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Constructing an Extensive Hail Damage Swath Database for Impact Analysis and Future Applications

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Constructing an Extensive Hail Damage Swath Database for Impact Analysis and Future Applications

by

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Table of Contents

Abstract

During the prime agricultural growing season from early spring to summer, severe and intense thunderstorms that occur throughout the Great Plains and Midwest have the potential to bring tornadoes, damaging winds, and large hail. On occasion, these storms have the ability to produce large, visible swaths of damage that can be seen from satellite remote sensing platforms for days to weeks after the initial event has occurred. Currently, there is no public database that identifies these events, like that is done with confirmed tornado tracks by the National Weather Service. This database was constructed by using daily satellite remote sensing imagery from NASA and daily storm reports from the Storm Prediction Center. Cross referencing the storm reports with True Color satellite imagery from MODIS and VIIRS, suspected hail damage swaths were cataloged in a spreadsheet. These suspected swaths were then validated by other investigators. All confirmed swaths and their spatial extents were digitized by drawing an outline around the damage using GIS software. From here, an extensive analysis took place. This analysis includes identifying potential geographic trends in both frequency and location of damage swaths throughout the study area as well as investigating annual agricultural losses due to significant hail events. Finally, this paper will discuss future work associated with this database, including using it as a training set for developing a machine learning technique for automatic detection and in turn, expanding databases to international locations that experience similar levels of hail damage and loss.

Introduction

Severe convective events and hail damage losses have contributed to billions of dollars in payouts in North America. Numerous studies have aimed to quantify these losses and have found that the average annual losses from hail across North America exceeds $10 billion annually (Loomis 2018). Additionally, losses attributed to severe convection in the United States in 2016 were estimated at $11.23 billion compared to $11.28 billion in damage from hurricanes in the same year (Gunturi and Tippett 2017). More recently, severe convective events in 2019 caused insurance payouts to reach $20 billion USD globally for the fourth straight year (Podlaha et al 2020). Studies have been performed over the last 50 years in order to better understand hail occurrence and update the current climatologies available in the United States due to the significant economic impacts on infrastructure and agriculture. The research that emerged in the 1960s and 1970s highlighted hail hotspots across the United States, with a particular focus on the Midwest and Great Plains regions. On a statewide level, there was a particular focus on understanding the spatial and temporal trends in Illinois. It was found that the maximum amount of intense hail occurred in September during the May to October agricultural growing season, and corn being most susceptible to damage during July (Changnon 1967). Changon and Stout (1967) then explored a more widespread analysis and identified 13 areas of hail maxima in the Great Plains and Midwest where meteorological conditions coincided with occurrence of hail.

Ground and space based remote sensing instruments and derived products have been the main sources of data when hail climatologies have been created during the past decades. Specifically, space based passive microwave missions such as the Global Precipitation

Measurement (GPM) mission has been utilized to create a nearly worldwide hail occurrence climatology through the use of brightness temperature observations (Bang and Cecil 2019). Within the United States, many other products can be integrated into the creation of hail occurrence climatologies due to derived products from the vast network of ground-based weather radars. These products include Maximum Estimated Size of Hail (MESH; Witt et al. 1998), Multi Radar Multi Sensor (MRMS), and MYRORSS. Compared to worldwide climatologies, this will allow U.S. climatologies to track hail occurrence at a higher spatial resolution and provide additional information about temporal trends as compared to other mediums (Murillo et al. 2019; 2021).

Severe convective events can bring strong winds, large hail, and tornadoes to the Great Plains and Midwest during the prime agricultural season from 1 May to 31 August. On occasion, some of these storms leave behind large swaths of hail damage that can be seen from satellite remote sensing platforms for days to weeks after the initial event occurs. Frisby (1962) investigated 10 years' worth of insurance records in South Dakota and categorized damage patterns into various groups. The pattern groups included "swath-type patterns with a northwest to southeast slant", "slightly curved lines or series of lying southwest to northeast", and "clusters without easily recognizable form". The paper also linked each pattern with a corresponding synoptic pattern but noted that hail may not be produced every time during similar patterns. Frisby (1963) also denoted hail damage swath length, which was found to range anywhere from 50 - 200 miles long and 5 - 15 miles wide. Contrary to the technology leveraged now, the main method of analysis in the 1960s were from aerial photography using both standard color and infrared film (Changnon 1971).

Over the past 25 years, there have been numerous studies investigating hail damage swaths using passive and active space based remote sensing instruments. Klimowski et al. (1998)

leveraged an operational geostationary satellite to measure a hail damage swath that occurred in South Dakota in 1996. The Normalized Difference Vegetation Index (NDVI) is a product derived from red-visible and near-infrared bands from optical remote sensing instruments. It has been useful in pinpointing differences between clouds and water, urban areas and potentially damaged vegetation, and healthy, green vegetation to help quantify damage accrued by hail damage swaths (Rouse et al. 1974, Tucker 1979). NDVI has been a central tool to numerous studies surrounding hail damage swaths and has been used in conjunction with other tools, such as radar products and surface-based reports for cross validation. Parker et al. (2005) mapped swaths from two events occurring in South Dakotas in July 2003 using NDVI composites as well as changes in land surface temperature and moisture content in and near where the swaths occurred. This paper also investigated the residual effects these swaths may have on localized convective initiation. Gallo et al. (2012) selected convective events that occurred on 9 August 2009 throughout Nebraska to Michigan and used NDVI composites to map damage swaths. Molthan et al. (2013) also utilized NDVI amongst other products to identify damage and potentially create near real time products for changes in NDVI after damaging events occur. Bell and Molthan (2016) incorporated both NDVI anomalies and land surface temperature imagery when examining hail damage in satellite imagery. Similar to many studies previously mentioned, it was found that the performance of NDVI greatly depended on the timing of the event within the prime agricultural growing season. The anomaly detection technique was recommended for near real time use due to its strong performance across many months, particularly in June, July, and August. Gallo (2019) utilized similar tools to the 2012 paper, but included the aspect of digital photography in order to distinguish three different levels of agricultural damage from hail swath events. This aided in filling some of the gaps the previous paper encountered because of the lack of surface observations

available. Bell et al. (2020) implemented synthetic aperture radar (SAR) and NDVI to observe hail damage, which found promising results, but needed further investigation on the scattering mechanisms from SAR data.

Previous work investigating hail swaths have been limited to particular case studies, so the overall knowledge of the spatial extent of these damage swaths is relatively unknown, despite the annual occurrence in the Great Plains and Midwest region. In addition to a lack of a central documentation source of these events, there is still great uncertainty when forecasting hail and the risk associated with it. Many papers discuss the limitations of the current hail record in the United States, which can partly be attributed to poor quantification compared to other severe weather reports and observations, such as tornadoes, which then leads to difficult analysis of the impacts of these events after they occur (Ortega et a. 2009, Allen and Tippett 2015). With these notions in mind, this study aims to document as many hail damage swaths as possible in order to fully understand the potential infrastructure and agricultural impacts over an extended period of time from 2000 to 2020. The creation of the database utilized open-source data, such as SPC Storm Reports and daily observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra and Aqua satellites. This will allow the database to continue to grow past the initial 21-year analysis. All documented and confirmed hail damage swaths would then be compiled into a public database to learn more about hail damage swaths as a whole. The primary question this paper aims to investigate is: What are the temporal trends and spatial extent of the occurrence of hail damage swaths across the Great Plains and Midwest region during the prime agricultural season?

With the creation of this extensive database, it will allow further exploration of agricultural impacts, automatic detection of swaths, improvement of sub-seasonal and seasonal forecasting, increased understanding of storm mode and conducive storm environments, and more.

Data and Methods

Data

SPC Storm Reports

Daily Storm Prediction Center (SPC) Storm Reports (available online at https://www.spc.noaa.gov/climo/reports/today.html) categorize events as tornado, wind, hail, and total reports. These products are considered preliminary, with a variety of factors influencing the number of reports received on a particular day by the SPC, such as population. For reports within the past 10 years, SPC Prototype Interactive Storm Reports Display (available online at https://www.spc.noaa.gov/exper/reports/) were used. This website allows the user to further interact with basic SPC Storm Reports for that particular day. From 2012 to 2017, the SPC Local Storm Report (LSR) vs Maximum Expected Hail Size (WDSSII MESH) Maps are publicly available (available online at https://www.spc.noaa.gov/climo/online/lsrmesh/) and were utilized in conjunction with storm reports. MESH is a radar derived product that produces values for hail size (Witt et al. 1998) and was used as an additional resource to locate potential hail damage swaths. This product worked especially well in rural areas, where there are little ground-based observations reported in daily SPC Storm Reports.

NASA MODIS Imagery

Daily True Color imagery from the Moderate Resolution Spectroradiometer (MODIS) instrument was obtained through the NASA Worldview portal (available online at https://worldview.earthdata.nasa.gov/). NASA Worldview is an interactive data portal from

NASA's Earth Observing System Data and Information System (EOSDIS), which provides over 1000 products from polar and geostationary satellites with data being available within three hours of observation (NASA EarthData). MODIS True Color (Bands 4, 3, 1) and false color (Bands 7, 2, 1) imagery were acquired from Aqua and Terra, two NASA polar orbiting satellites. The temporal coverage of Terra is February 24, 2000 to present, while Aqua is available from July 3, 2002 to present. There were periods of outages in 2000 and 2001 causing missing monthly products for August and June, respectively (available online at: MODAPS Services - Production (nasa.gov)). Images of confirmed hail damage swaths were downloaded through the NASA Worldview portal at 500-meter spatial resolution.

IEM Cow

IEM Cow (available online at https://mesonet.agron.iastate.edu/cow/) is an application produced by Iowa State University that stores a multitude of archived National Weather Service text products, past severe weather warnings, and other meteorological data. In order to provide an additional validation for hail damage swaths within the database, IEM cow was used to obtain all severe thunderstorm and tornado warnings dating back to 2000. This source also stores archived NWS radar imagery, which was particularly useful to verify discrepancies in dates of events.

Methods

The creation of this database can be separated into four steps: locating a potential hail damage swath, cataloging it in the database, creating a geospatial outline of the event, and performing multiple types of quality checks on the swaths included within the database.

Potential hail damage swaths were first identified in daily SPC Storm Reports between 1 May and 15 September in order to encapsulate the entirety of the growing season in the Great Plains and Midwest, spanning from planting in May to harvesting in September. Within the SPC Storm Reports, clusters of hail and/or wind reports, especially in a linear fashion, indicated a potential event for an area (Figure 1). For additional validation, the LSR Hail Reports vs. WDSSII MESH product was used during the available time frames. This dataset was especially useful for rural areas (Figure 2). These areas were then further investigated in satellite imagery. Daily True Color Imagery from the Aqua and Terra sensors aboard the NASA MODIS instrument were utilized to determine if there was a hail damage swath visible (Figure 3). The “Comparison Tool” within NASA Worldview aided in locating an event by comparing pre-event to post-event land cover (Figure 4). This method was especially useful for locating events occurring in May and September, when the land cover changes

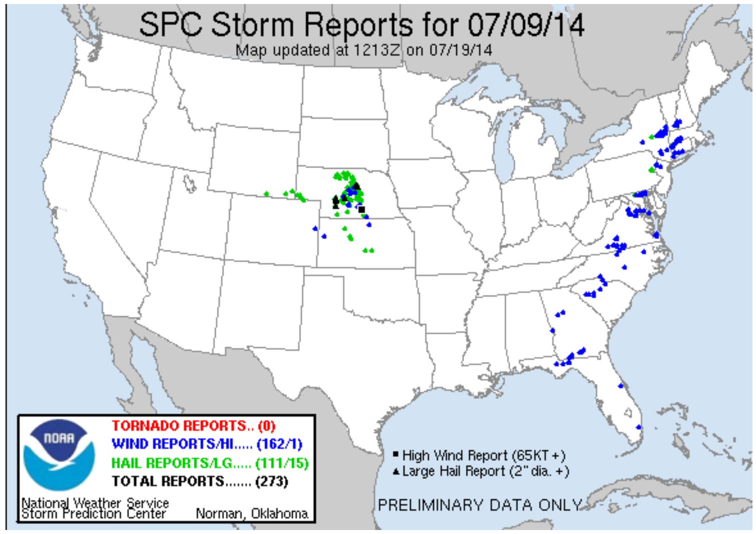

Figure 1. This figure represents the SPC Storm Reports for 07/09/2014. The area of interest is pinpointed by looking for reports in a linear fashion. In this case, Central Nebraska would be the region of interest for a potential hail damage swath.

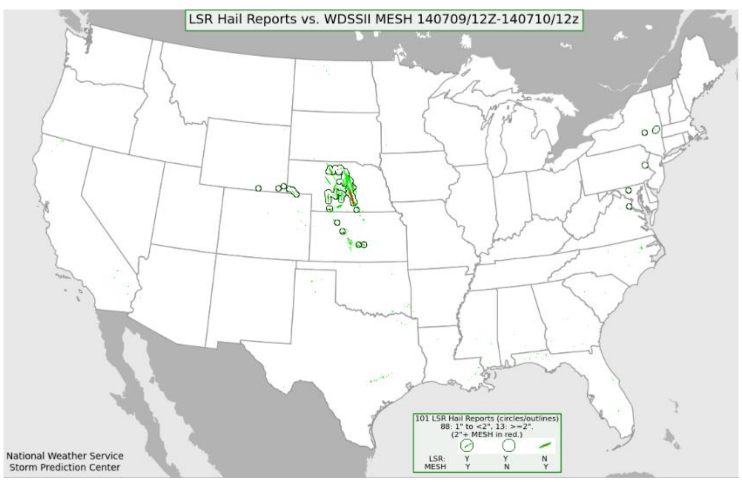

Figure 2. The figure represents the LSR Hail Reports vs. WDSSII MESH for 07/09/2014. It indicates there was hail greater than 2” in Central Nebraska, furthering that there may be a hail damage swath in this region.

Figure 3. Hail damage swath in Central Nebraska from a severe storm that occurred on 07/09/2014.

were not apparent. Additionally, this tool helped in states located in the Western region of the study area, where there are dense fields of agricultural crops, but more grassland land cover types. Due to the limitations of True Color Imagery, such as cloud cover and sensor recalibration, imagery was analyzed up to 15 days after the targeted storm report date, except in rare cases where cloud cover was present for more than two weeks post event. The 15-day time frame set a fair threshold to ensure the entirety of the damage caused by the storm was able to be seen without a chance for the crop to recover, which was a particularly important element for swaths occurring early on in the growing season (Bell and Molthan 2016).

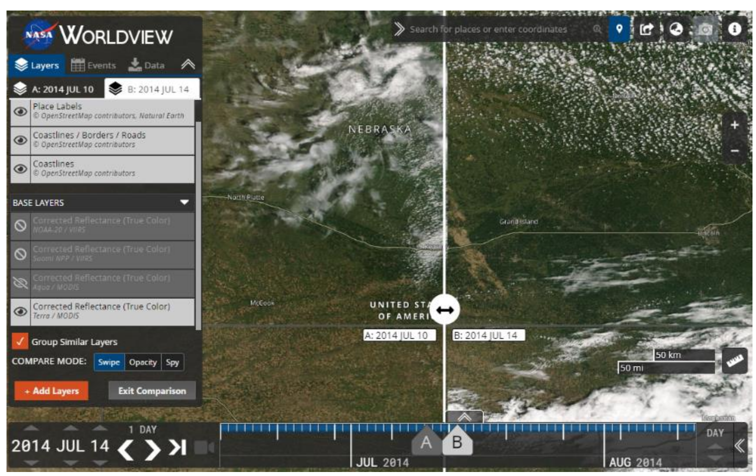

Figure 4. Comparison tool from NASA Worldview. Image A shows the land cover pre-storm and Image B shows the land cover post-storm, where the hail damage swath can be seen.

If a hail damage swath was located in both SPC Storm Reports and NASA Worldview, the swath was cataloged into a spreadsheet. A series of metadata accompanied the swath (Appendix A) to provide key information for each potential swath. Each swath was assigned a confidence level by the member of the research team that initially located the swath. This was a

subjective assessment on if the potential hail damage swath would be included in the final database. After the process of locating swaths was finalized, other members of the research team provided confidence levels for swaths that had low to moderate initial confidence levels (7 or lower). If swaths had multiple confidence levels lower than 5, then the swath was not included in the database, but remained as a cataloged event. There were hail damage swaths found that did not correspond to a SPC Storm Report, but was located in satellite imagery by accident when looking into specific areas of interest for other events. This is a limitation of using observational data, such as SPC Storm Reports, due to the reliance on population. This was especially proven to be true in rural areas, where reports are more limited (Bunkers et al. 2020).

The next step in the formation of the database was to create geospatial outlines of the confirmed swaths (Figure 5). For each confirmed event, images with geographic properties (GeoTIFFs) were downloaded using the 'Best Date' from the metadata for a specific event. The 'Best Date' was within the 15-day window as previously discussed, and was mostly free of cloud cover that would impact the view of the surface.

Figure 5. Geospatial outline that was manually drawn in ArcGIS Pro for the event occurring on 07/09/2014.

This imagery was then brought into Esri's ArcGIS Pro, which is a Geographic Information System (GIS) software program. This software was used to create geospatial outlines or polygons of all

of the confirmed hail damage swaths. Metadata for each swath was manually entered into the shapefile attribute table for each polygon, which was pulled from the Google spreadsheet of events. For long swaths of damage, numerous polygons were drawn in order to avoid overestimation of potential damage that occurred. However, this is not a flawless method due to cloud cover in the imagery, spatial resolution, and human error. Even with these factors, there is a high confidence level among investigators that the database is accurate due to the extensive quality control and quality assurance process throughout the study.

Over 1800 hail damage swaths were identified and outlined in the initial iteration of the database that spanned from 1 May to 15 September. Each of the polygons were then quality checked using archived severe thunderstorm and tornado warnings, archived NEXRAD radar storm tracking data, and daily SPC Storm Reports in geospatial form. Storm dates from the metadata within the shapefile were used to identify the corresponding severe thunderstorm and tornado warnings that intersected the geospatial outlines of the hail damage swath. If the polygon was associated with warning, radar data, or SPC Storm Reports, it was included in the final iteration of the database. If the polygon did not have any overlap with the warnings, radar, or storm reports, the team investigated potential storm dates within 7 days pre- and post-date that was currently being used. For each date discrepancy, a member of the team investigated. If a new date was not found, or there was low confidence in the swath in general, the event was tossed from the database. The majority of the discrepancies were due to SPC Storm Report dates being in UTC time, while date warnings were issued in local time.

Analysis of the Database

Hail damage swaths were identified between 1 May and 15 September, however, swaths occurring from 1 May to 31 August were included in the final form of the database. Swaths occurring in September were removed from the final iteration of the database because they were difficult to decipher due to the overlap with the beginning of autumn harvest. Since there was also a sharp decline in events occurring halfway through the month, it was decided to remove September from the database entirely.

The final form of the database included 1646 hail damage swaths that occurred during the 21-year time period. Swaths spanned across the Great Plains and Midwest and impacted 12 states altogether (Figure 6). Hail damage swaths that crossed state borders were counted as swaths in

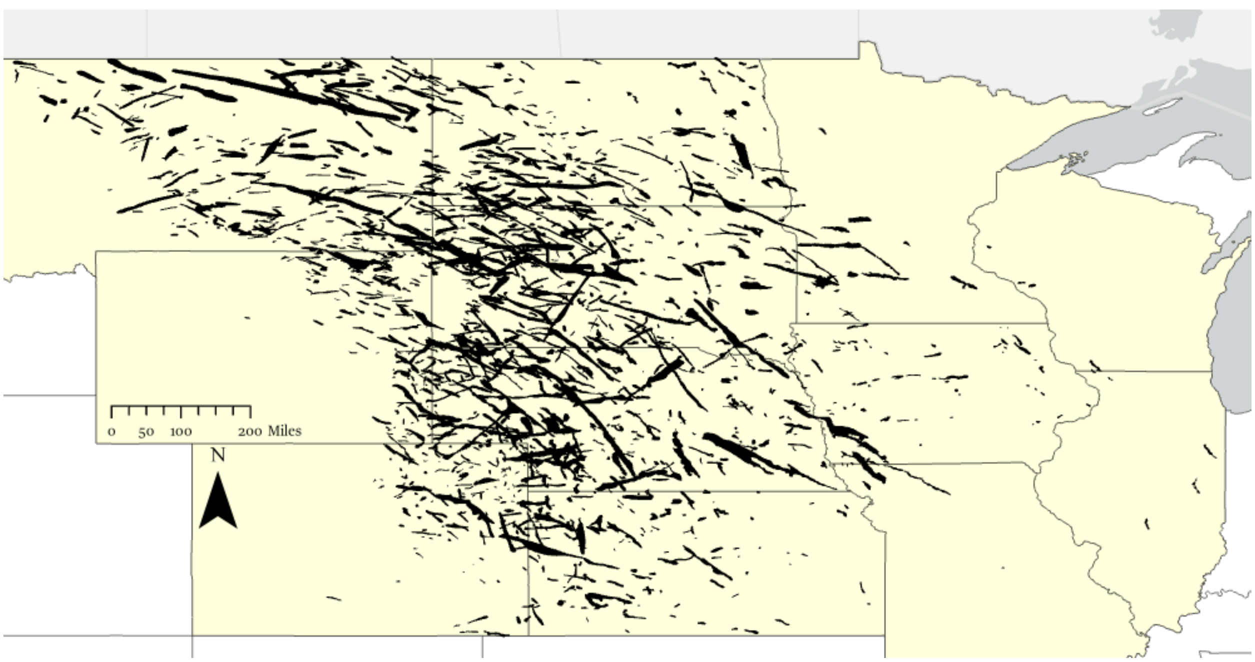

Figure 6. Full spatial extent of swaths found and included in the final iteration of the database.

both states impacted, similar to the process the National Weather Service (NWS) uses when counting tornadoes that cross County Warning Area (CWA) boundaries.

The study region for this database was quite expansive, as it covered much of the Central United States. Hail damage swaths were found as far west as Montana and as far east as Wisconsin and Illinois. Additionally, swaths spanned from the Canadian border down through Kansas and into Oklahoma. Although hail damage swaths can occur outside this domain, this region of the United States was chosen due to the high concentration of agricultural land, as well as the susceptibility that land has to damage from severe convective events. Specifically, South Dakota had the most confirmed hail damage swaths at 358, followed by Nebraska at 299, and North Dakota at 293. The states with the least number of hail damage swaths included Missouri at 9, Illinois at 6, and Wisconsin at 5, for a combined total of only 20 confirmed hail damage swaths from 2000 to 2020 (Figure 7). Categorizing damage swaths by state allows for visualization of risk by location.

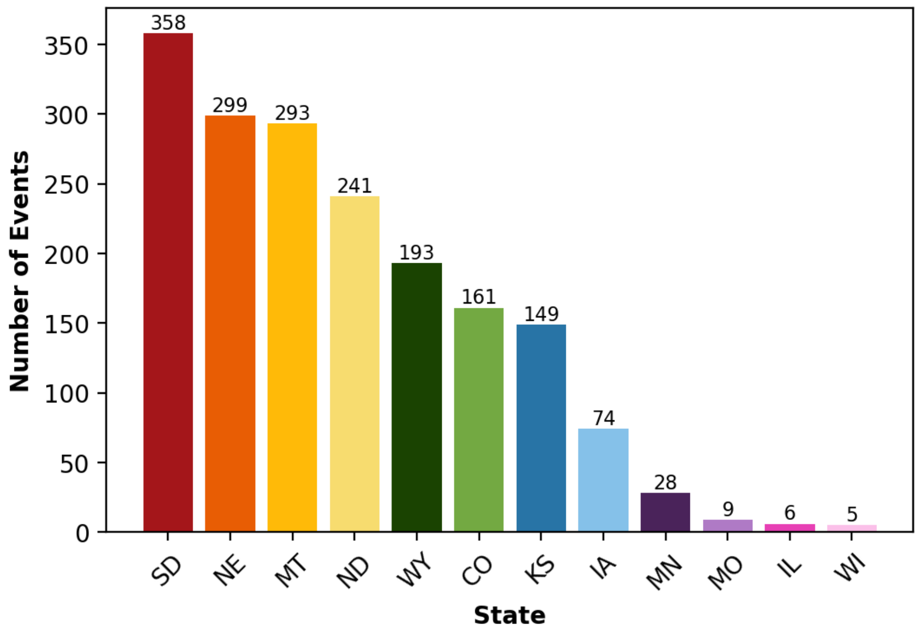

Figure 7. Hail damage swaths per state.

Figure 8 breaks down the number of confirmed hail damage swaths by year to investigate potential temporal trends. Based on the findings, it is evident that there are fluctuations from year-to-year. The number of events per year can be attributed to many things, such as drought conditions and the state of the vegetation, and possibly, background climatological cycles. The year with the most confirmed swaths was 2011 with 126, then 2010 with 124, and then 2009 with 121 events. The years with the least number of swaths identified were 2002, 2006, and 2012, with 34, 40, and 42 swaths identified, respectively. A trendline, shown in Figure 8, identifies a general upward trend in the number of confirmed hail damage swaths, however there is great variability occurring yearly. As the database expands each year and covers a longer period of time, there will be more data points to investigate yearly trends and provide greater insight into potential factors that contribute to the impact of hail damage swaths on a yearly basis.

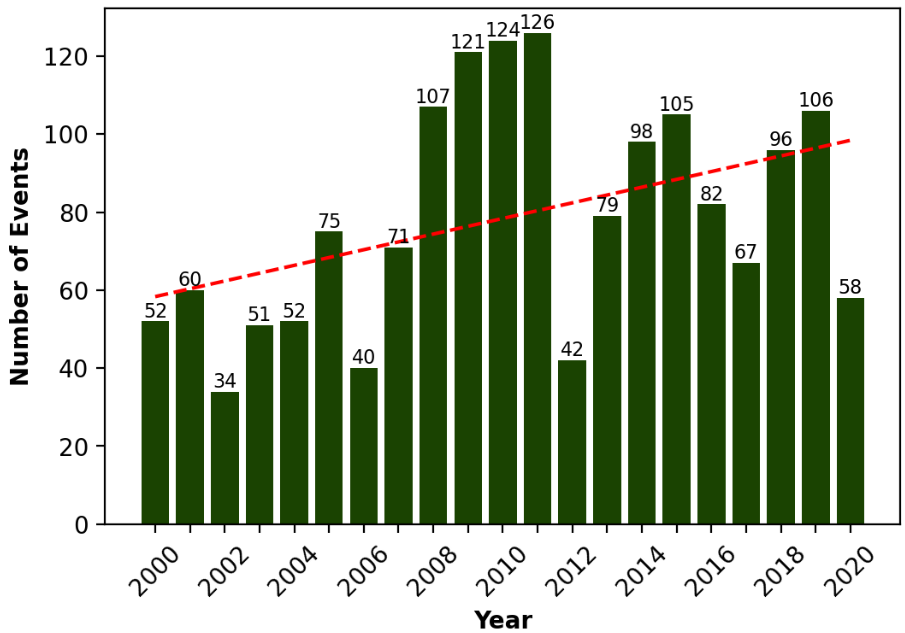

Figure 8. Distribution of events by year. A general upward trend of events occurs over the 21-year time frame.

Swaths were also broken down by month (Figure 9). Out of the months surveyed in the study, July had the most confirmed hail damage swath events with a total of 650 swaths. The majority of events occur during the months of June and July when lush, green vegetation is present.

It is more susceptible to damage from severe convective events, in particular, hail and wind damage. Additionally, peak storm season for the Great Plains and Midwest is during the summer months. This coincides with previous literature which observed corn crops in Illinois, Iowa, Minnesota, Missouri, and Nebraska were most susceptible to damage and thunderstorm intensity during the month of July (Changnon 1977). Additionally, Changnon 1977 also found that July corresponded with peak hail intensity, further contributing to potential damage to agricultural crops. The month of June has the second most amount of hail damage swaths with 569, followed by August with 295, and lastly, May with 132. This solidifies that hail swaths primarily occur during the months of June and July due to peak storm season and the stage of vegetation growth in the summer.

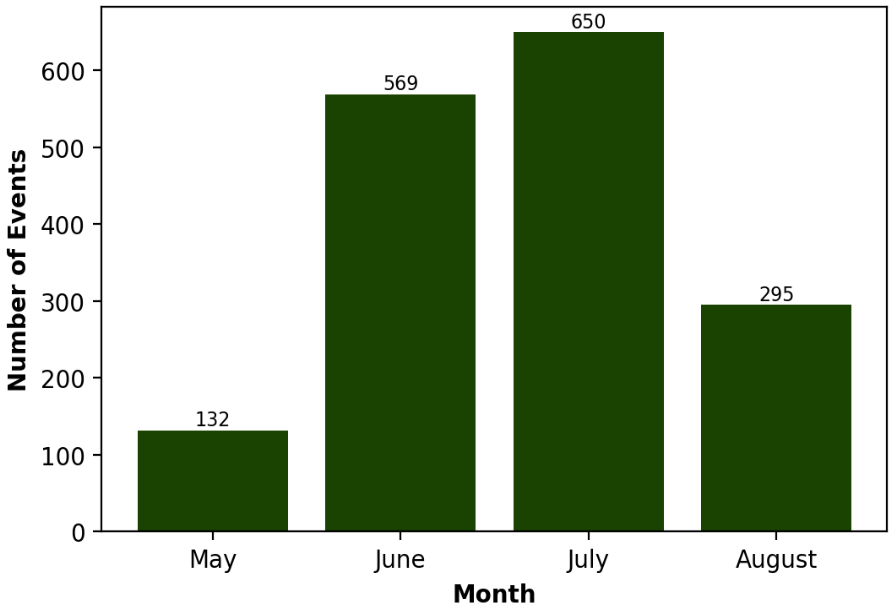

Figure 9. Hail damage swaths per month.

To further the visualization of spatial hotspots in the study region, a 0.1-degree gridded hotspot analysis was performed (Figure 10). It is seen that there are localized hotspots occurring in Southwestern North Dakota, Northwestern South Dakota, Northeastern Wyoming, Southwestern Nebraska, and Eastern Colorado. The majority of hotspots occur East of the Rocky Mountains, which may indicate a potential link between hail damage swaths and storm systems that form off the lee side of the Rocky Mountains. In order to confirm this, more investigation into

storm mode, direction, and characteristics would help better understand potentially favorable environments for hail-swath producing storms to occur within. This initial analysis of spatial and temporal trends paves the way for numerous avenues for future work to occur.

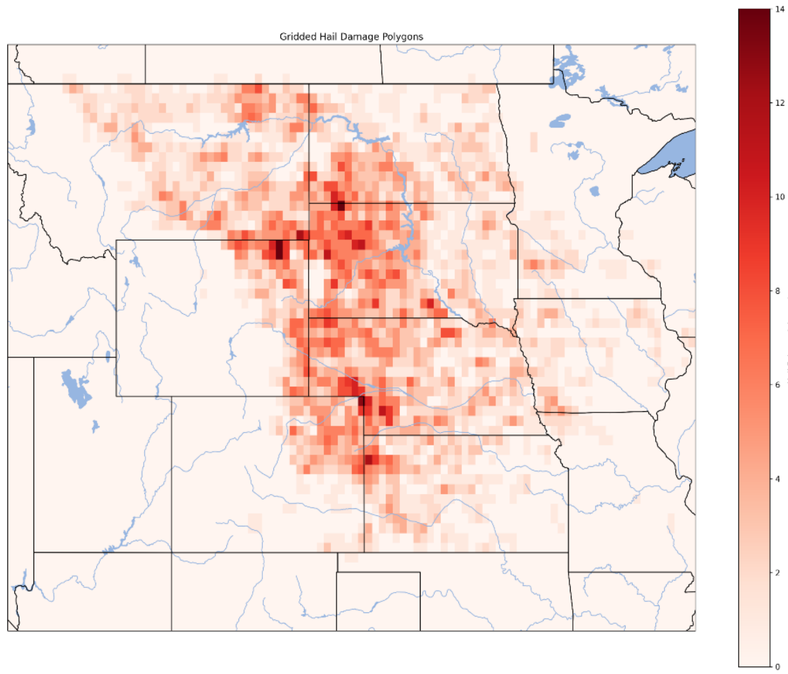

Figure 10. Hotspot analysis on a 0.1-degree scale. Potential hotspots are shown to be in Wyoming, the Dakotas, and Nebraska.

Summary and Future Work

Severe convective events can cause large swaths of damage to agricultural crops during the summer growing season due to damaging winds and large hail. Based on previous literature, these hail damage swaths can cause hundreds of millions of dollars in damage annually and impact infrastructure and agricultural crop yields across the Great Plains and Midwest. Due to their size, satellite remote sensing instruments have frequently been used to analyze hail damage swaths.

Previous studies on hail damage primarily focused on analysis of specific swaths with a collection of different remote sensing instruments and techniques in order to quantify damage, recovery, and loss. These studies utilized optical remote sensing instruments to investigate damage in the common red-visible and near-infrared bands. This allows analysis of short- and long-term changes in NDVI values. Occasionally, studies have used thermal-infrared to better understand surface processes after swaths occur. More recently, studies have integrated SAR instruments in order to provide additional information on the surface regardless of weather conditions for the specific location.

These studies have provided an in-depth analysis of specific swaths, but have not been able to look at the larger scale of these events. The creation of a hail damage swath database would aid in the understanding of spatial and temporal trends in events that occurred from 2000 to 2020 in the Great Plains and Midwest region. The database leveraged public datasets, such as SPC Storm Reports and daily True Color Imagery from NASA Worldview. After the completion of the database, it went through several rounds of quality checks, including confidence levels for events from other investigators.

The development of this database allows for several different future applications. First, this database was created manually, which was time consuming and cumbersome. Moving forward, this database can serve as a training and validation dataset for a machine learning technique to automatically detect swaths. In addition to expanding the current database, this machine learning technique may provide the opportunity to create hail damage swath event databases in other countries as well. This database will also allow for comprehensive case studies to be conducted on particularly impactful swaths, especially those with large agricultural impacts. Similarly, the geospatial polygons drawn around swaths allow for a complete picture of agricultural impacts for a specific region and year. This will allow there to be a better understanding of trends on a year-to-year basis, and potentially provide more information on specific hot spots. Lastly, this database would allow investigation into storm mode, storm environment, and analysis of mesoscale processes associated with impact hail damage swath events. This could be especially useful for seasonal to sub-seasonal forecasting and operational meteorology applications in the future.

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Appendix A

Field Name	***Description***
Location	Specific location where the extent of the hail damage swath occurred. Town names were utilized to pinpoint specific areas impacted.
States Impacted	It was noted what state the hail damage swath occurred in. If swaths crossed state borders, it was extremely important to note for accurate counts.
Analyst Initials and Confidence	The investigator who found the swath provided their initials and confidence level in the event. From here, additional analysts would provide their confidence levels on the event if the initial confidence level was under a specific threshold.
Swath Date	The day the swath occurred, which was primarily found from the date of the SPC Storm Reports.
Worldview Link	Once the swath was located in NASA Worldview, the link to the best date was pasted into the Google Sheet. The comparison tool was used in order for additional investigators to provide confidence levels.
First Appears Date	This date indicates the first date the swath was found in NASA Worldview. This was not always the Best Date. Worldview imagery often has cloud cover for multiple days and sensor calibration that distorts images. As long as part of the swath was present in this imagery, that determined the First Appears Date.
Best Date	The Best Date is when the hail damage swath was best seen in the NASA Worldview imagery. There was a 14-day threshold post event to find the Best Date image in order to prevent images where parts of the swath could have been recovered or replanted, depending on the time of the growing season.
Best View Sensor	Both Aqua and Terra were utilized to find hail damage swaths in NASA Worldview. This field could be populated with Aqua, Terra, or both, if both sensors provided clear images for the swath.
SPC Reports Link	The link to the Storm Reports for the Swath Date were entered into the database for reference of the event.
Notes/Social Media/WFO Event Summaries	If there were any additional notes or comments about the event from WFO or social media outlets, they were included in this section of the Google Sheet.

Additional Validation	Once a swath was deemed probable by the first investigator, there would be 1-3 additional validations done by other investigators to determine if the swath would be included in the database. If the swath had multiple confidence levels lower than 5, it was not included into the database.