly as a judgment about an event or situation that has potential to cause negative effects (Renn 2008). Renn and Rohrmann (2000) describe four levels that shape risk perception, traversing through cultural background considerations, sociopolitical institutions, cognitive-affective factors, and specific information processing. Here, eastern Colorado farmers and ranchers are asked to provide their risk perceptions of hailstorms through the three elements of severity, exposure, and sensitivity, all of which contribute to overall hazard risk. A similar three-pronged conceptual model of risk perception was recently described by Walpole and Wilson (2020), who use the term susceptibility in essentially the same way as our treatment of the term sensitivity. Interviewees are also asked to comment on whether their perceptions of hailstorm severity, exposure, and sensitivity have changed over time, and if so, what factors were driving these evolving perceptions. One's beliefs and perceptions related to severity, exposure, and sensitivity may not necessarily align with scientific measurements of these factors. Therefore, understanding risk perceptions can help reveal knowledge gaps and also promote more effective risk communication strategies.

3. Method

Participants were recruited through purposive and convenient sampling, stemming from initial organizational contacts and then expanded via snowball sampling (Patton 2002). Recruitment language was developed that explained the study's purpose and contained a link to a Google Form on which interested parties could sign up to participate. In spring 2019, the recruitment letter was sent to extension agents in 26 counties across eastern Colorado, along with the Colorado Corn Growers Association, Colorado Wheat Growers Association, USDA Agricultural Research Service, and the NWS. These organizations disseminated the invitation either directly to farmers on their contact lists and/or via social media or newsletters. In addition, the Colorado Climate Center, which oversees the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), forwarded the invitation to members who had submitted at least

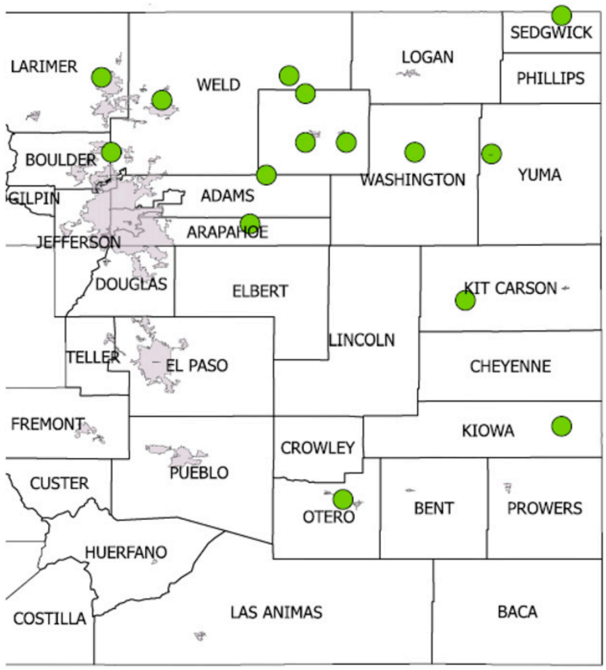

FIG. 3. Approximate locations of interviews ($n = 15$). Urban areas (shaded) and county names are also shown for reference.

two hail reports in the past five years. The first author also recruited two participants in-person at an annual wheat field day in Akron, Colorado.

Two interview pretests, one with a graduate student at Colorado State University and one with a farmer, were conducted to assess timing and content. Minor adjustments were made to the protocol after the pretest farmer interview, but its success allowed for its retention in the sample. A total of 15 interviews were conducted from June to August 2019, of which 14 were in person and 1 was via telephone. The average interview length was 28 min (range of 18–47 min), and interviews took place in a home, place of work, or a local restaurant.

Participants resided throughout the study area, with the greatest concentration across northeastern Colorado (Fig. 3). The interviewees represented a wide range of farming experience within eastern Colorado (3–73 years), with the majority having farmed in the area for at least 20 years (Table 1). The sample also included a mix of small and large farmers, from a 3-acre (1 acre = 0.4 ha) vegetable farmer to operations exceeding tens of thousands of acres. The most common crops farmed were wheat and corn (seven each), and vegetables, millets, sorghum, and sunflowers were also each grown by at least three people. This is representative of the distribution of eastern Colorado crops, with wheat, corn, and sorghum being the top three crops planted by acreage (USDA 2018). Five interviewees reported raising cattle, the highest number of any livestock. One-third of the respondents were CoCoRaHS observers, and nearly half had filed a crop insurance claim due to hail damage within the last two years (Table 1), but these were not distinguishing factors in participant responses.

TABLE 1. Demographic characteristics ($n = 15$).

Variable	Responses
Years farmed in eastern Colorado	3–73 yr (median 28 yr)
Years farmed overall	11–73 yr (median 32 yr)
Acres currently farming	3–50 000 acres (median 1400 acres)
CoCoRAHS hail observers	5
Filed hail claim in past 2 yr	7
Gender	
Male	14
Female	1

One strategy to immediately explore a stakeholder's mental models is to begin the interview by allowing the respondent to freely address broad, open-ended statements about the topic at hand (Morss et al. 2015; Bostrom et al. 2016; Lazrus et al. 2016). As such, this study begins with an invitation for the interviewee to respond openly to the statement, "Tell me about hailstorms (in eastern Colorado)," thereby revealing initial, unprimed beliefs and emotions associated with hailstorms. The interview protocol was then divided into five main sections. Interviewees first were asked about the effects of hailstorms on personal and career livelihoods. The second section focused on hailstorm hazard and severity by probing farmers and ranchers for the most serious negative impacts associated with hailstorms. Interviewees were also asked when they considered a hailstorm to be severe, for comparison with the NWS definition, which is currently based solely on maximum hailstone size and does not include characteristics such as duration, volume, or accompanying wind speed. Interviewees specifically commented on two scenarios for comparison, namely, 1) a hailstorm that produces a lot of small hail that accumulates to appreciable depth and 2) a hailstorm that produces a few very large hailstones in excess of baseball size, both of which are common in eastern Colorado but can have very different effects on a field of crops. Drawing on the PADM, the third section of the interview gauged perceptions of vulnerability to hailstorms through the framework of exposure and sensitivity. The exposure component was measured by asking interviewees to provide a 1–10 rating of how likely they perceived severe hail to occur on their property during a given year (according to their definition of "severe"), and sensitivity was assessed through a 1–10 rating of how sensitive they perceived themselves to be toward the effects of hailstorms (using the definition of sensitivity given in section 1). This rating scale style is preferred for its simple interpretation and ease of performing statistics such as mean and median (Harpe 2015). Each respondent was also asked to comment on any perceived changes in exposure or sensitivity over time, as well as changes in other hail characteristics such as size and season length.

Consistent with the PADM framework, warning message effectiveness has been shown to be of great importance in determining public action in response to a threat (Trumbo 2013; Morss et al. 2015; Carr et al. 2016; Lazrus et al. 2016). As such, section 4 the interview protocol appealed to the efficacy of SVR in their current operational structure, seeking input on the risk information most critical to farmers and ranchers about an impending hailstorm. Specifically, respondents were asked to provide their preferred channels of hail forecasts and warning messages, as well as environmental cues used to deduce the threat of hail. Perceptions of the accuracy and contents of warning messages, affective responses, and any stimulated real-time action steps were also measured. The final interview section sought input on future mitigation strategies to combat the impacts of hailstorms and also inquired about crop insurance influences on perceived risks and vulnerabilities. Each interviewee was given an opportunity to share any closing thoughts, and then the interview concluded. Prompts such as "Tell me more about" or "Can you elaborate?" were used to encourage participants to explain their thinking as much as possible. For their time, each interviewee was given a small gift courtesy of CoCoRaHS. The complete interview protocol, which contains 29 questions and a short demographic questionnaire, can be found in the online supplemental material.

Interviews were transcribed by Kelsey Transcripts and inductively analyzed using NVivo Pro, version 12. The reflexive thematic analysis procedure (Braun and Clarke 2006, 2019; Terry et al. 2017) was followed to create common themes among the interviews. This approach allows for transcripts to "speak for themselves," with themes developed as transcripts are coded rather than determined a priori. Thematic analysis has been used in other studies within the atmospheric sciences that apply social science methods to better understand risks from tornadoes, hurricanes, and flash floods (Demeritt et al. 2010; Demuth et al. 2012, 2020; Ash 2017). Here, 75 unique codes were generated, and they were subsequently combined, defined, and grouped under five preliminary categories according to the interview structure. The codes within each category were consolidated into common themes, some of which overlapped into multiple categories. A final synthesis narrowed the focus to two overarching categories: 1) vulnerability and severity, which represent two leading factors of overall hazard risk, and 2) forecast and warning messaging, which serve to assess reception and response to impending risk. The thematic analysis was performed by the first author and cross-checked by the third author, with mutual agreement reached. Given the sampling approach, the results presented herein cannot be generalized to the entire agricultural sector of eastern Colorado, yet the sample is adequate to gain valuable insights (Braun et al. 2018). In the following discussion, interviewees are referred to as "interviewee 1" and so forth to protect personal information.

4. Risk: Vulnerability and severity

To better understand how eastern Colorado farmers and ranchers deal with the effects of hailstorms and thereby reveal strategies for potential improvements in risk communication, it is worthwhile to investigate the aspects of exposure and sensitivity (which make up one's vulnerability), and severity.

a. *Exposure—Life in "Hail Alley"*

Perhaps the most prevailing assertion among interviewees is that eastern Colorado is a hot spot for hailstorms, to the point where farmers and ranchers assume that they will be impacted by at least one hail event each year. As interviewee 4 said, "this is just part of Colorado and it's always been a part of Colorado," and interviewee 11 stated bluntly, "in this country, it's gonna hail somewhere, and it's gonna be severe somewhere." References were made to Colorado lying within "Hail Alley," and interviewee 11 referred to the area as the "hail capital of the United States." Some interviewees even associated hailstorms with specific towns or creeks along which they seem to travel, and one interviewee correctly stated that Colorado was the leading state for hail claims in 2018 (State Farm 2019). While most farmers and ranchers did not posit a theory for the area's propensity for hailstorms, moisture patterns and the mountainous terrain were seen as local factors influencing hail events. This perception of hail as a common and formidable threat in eastern Colorado is consistent with meteorological data (Allen and Tippett 2015; Childs and Schumacher 2019).

When asked to give a 1–10 rating of perceived exposure to severe hailstorms occurring on his or her property on any given year, a bimodal distribution resulted with a mean response of 5 (Fig. 4a). In other words, while perceiving hailstorms as ubiquitous across eastern Colorado, the sample deduces either a very low or very high chance of severe hail occurring on their property. One explanation given for this wide range of perceived exposure is the localized nature of hailstorms. Interviewee 1 shared that "it's so localized. You're driving down the road and you see this swath and it looks like somebody took a shotgun to the plants. And then you drive another half a mile down the road and nothing . . . or very little damage."

A common thread emerged of a steady long-term state of damaging hail events but a recent increase in their occurrence. Several historical references, as early as the 1940s, were given as evidence for the perceived long-term pattern of hailstorms. Interviewee 5 recalled a particularly memorable hail event from the 1960s in which she rode through "icebergs" of hail on horseback to search for a man caught in floodwaters generated from "five to six hours of continuous hail." In addition to personal experiences, several interviewees recalled how their ancestors dealt with hailstorms or communicated harrowing experiences, which both affirms the strong familial ties often present in agriculture as well as the resonance of major hailstorms on their livelihoods. Others called upon life experiences more generally, such as interviewee 11 who stated, "It'll always be that way. Nothing's going to change or has changed that I can see." A cyclical nature of hailstorms was also noted. Interviewee 4 said, "You always [figure] you're going to have one bad year out of every seven years," and interviewee 7 asserted, "if you've gone . . . six, seven years, [then] you're kind of thinking you're due." Interviewee 9 linked the cycles with moisture: "The old adage here is . . . if it's dry weather, you don't get rain [and] you don't get hail . . . a wetter type scenario, more moisture, higher chance of hail."

A majority of interviewees were quick to express a recent uptick in damaging hailstorms, from "this year" (i.e., 2019; interviewee 2) to "in the last decade" (interviewee 9). Five interviewees made reference to the record-breaking 2018 hail season, which saw an unprecedented number of very large

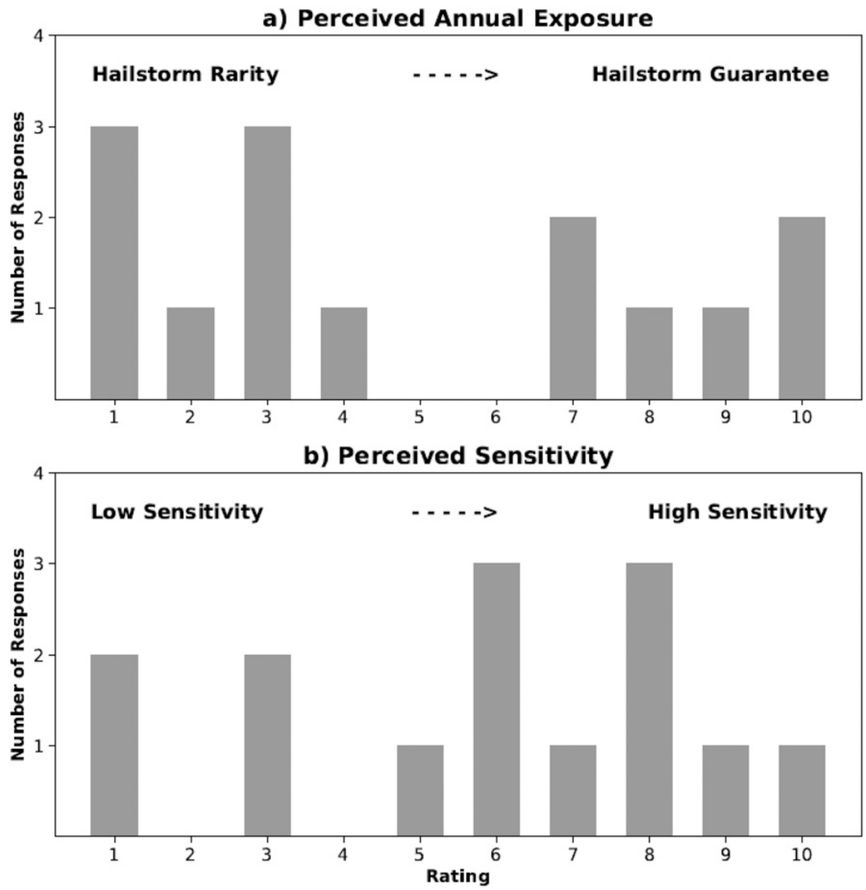

FIG. 4. Perceptions of (a) exposure to hailstorms on a given year and (b) sensitivity to hailstorms among the interview sample (n = 15).

hailstones reported (Childs and Schumacher 2019). Interviewee 4 summarized the 2018 season succinctly:

> then 2018 last year, it was up and down the entire Front Range. That one I would say . . . was very different. You never hear about everybody getting it—like, Colorado Springs got it multiple times. Our insurance adjuster for the crops visited us multiple times in 2018, and she had two roofs put on her house from hail . . . within about a three-month span. [Y]ou had Colorado Springs where those animals were killed and . . . the Cheyenne [Mountain] Zoo; you had [it] in Denver, you had it up along the Front Range like Fort Collins . . . and then we got it [here] on 19 June. That was grapefruit-sized—we lost 70% of everything that was planted. And then up here, we got clipped on 27 July. So I would say 2018 is definitely an asterisk, like ''What the heck was that?''

Observational data affirm an increase in both severe hail reports and severe hail days across eastern Colorado since 1997, with the latter metric notable for its smaller population bias (Childs and Schumacher 2019). While it remains to be seen if this trend will continue, a few interviewees hinted that climate change may result in more frequent extreme events such as hailstorms, which is supported in modeling studies (Brimelow et al. 2017; Rasmussen et al. 2020; Trapp et al. 2019). The influence of climate change on perceptions of hailstorms is beyond the scope of this assessment (and indeed a lack of substantive treatment of climate change by interviewees precludes further inclusion) but is worthy of future investigation.

b. *Sensitivity—The growing costs of hail events*

As with exposure, interviewees were asked to give a 1–10 rating of their perceived sensitivity to hailstorms and whether that rating had changed over time (Fig. 4b). The mean response of 6 indicates that most interviewees deem themselves more sensitive than not. Of greater intrigue is the theme of increasing sensitivity over time, indicating the ability to deal with effects of hailstorms is becoming more difficult. Most interviewees attributed their perceptions of sensitivity either to market trends or crop selection. Interviewee 12 explained how in response to the boom of the early 2010s when wheat and corn were sold for \$9 or \$10 per bushel (1 bushel ≈ 0.035 m^3), ''everybody raised their prices, but as soon as commodities dropped to half, all your input suppliers and machinery dealers did not lower their prices,'' thus putting financial strain on the farmer. The recent years of low commodity prices was also described as ''using up our war chest (interviewee 9),'' meaning smaller cash reserves available in case of unforeseen costs from hailstorms.

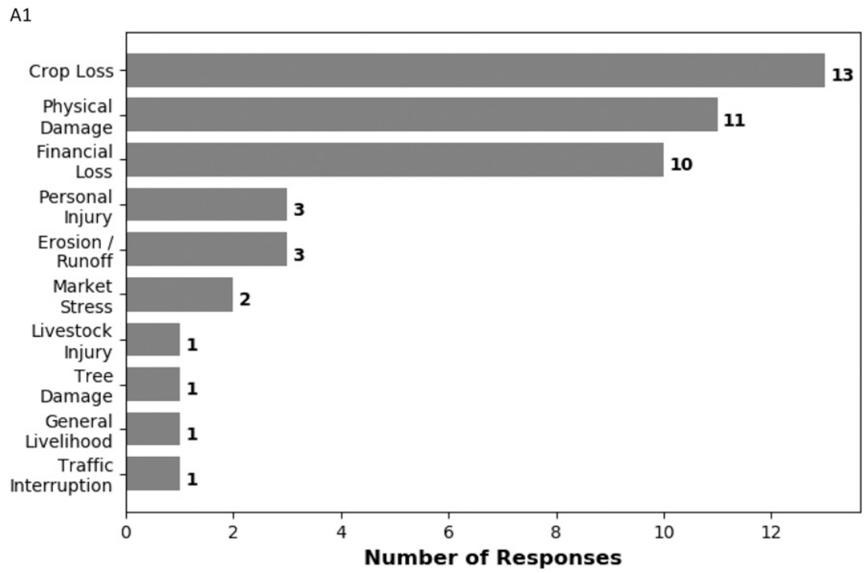

FIG. 5. Perceived negative effects associated with hailstorms across eastern Colorado ($n = 15$).

Aside from the market, crop selection can determine one's sensitivity. Considering the two most prevalent crops, interviewees perceive wheat as more susceptible to hail damage than corn due to its smaller seeds and heads. Interviewee 10 considered himself

> more highly at risk because of wheat being our primary crop. If we had a rotation of some spring crops, we'd have a little bit less risk probably, but even those crops that have some risk, [like] corn and sorghum . . . have some fairly significant damage as well, although they might be able to come back a little bit better than wheat.

Specialty crop and vegetable farmers expressed amplified sensitivity due to the public tendency to purchase only the most pristine-looking or trendy vegetables. As interviewee 3 humorously said, "You get hail through Swiss chard and it's literally Swiss chard. You get hail through heads of lettuce and it's turning brown and the edges are all black a couple days later. You cannot market it." Interviewee 4 shared that if "one hailstone . . . bumps [a watermelon], it immediately starts a rotting process internally." Sensitivity to hailstorms also depends on time of year. In spring, when most crops have recently been planted and are yet to mature, farmers have a greater chance of bouncing back from a hailstorm. However, hailstorms during June and July preceding the wheat harvest are particularly concerning since by this time heads have developed and are vulnerable to being stripped by hail. Perhaps interviewee 3 summarized the aspects of sensitivity best with the statement, "I don't think our risk [i.e., sensitivity] has changed; I think the likelihood of that risk actually coming to fruition has changed." In other words, meteorological and nonmeteorological factors alike are leading to a more frequent realization of the potential negative impacts from hailstorms.

c. *Severity—Effects of small and wind-driven hail*

When asked what should render a hailstorm "severe," some interviewees gave a specific size threshold and others discussed the nature or the impacts of the hailfall. A common theme emerged that small (i.e., less than 25.4 mm) hail, either in large volumes or wind driven, contributes most to crop loss, whereas very large hailstones (e.g., at least 50.8 mm) are most damaging to physical structures. Interviewee 15 spoke of the wind effect:

> The ones that have the winds with them . . . are the ones that seem like they do the most damage. [It] can be smaller hail, the size of a dime or pea-sized but boy, if the wind there is with it, it destroys things fast. You can have bigger ones that . . . come straight down, and they do not do near the damage.

Interviewee 6 said, "It's not necessarily the size of the stone that matters. It's the amount of them and how hard they are . . . [Large hailstones are] probably the ones that hurt that roofs, but the crop damage is caused by not necessarily size of stone but volume of hail." Interviewee 6 also articulated a positive correlation between duration of hailfall and damage: "Most of the time, the most severe damage that we see is when you have a lot of marble-sized hail [that] lasts for more than just a few minutes."

That volume and wind speed are commonly associated with perceived hailstorm severity affirms a farmer's focus on what produces the greatest crop damage. Indeed, when asked to identify the most serious risks (defined in context as negative effects) of hailstorms, 13 interviewees specifically mentioned crop loss, and 10 interviewees mentioned financial impacts (Fig. 5). Physical damage received the second most responses, but almost always proceeded mention of crop loss. Two interviewees referred to hail as "the great white harvester" that can destroy an entire field of crops. The consequences of losing crops to hail goes far beyond the field, however. For farmers, crop yield equals monetary gain, so hailstorms can literally strip them from an income source. This paradigm was summarized by interviewee 6 whose greatest perceived negative

TABLE 2. Use frequency of severe hailstorm warning message channels. Boldface numbers indicate a selection by at least one-third of participants ($n = 15$).

	How regularly do you receive warning messages for severe hail from the following channels?				
	Always	Most of the time	Sometimes	Rarely	Never
Telephone alert (EAS; apps)	**7**	4	3	0	1
Internet	3	1	2	4	**5**
NOAA weather radio	2	1	2	1	**9**
Friends or family	1	3	**6**	3	2
Television	0	4	1	4	**6**

effect is ''the crop loss . . . it's millions of dollars.'' Furthermore, the trickle-down effects from hailstorms can be far-reaching and have significant impact on the farmer's and community's livelihoods. Most interviewees have a number of market streams for their crops and livestock, and removing just one of these pathways from hail losses can be devastating. Interviewee 7 related a typical scenario:

> So in years when things are bad in the agricultural community, tire shops layoff. The tire shop [owner]—his wife doesn't get her hair done . . . so the beauty parlor sees a dip. [And] it trickles down to grocery stores each time. [T]hey talk about the ag[ricultural] dollar rolls in seven times in a community, so you take that dollar out—seven bucks out of the community—it's a severe adverse effect to agriculture communities, not only the farmer.

Interviewee 8 also articulated the trickle-down effect that can ensue from losing a wheat crop:

> Well, we lost all this wheat. Well, that also means that's less wheat to go for the cattle. That's less wheat to go for the hogs. It's less wheat to go for bread and all this other stuff. And, if an entire area is wiped out of wheat or corn or whatever the case may be, that has to be absorbed somewhere. And usually it's at the grocery store, and people who spend are like, ''Why are the prices so high?''

Cutter et al. (2016) plotted six components of rural resilience and found that the eastern plains of Colorado have their lowest resiliency in the environmental and community capital categories, affirming the toll natural disasters can have on agricultural production and the local economy. Interviewee 8 concluded that ''the entire community depends on farming and ranching.'' Indeed, the rural communities of eastern Colorado are small and close-knit, so the local farmer is often well-known and seen as an integral part of the community's well-being. This was evidenced during an interview at a ''mini-mart'' in a town of only a handful of businesses when the local fire marshal and a shopkeeper came in to buy lunch and exchanged friendly banter with the interviewee, signaling his familiarity and respect within the community. A secondary trickle-down effect mentioned by multiple interviewees is that of soil erosion that occurs when hail that strips a field bare melts and take the soil with it as runoff. This can render the field unplantable the following year, as the nutrients necessary for crop growth are removed. Even if a field is not entirely destroyed, crops struck by hailstones become susceptible to bacteria that can degrade productivity.

5. Risk communication: Forecast and warning messages

Given that hailstorms are a palpable threat to eastern Colorado farmers and ranchers each year, it is worth investigating how the various components of forecast and particularly short-term warning messages are utilized and perceived by the agricultural sector.

a. *Sources and channels—An eye to the sky*

Weather is an integral part of the farming lifestyle, and as such many farmers and ranchers are avid weather watchers and stay engaged with impending threats. For the majority of interviewees, the most effective tool for ascertaining a potential hailstorm threat is to assess the surrounding environmental conditions and sky features, one of the factors that initiates the PADM process (Lindell and Perry 2012). Several respondents mentioned that a warm, humid, moisture-rich atmosphere, particularly in the morning, is an omen for hailstorms. On shorter time scales, a sudden temperature drop, deep and dark clouds, strange animal activity, and noisy clatter were cited as precursors for hail. Over half of the interviewees specifically mentioned a greenish hue to the clouds in advance of a hailstorm. Interviewee 14 said that ''if we see a green cloud up in there somewhere . . . it's amazing as a [hail] predictor,'' and interviewee 8 mentioned that from ''years of experience, if it's got a greenish tint, it's most likely it's going to have some hail in it.''

The most frequently utilized channel for receiving hailstorm information is mobile telephones, either via Emergency Alert System (EAS) notification, county-level alert systems such as Code Red, or private-sector applications (''apps'') (Table 2). On the other hand, television, the internet, and NOAA weather radios are rarely or never utilized by most farmers and ranchers. Most interviewees cited availability of their telephones relative to other channels, particularly when they are working outside. Five interviewees reported using the NWS telephone app, with The Weather Channel, Wunderground, Weather Bug, and Storm Radar each commonly used by three interviewees. Radar displays are often used by the interviewees to verify warnings and see where the warned hailstorm is specifically located. Interviewee 15 even said that when storms are developing, ''the first thing I do is go to my radar app on my phone and look to see what the colors are . . . for that cell that is coming [my] direction,'' and interviewee 8 added that ''based on the reflectivity, I can get a better idea of what is going on.''

b. *Perceived accuracy—Predictability at a premium*

The Storm Prediction Center (SPC) issues probabilistic convective outlooks for severe hail each day, and severe weather watches issued by SPC are generally in effect up to six hours. While these metrics are helpful, more precise short-term prediction of the path and severity of individual hailstorms is the subject of ongoing research efforts, such as machine learning techniques (Gagne et al. 2019), development of the HAILCAST model (Adams-Selin and Ziegler 2016), and the NWS Warn-on-Forecast initiative (Stensrud et al. 2009). When asked to assess the accuracy of warnings for severe hail, the interview sample confirmed the challenge of short-term prediction. A common sentiment was that warnings are spatially accurate within about a countywide radius, but as interviewee 10 remarked, ''whether it hits you or not is another story.'' The expected hailstone size is also perceived as hard to predict; as interviewee 14 stated, ''it could be three inches of pea-sized or it could be a spattering of golf ball size.'' Despite the forecasting challenges, interviewee 12 believes that forecasters ''do the best with what they can,'' and interviewee 5 said ''all they can do is say 'mild' or 'moderate to severe.''' The interview sample perceives warnings that are verified by trained spotters or storm chasers as providing more accurate hailstone size estimates, and radar-indicated warnings are perceived to overestimate hailstone size. In fact, there are documented overestimations of hailstone size in Doppler radar algorithms (Cintineo et al. 2012; Ortega et al. 2016). When asked to provide the single most desired piece of information related to a coming hailstorm, the most common response was, as interviewee 10 put it, ''whether it's coming right at me.'' The ability to pinpoint the exact path of a hailstorm would help farmers know what action steps need to be taken to protect life and property, but the rural eastern plains of Colorado complicate location-based warnings because of the scarcity of towns and roads used as reference points in the warning message, as well as the relatively large area within a town's jurisdiction. ''It would be more accurate to the locals . . . and to our families'' to have more pertinent geographical information in the warnings, interviewee 14 concluded. This desire for more place-based information is a common theme in risk communication of hazards (Nagele and Trainor 2012; Klockow et al. 2014; Morss et al. 2016; Childs and Schumacher 2018a).

c. *Affective responses—''Here we go again''*

The behavioral responses to a threat message, including those of natural hazards, are influenced by affect and emotions (e.g., Slovic et al. 2004; Lindell and Perry 2012; Demuth et al. 2018), which are triggered by a variety of factors. For the interview sample, three camps of affective responses emerged. First, words such as ''nervous,'' ''anxious,'' ''ill-at-ease,'' ''frightening,'' and ''apprehension'' were used to convey a sense of anxiety at the prospect of a hailstorm and its potential financial losses. Interviewee 8 commented, ''It causes a lot of stress . . . and it really is something that everybody worries about.'' A second common response was acceptance. As interviewee 11 put it, ''If it happens, it happens. Nothing you can do about it [except] accept it.'' This feeling is tied to the concept of lack of efficacy (Lindell and Perry 2012), wherein a person feels unable to do something in the face of an event. A perceived lack of self-efficacy manifests in relinquishing control to the natural world, such as interviewee 13 who stated, ''You can't do anything about it. That's Mother Nature.'' Others spoke of a supernatural authority governing the weather, such as interviewee 7, who said ''You're just at the mercy of God,'' or interviewee 11, who said, ''It doesn't bother me. That's God's business—He can take care of that.'' Indeed, although attribution of natural hazards and disasters have trended away from ''acts of God'' and toward ''acts of nature'' in recent decades, it has been shown that one's spiritual beliefs can and still do affect his or her hazard risk perceptions (Slimak and Dietz 2006; Sherry and Curtis 2017). A third and perhaps most heartfelt affective response expressed by farmers and ranchers is that of dejection or sadness. This response is primarily sourced from the hardworking farming lifestyle, which prides itself on providing food for the people. When that ability is taken away by a hailstorm, one is left feeling defeated. Interviewee 9 exemplified this mindset: ''We're all here for a reason, and part of that reason is the gratification of our hard work . . . there's a hole in your psyche that takes a while to fill back up with something else.'' Feelings of dejection are amplified when losses from a hailstorm mean fewer financial resources for other critical farming expenses. Interviewee 9 continued:

> Well, I can remember last summer . . . you go through the planting process and the crop's coming and it's looking nice, so then your mind starts thinking about . . . we got to get the combine tuned up, do I need any parts for that or . . . grain bins cleaned out, do we need a new [one of these] . . . your mind starts getting down that [path] and then within three days, that's all moot, [and] now your mind changes into ''Cannot buy this, cannot buy that'' because now I have a finite amount of money and [have] to stay within the confines of that . . . so it puts a lot of pressures on you.

Interviewee 4 expressed that in agriculture, ''there's always a need [for] a new tractor, a new truck, or . . . taking the next step that every business wants to take.'' When hailstorm recovery mandates postponing such upgrades, hope is deflated.

d. *Protective action—Nothing you can do for the crops*

Affective responses to natural hazards are linked to what protective actions people do and do not take (Lindell and Perry 2012; Demuth et al. 2018; Weyrich et al. 2020). Here, given the prevailing feelings of anxiety and acceptance toward hailstorms, the interview sample concluded that ''there's really not much you can do (interviewee 15).'' For large operations, covering crops or herding livestock into barns is not feasible before a hailstorm. Interviewee 12 joked that perhaps one day there would be ''a force field that you could bring up over your farm,'' but until that comes to fruition, crops and animals are largely on their own. Smaller vegetable farmers mentioned spreading protective tarps or nets over their vegetables but admitted that larger hailstones can still puncture or penetrate through these devices. The most tangible action steps routinely taken upon receipt of a warning for severe hail include alerting family or workers, moving vehicles and equipment under shelter, and closing windows.

Given the inability to hail-proof crops or rangeland, respondents were not overly enthusiastic about implementing adaptive strategies to protect against future hailstorms. A few smaller farmers mentioned changing roofing materials or building additional greenhouses to protect specialty crops from hail, while larger farmers tended to suggest crop diversification and rotation to reduce losses. As interviewee 14 put it, ''we're gonna have to find substitute crops here if we're going to stay around.'' Some interviewees mentioned adding sorghum or millets to their crop rotation because of the relative resiliency of their residue compared to other crops. Interviewee 3 was a big proponent of increasing organic matter in the soils as a buffer against hail impacts: ''Building soil organic matter and appropriate level of nutrients and biomass and microbacteria . . . all the soil health practices really aid in plant recovery time.'' Similarly, interviewee 9 sees ''regenerative value, cover crops, living roots, [and] soil biology'' as ''vehicle[s] to continue increasing organic matter and building resilience'' against hail and other natural hazards. For all that can or cannot be done to mitigate the effects of hail, the idea of perseverance was on peoples' minds. As interviewee 5 concluded, ''you just go on with your life.''

6. Summary and applications

Because hailstorms will inevitably continue to affect the communities of eastern Colorado and the United States as a whole, it is important to understand the human elements of dealing with them. The agricultural community is arguably the sector most directly impacted from hailstorms, not only physically with destruction of crops and equipment but also emotionally as hail penetrates into the livelihoods of farmers and ranchers. This study offers a first look at some of the unprimed beliefs, emotions, and behaviors associated with hailstorms through 15 mental models interviews with eastern Colorado farmers and ranchers. The overarching sentiment toward hailstorms is one of disdain and anxiety for their potential for significant crop and financial losses. Small hail, either in large quantities or wind driven, is of greatest concern to interviewees for its ability to strip, flatten, or even freeze crops if hail accumulates on saplings early in the season, whereas large hail is perceived to primarily pose a threat to physical structures. Adding language to the current SVR framework to account for hail volume, duration, and wind effects would greatly benefit the agricultural community. Moreover, advanced warning of these small-size-large-volume scenarios would also be of worth to those living along the Front Range urban corridor, which has experienced several impactful accumulating hail events in recent years. Toward this end, research that particularly identifies environmental conditions favoring these high-volume or wind-driven subsevere hail events (in addition to ongoing work in large hail prediction) through modeling or machine learning techniques is recommended.

Many interviewees expressed a sentiment that the agricultural impacts of hail should be recognized and acknowledged more broadly. In the words of interviewee 8,

> I see hail as something that needs to be a little more recognized. I know that when it happens in the cities it's a bigger deal because there's more personal property damaged. But people do not see the crops as a big deal even though maybe one crop costs more money in insurance than all the cars on a city block [that] are damaged . . . People do not stop to realize the long-term effects of that.

Even new farmers can be unsuspecting of the consequences of hailstorms. Interviewee 4 stated that ''you get a lot of people come to Colorado, they love Colorado, they love the outdoors, they want to get reconnected with nature so they start the farming, and they just don't have any idea . . . Colorado will punish you.'' While the agricultural community is highly influenced by the weather, it is possible that their needs are not being met by the forecasting community relative to the impacts they face. Interviewee 14 expressed a desire for ''the weather people . . . to be more relative to the agricultural community,'' and interviewee 4 felt that ''news is more focused on [the] Denver area.'' Facilitating stronger relationships between the weather and agricultural sectors could help farmers feel more recognized and also express their weather and forecasting needs as revealed in this study. One platform to potentially promote this relationship is with Impact-Based Decision Support Services (IDSS; NWS 2018; Uccellini and Ten Hoeve 2019), whereby NWS provides critical weather information to their partners and constituents. In addition, Integrated Warning Teams (Morris et al. 2008) that aim to improve weather messaging could benefit from including representatives or seeking input from the agricultural sector. Fostering these relationships can also help farmers and ranchers establish trust in the weather community, a quality that has been shown to promote greater behavioral response to warning messages (Sherman-Morris 2005). As such, future work by the authors will take the findings gleaned from this study to NWS forecasters to help spur discussion toward improvements in hailstorm risk communication.

Interviewees perceive an increase in both frequency of damaging hail events and personal sensitivity to their impacts in recent years. While some farmers are motivated to plant alternative crops that better withstand hailstone impacts and erosion, there is a general lack of energy toward mitigation of negative effects due to the perception that very little can be done to protect crops. Yet given the increasing trend in severe hail reports and days over the study domain (Childs and Schumacher 2019), and the projected future increases in hailstorms in the agricultural areas of eastern Colorado (Childs et al. 2020), we recommend research into resilient crops and crop management practices to help ease the consequent financial losses. Further, while not discussed at length here, interviewees were also asked to give their perceptions of crop insurance, which is utilized frequently after a damaging hailstorm. In short, almost all interviewees were quick to deem crop insurance a necessity that offsets at least in part the economic burden from a hailstorm. However, rising premiums and lack of coverage on certain crops are common frustrations, and as interviewee 4 stated, ''you hope you never have to use it.'' We anticipate bringing the insurance sector into this conversation to see how projections of future exposure to hailstorms and sentiments of current farmers can help advise policy creation.

The unique local hailstorm climatology and crop selection in a largely dryland farming regime may bias some of the results presented here, and future interviews using similar methods with farmers in other regions such as the Midwest and Southeast are warranted. Even if the notion of having limited options for protecting crops during a hailstorm prevails, promoting a greater awareness of the needs and sensitivities of farmers and ranchers, in addition to making strides in short-term hail predictability, will go a long way toward the goal of protecting life and property from future hail events.

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