NDVI ANALYSIS OF HAIL SWATHS ASSOCIATED WITH THE 5 MAY 1995 PARKER COUNTY AND TARRANT COUNTY, TEXAS, HAILSTORM

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Abstract

A devastating hailstorm moved through the north Texas counties of Parker and Tarrant on the 5th of May 1995, causing extensive damage to structures and vegetation. Remote sensing techniques by means of normalized difference vegetation indices (NDVI), image differencing, and change detection were utilized to assess severe hail damage areas associated with the storm. Weather Surveillance Radar – 1988 Doppler (WSR-88D) Level II data from the time of the storm were spatially compared to the NDVI classified hail damage swaths. Analysis shows a statistical correlation exists between WSR-88D radar returns and hail damage for the rural areas of Parker County, with no correlation evidenced for the urban areas of Tarrant County; although hail damage areas can be visually identified for parts of the city of Fort Worth. Statistical results indicate that remote sensing NDVI methods are valid for identification of hail swaths in relatively rural areas, but have a lesser application for detection in densely populated urban regions. Comparison of the NDVI change detection to in-situ observations of the hail event show that greater negative NDVI change values are indicated in areas that experienced the greatest hail density compared to areas which experienced the largest hail size.

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1. Introduction

On May 5th, 1995, an extraordinarily severe supercell thunderstorm developed over the southwestern portion of Parker County, Texas (Calianese et al. 2002). The storm began producing hail at 2317 Universal Coordinated Time (UTC), as it moved slowly to the east-northeast. The storm exited Parker County to the east after causing an estimated 4 million dollars in damage (NCDC 2010a). As the storm moved through Tarrant County Texas, it produced devastating hail up to 10.2 cm in size across parts Fort Worth, Texas, including the densely populated downtown area. The storm injured more than 100 people before weakening shortly after 0100 UTC in the northeastern part of Tarrant County. The total monetary damage from the storm toped more than 2 billion dollars, making it the costliest thunderstorm in United States history (Hill 1996).

The purpose of this paper is to use remote sensing techniques to analyze the May 5th, 1995 hail damage over Parker and Tarrant counties. Using methods outlined by Bentley et al. (2002), normalized difference vegetation indices (NDVI) are defined for two Landsat-5 Thematic Mapper images, which represent times before and after the hailstorm. Change detection methods are then used to create a composite image which identifies areas where the vegetation has been “stressed” or is unhealthy, where negative change in greenness value indicates vegetation damage. Spatial visual analysis of the resulting image is then used to define hail swaths. Hail swaths are then compared to Level II WSR-88D data for the entire time period of the storm.

The May 5th, 1995 hailstorm event provides a unique opportunity to compare the performance of NDVI change detection techniques for rural and urban areas. Parker County represents a relatively rural county, with a year 2000 population of 88,495 persons and a population density of 254 persons per square kilometer; whereas 1,446,230 people reside in Tarrant County, with a population density of 4340 persons per square kilometer (U.S. Census Bureau, 2010). Bentley et al. (2002) show that the use of vegetation indices is a valid method for hail detection in rural and predominantly agricultural regions. Yuan et al. (2002) demonstrate that NDVI techniques are applicable for the detection of tornado damage over urban areas, and in some cases, outperform the statistical technique of principle component analysis of remote sensing data for this application.

2. Study Area

The location for this study is in the north-central part of the State of Texas (Fig. 1). This region is climatologically prone to west to east moving hailstorms which frequently occur during the springtime months of April and May (Basara et al. 2007). The study area represents two counties within the state of Texas. Parker County covers a total area of 2340.09 square kilometers, and Tarrant County has an area of 2236.26 square kilometers (U.S. Census Bureau 2010). Parker County is relatively rural, but is considered to be within the geographically defined Dallas/Fort Worth Metroplex. The largest city in Parker County is Weatherford, with a year 2000 population of 19,000. Tarrant County is a densely populated urban county, with Fort Worth being the largest city, with the year 2000 population of 534,694. Tarrant County is the location of the Fort Worth/ Dallas (FWD) Weather Forecast Office of the National Weather Service. The Weather Surveillance Radar - 1988 Doppler (WSR-88D) is located at the extreme southern end of Tarrant County at the Fort Worth Spinks Airport in Burleson.

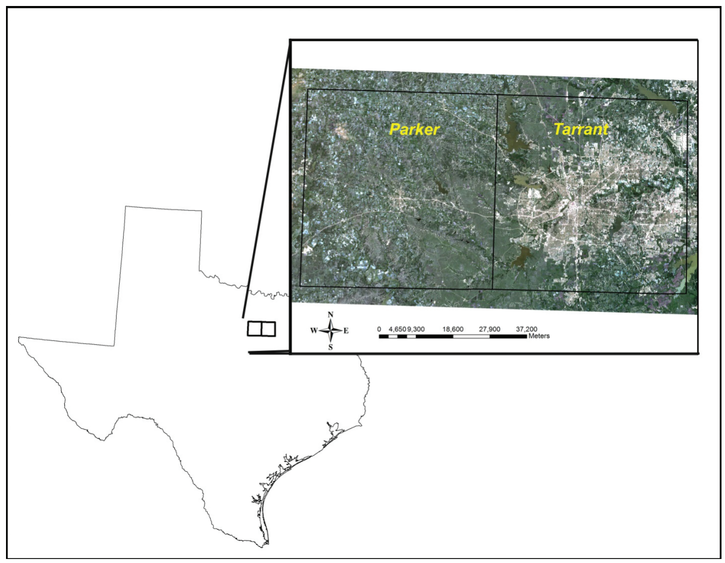

Fig. 1. Location of study area. Image is a Landsat-5 Thematic Mapper false color composite. Note the easily distinguishable dense urban area covering most of Tarrant County.

Fort Worth is the home of two major television news media outlets; KXAS-TV and KTVT-TV. This is important for this study due to the fact that the physical locations of the television stations are within an area that experienced severe hail during the storm event. Both stations provided continuous televised coverage of the storm as it moved through the Fort Worth area (KXAS 1995).

3. May 5, 1995 Storm

Supercell thunderstorms are considered the most severe and destructive of all non-tornadic/non-hurricane related severe weather events, and the May 5th, 1995 Parker and Tarrant County hailstorm was the archetypical example of a storm of this type (Bunkers et al. 2006). Supercell thunderstorms in their most severe forms tend to be long lived. The May 5th storm lasted for more than 2 hours, producing severe hail for much of its existence. Table 1 illustrates the timeline for the storm, starting with its development along the western edge of Parker County, and continuing through its exit to the east into Dallas County. During the time the storm was at its peak, it was producing hail up to 10.2 cm in diameter. At one point, the extreme amount of hail being produced by the storm covered an area more than 5 km wide, with "hail drifts" of 45.7 cm in depth (NCDC 2010a).

A combination of meteorological events occurred on the afternoon of May 5th that would lead to the development of the intense storm. During the early afternoon hours, a squall line of storms formed in response to a dryline along the Texas-New Mexico border (Calianese et al. 2002). The squall line moved quickly eastward into an area of strong upper level winds and unstable air, associated with a warm front stalled to the south of the Fort Worth area. The supercell hail producing storm formed in southwestern Parker County, ahead of the approaching squall line. WSR-88D data showed low level reflectivity above 70 dBZ, indicating intense precipitation and hail. As the storm moved through the central part of Parker County, it produced the "hail drifts" that covered an area approximately 4.8 km wide, stripping leaves from the trees and shrubs that were not covered with hail (NCDC 2010a). It is interesting to note that reports of the largest hail occurred in the Fort Worth area of Tarrant County, while the greatest hail density was observed in Parker County.

During the late afternoon hours of May 5th, more than 10,000 people were celebrating Mayfest at Trinity Park which is located just to the west of Downtown Fort Worth (Hill 1996). Mayfest is an annual outdoor festival held in an area that provided little shelter from the approaching storm. As the strongest part of hail storm moved across

Time (UTC)	Event
~2200	Storm develops to the west-southwest of Parker County.
2248	Severe thunderstorm warning issued for Parker County.
2317	4.4 cm hail and thunderstorm wind gust are reported near Dennis in Parker County.
2327	Severe thunderstorm warning extended for Parker County.
2330	4.4 cm hail covering the ground to 45.7 cm deep is reported in Annetta.
2345	Severe thunderstorm warning issued for Tarrant County.
0000	7 cm hail reported in Aledo.
0005	7 cm hail and wind damage reported in White Settlement and Benbrook
0006	Tornado Warning issued for Tarrant County. No tornadoes are reported.
0008	2.5 cm hail reported at the Carswell Naval Air Station.
0020	8.9 cm hail reported at the Mayfest outdoor festival in Trinity Park, just west of downtown Fort Worth. More than 100 people are injured.
0030	10.2 cm hail reported in downtown Fort Worth. Considerable damage to structures.
0030	Severe thunderstorm warning expires for Parker County.
0035	3.8 cm hail is observed at the National Weather Service Office location north of downtown Fort Worth.
0035	7 cm hail reported in East Fort Worth.
0035	10.2 cm hail and 65 knot wind gust observed at the KXAS-TV studios in East Fort Worth.
0045	Severe thunderstorm warning expires for Tarrant County.
0046	1.9 cm hail reported in North Richland Hills.
0050	4.4 cm hail reported in Hurst.
0050	2.5 cm hail reported in Redford.
0100	4.4 cm hail and 70 knot winds reported in Arlington in the eastern part of Tarrant County.
~0105	Storm dissipates from a hail producer into a heavy rain producer as it moves to the east into Dallas County.

Table 1. Timeline of May 5th, 1995 Severe Thunderstorm Events for Parker and Tarrant counties. Warning data obtained from Iowa State University Iowa Environmental Mesonet (IEM 2011) and event data from the National Climatic Data Center (NCDC 2010a).

the Trinity Park area, 8.9 cm hail (larger than baseballs) began falling at speeds believed to be more than 160 km/h. Witnesses reported the hail as having sharp edges, as opposed to being totally smooth. More than 100 people were injured, with 60 having injuries requiring hospitalization (Calianese et al. 2002).

WSR-88D radar loops of the event indicate that the storm moved to the east-northeast at a heading of approximately 85 directional degrees across Parker and far western Tarrant County (NWS 2010). As the storm moved through Fort Worth, it turned to a heading of approximately 60 degrees to the northeast. After the hail intensity of the storm diminished, the wind increased to greater than hurricane force at 70 knots near the western part of the city of Arlington in eastern Tarrant County (NCDC 2010a).

As the dryline caught up with the supercell thunderstorm, the entire storm system moved to the east into Dallas County as a heavy rain producer. The storm produced torrential rainfall over the city of Dallas (rainfall rates of 15.2 cm per hour), causing 18 deaths directly related to flash flooding (NCDC 2010a). Hundreds of structures were destroyed or severely damaged by the flooding in Dallas County.

Severe thunderstorm warnings were issued by the National Weather Service Weather Forecast Office in Fort Worth 29 minutes before the first hail reports in Parker County, and 18 minutes prior to the first hail reports in Tarrant County. This points to the fact that National Weather Service forecasters and storm spotters were aware of the severity of the storm as it approached the heavily populated areas in the vicinity of Fort Worth. A tornado warning was issued for Tarrant County shortly after the storm moved into the county, though no tornadoes were observed and no damage was directly attributed to tornadic winds.

4. Methodology

a. Data

Satellite imagery was obtained from the United States Geological Survey Earth Resources Observation and Science (EROS) Center's Earth Explorer internet download utility (USGS 2007). Landsat-5 data used for this study have been geometrically and radiometrically corrected by EROS, and geometrically projected to the World Geodetic System 84 (WGS 84) coordinate frame. Two sets of Landsat-5 Thematic Mapper (TM) data where used for this study in order to apply image differencing methods. The first image was acquired on April 24th, 1995, and represents the time period before the storm event. The post-storm event is represented by an image acquired on May 10th, 1995. Both images were acquired on dates in which there was less than 10 percent cloud cover. Since both image data sets were taken within a time period of 17 days, it is assumed for the purpose of this research that the images represent the same phenological period for the study area. Due to the quality of the data, it was determined that no further atmospheric or radiometric correction was necessary.

KFWS WSR-88D Level-II data were obtained from the National Climatic Data Center (NCDC 2010b). Base reflectivity at the 0.5 degree elevation angle was used for this study. Geographical information systems (GIS) mapping software was utilized to map the radar data. Moreover, raw WSR-88D data were converted into ESRI format shapefile features for use in ESRI ArcMap 9.3, utilizing the National Oceanic and Atmospheric Administration's Weather and Climate Toolkit. The data were then projected in ArcMap to World Geodetic System (WGS) 84. Due to beam angle widening and changes in elevation due to the Earth's curvature, the resolution of the resulting GIS layer varies with distance from the KFWS radar site which is located in southern Tarrant County. Resolution near the radar site is 0.017 square kilometers with a beam height of 4.6 meters, while resolution is 1.513 square kilometers at the farthest extent of the study area with a beam height of 1179 meters. Average radar resolution is 0.474 square kilometers within Parker and Tarrant Counties.

Spatial representations of hail reports related to the May 5th, 1995 severe storm event were obtained in GIS shapefile format from the Storm Prediction Center (SPC 2010). Actual storm reports were obtained from the National Climatic Data Center (NCDC 2010a).

b. NDVI calculations

The Normalized Difference Vegetation Index (NDVI) calculation is used in this study to determine the abundance and overall health of green vegetation for the study area. It has been shown that NDVI can be used as an indicator of land cover areas which have received damage from hailstorms (Bentley et al. 2002; Henebry and Ratcliffe 2003). NDVI is calculated for this study using 30 square meter resolution multispectral bands from the Landsat-5 Thematic Mapper. The red visible band (band 3) reflectance along with the near infrared (nir; band 4) reflectance are used in calculating the following equation (Jensen 2005).

$$\mathrm{NDVI} = \frac{\mathrm{nir\ (band\ 4) - red\ (band\ 3)}}{\mathrm{nir\ (band\ 4) + red\ (band\ 3)}}$$

NDVI calculations for the image data were processed using ERDAS IMAGINE 9.3. - a remote sensing application with raster graphic editor abilities. Calculation output resulted in image data with values ranging from -1.0 to 1.0. High positive values represent areas with "healthy" vegetation, and 0 to negative values generally represent areas with little to no vegetation or areas where the vegetation is "stressed" or unhealthy (Fig. 2).

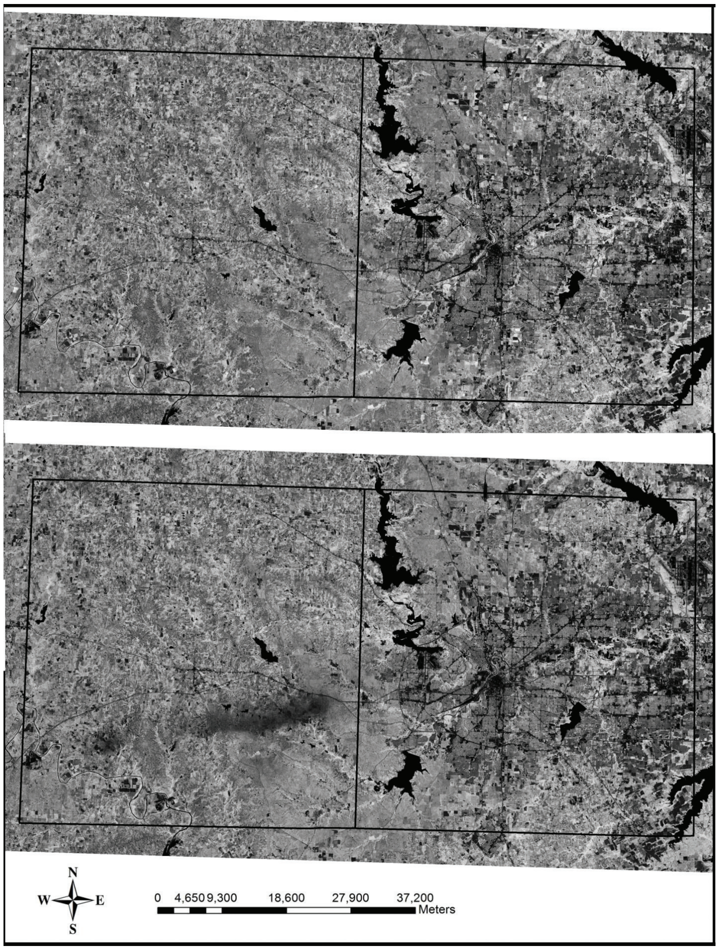

Fig. 2. Normalized Difference Vegetation Index (NDVI) images for pre-event (4/24/1995, top) and post-event (5/10/1995, bottom).

c. Image differencing

The two NDVI converted images were composited into a differenced image employing ERDAS IMAGINE 9.3 (Fig. 3). Positive image data values represent a positive change between April 24, 1995 and May 10, 1995; whereas negative data values indicate a negative change. Comparable to the separate NDVI images, data values for the differenced image range from -1.0 to 1.0. The resulting differenced image is used for visual and spatial statistical change detection analysis to identify and define the areal extent of potential hail swaths. It should be noted that in-situ hail damage area data were not available for this study.

d. WSR-88D

Data from the FWS WSR-88D were processed in ESRI ArcMap 9.3 to eliminate values below 60 dBZ for 22 individual radar scans. The scans range in time from 2258 to 0100 UTC, and occur at intervals of approximately 5 minutes. Values of 60dBZ and above indicate regions of the storm where large hail was likely occurring (Calianese et al. 2002). A composite image of all 22 radar scans can be seen in Fig. 4.

Utilizing the "Identify" feature within ArcMap 9.3, FWS NEXRAD dBZ values were compared spatially to the NDVI differencing image. Pixel values were randomly selected at the same spatial location for the NEXRAD and

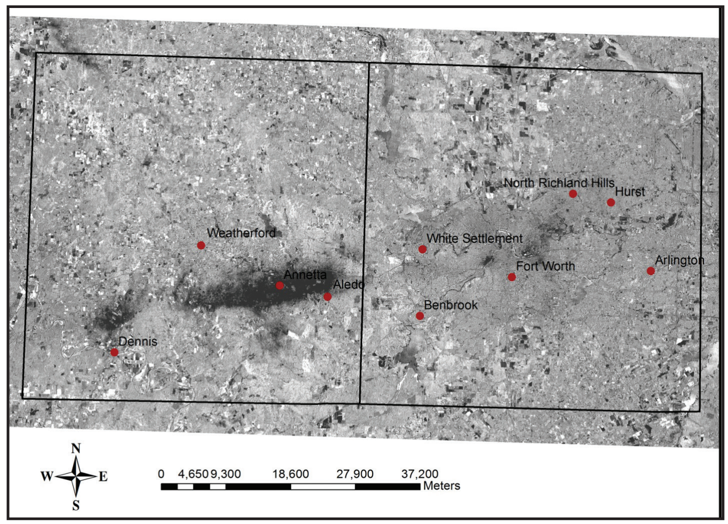

Fig. 3. NDVI Differencing image. Darker shades denote negative change values, indicative of hail damage to vegetation.

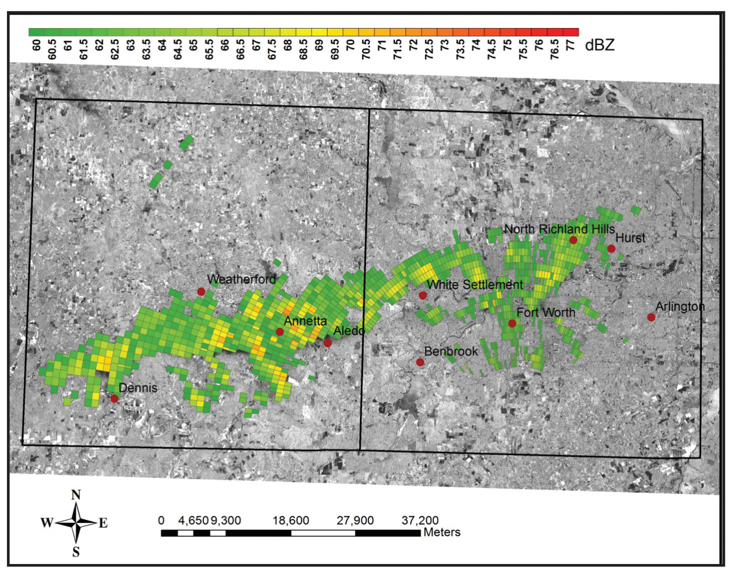

Fig. 4. Time composite image of KFWS WSR-88D Level II base reflectivity data superimposed on NDVI Differencing image. This composite represents a time frame from 2258 to 0100 UTC.

NDVI differencing image datasets, generally within the area of highest radar return. Because of the difference in spatial resolution of the two data layers, random pixel values from the 30 square meter resolution NDVI image were selected from within the coarser resolution NEXRAD reflectivity pixels. In order for this method to be accurate, visual interpretation of NEXRAD radar data must relate to the inferred location of the storm. Because this method relies on visual interpretation and comparison of data of varying spatial resolution, implications for error in results must be recognized.

5. Results

a. Hail swaths

Three distinct hail swaths were interpreted from the spatial locations of severe hail reports (Fig. 5), and the NDVI differencing images (Figs. 3 and 6). The first hail swath is centered approximately 5 km due north of the town of Dennis and measures 28.18 square kilometers in area. NDVI differencing values are commonly below -0.3 within Hail Swath 1. The orientation of Hail Swath 1 indicated that the maximum region of hail within the storm was traveling on a heading of 50 directional degrees, to the northeast.

Hail Swath 2 begins 15.29 km west of the town of Annetta, and ends approximately 13.94 km east-northeast of Annetta. The total area of the swath is 175.9 square kilometers, with a total length of 29.74 km. At its widest point, the swath measures 14.42 km, with an average width of 6.27 km. Orientation indicates a hail shaft movement of 83 directional degrees; almost due east. NDVI differencing values are as high as -0.6, and average -0.14. Hail Swath 2 is the area were hail "drifts" up to 45.7 cm deep were reported (NCDC 2010a). Of interest is the "V" like feature seen on the far eastern periphery of Hail Swath 1 (Fig. 7). This feature could have been caused by downdraft winds and hail associated with the weakening radar returns over this location. Further attempts to define this feature relate to specific storm dynamics, which are beyond the scope of this study.

The location of the Mayfest Festival near Trinity Park represents a smaller identifiable area when compared to the other defined hail swaths. However; the damage appears to have been severe within the smaller area, as is evidenced by NDVI differencing where an average value of -0.24 was calculated. This may be due in part to the location of the Fort Worth Botanical Gardens within this hail swath. The decorative vegetation within these gardens would have been particularly susceptible to hail damage. The total area of the Mayfest Swath is 2.41 square kilometers, with a length of 2.4 km and a width of 1.17 km. Because this swath is defined by the outline of the vegetated areas of Trinity Park and the Fort Worth Botanical Gardens, it may well be much larger.

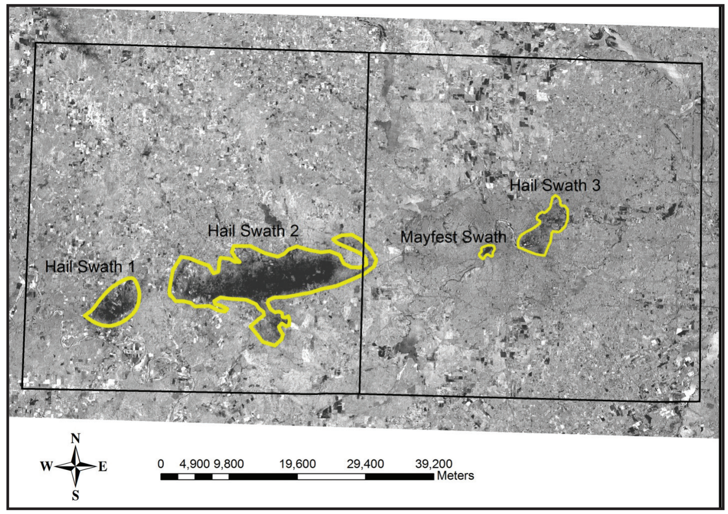

Fig. 6. Hail swaths identified from the NDVI Differencing image.

Hail Swath 3 occurs on the eastern side of downtown Fort Worth, and is not as easy to interpret as the previous two hail swaths. It covers 25.61 square kilometers in area, has a length of 8 km, a maximum width of 3.8 km, and an average width of 2.7 km. The studio of KXAS-TV, which reported hail of 10.2 cm in diameter, is located within this hail swath. NDVI differencing values range from a high of -0.5 to an average of -0.09 within this swath. Direction of movement of the storm at this point is interpreted to be 55 degrees to the northeast.

It should be noted that although large hail and resulting damage was reported for downtown Fort Worth, there is no obvious indication of NDVI differencing value change for the downtown area. This is likely due to the lack of vegetation within this area.

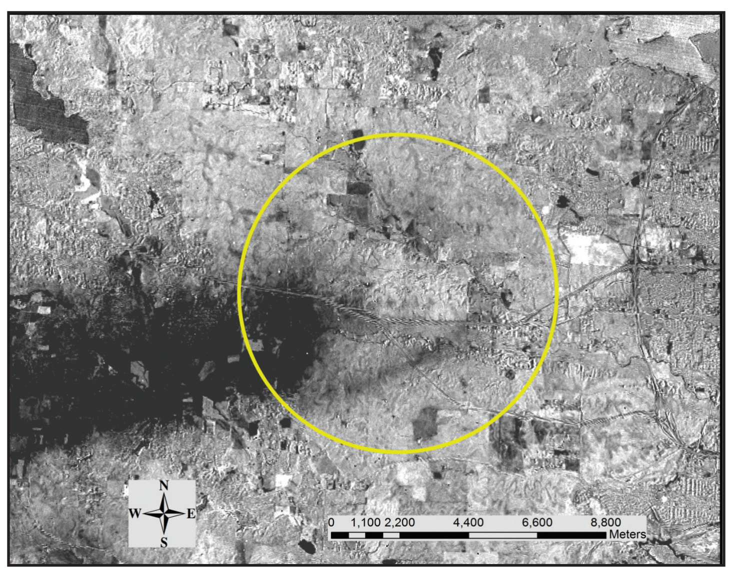

Fig. 7. "V" Feature located on the eastern edge of Hail Swath 2.

Based on the location and orientation of the hail swaths, a general representation of the movement of the hail producing supercell was produced (Fig. 8). The general movement of the storm appears to be to the east-northeast with a heading of approximately 82 degrees through Parker County to downtown Fort Worth. After moving through the downtown area, the storm then veers sharply to the northeast on a heading estimated at 50 degrees.

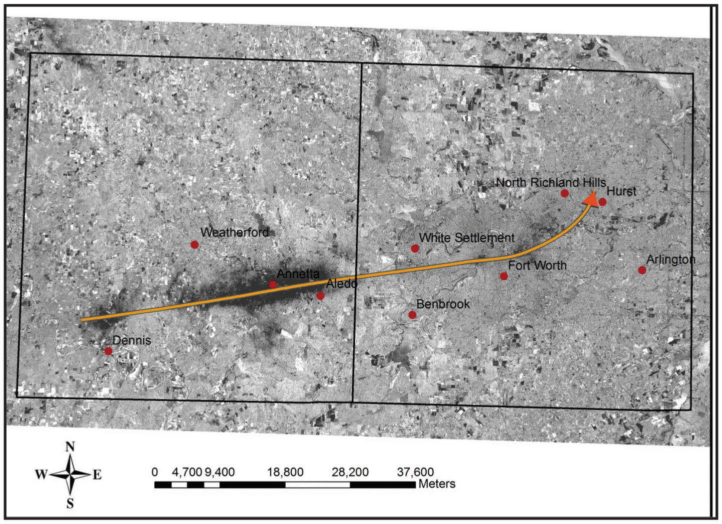

Fig. 8. Movement of the May 5, 1995 supercell hailstorm as interpreted from the NDVI Differencing image. The orange line indicates the path of the storm from west to east as it moved through Parker and Tarrant counties.

WSR-88D/NDVI difference comparisons

b. WSR-88D/NDVI difference comparisons

KFWS WSR-88D comparisons were performed individually for both Parker and Tarrant counties. This was done to achieve an overall comparison between the relatively rural Parker County and the urbanized Tarrant County, and to test the validity of using NDVI differencing techniques within an urban area.

Figure 9 shows an example of FWS WSR-88D data layered on the NDVI differencing image. The WSR-88D return from 2338 UTC indicates extreme hail directly over the area with the lowest differencing values within Hail Swath 2. This suggests that extreme hail damage 4 km to the west of Annetta was occurring at this time. A WSR-88D reflectivity value of 76.5 dBZ corresponds to NDVI differencing values in the -0.4 range for this time frame.

Figure 10 shows scatter plots of the comparisons for Parker and Tarrant counties. 56 random samples were taken for Parker County, with 89 acquired for Tarrant County. Samples in Parker County indicate a negative linear relationship for the WSR-88D dBZ values and

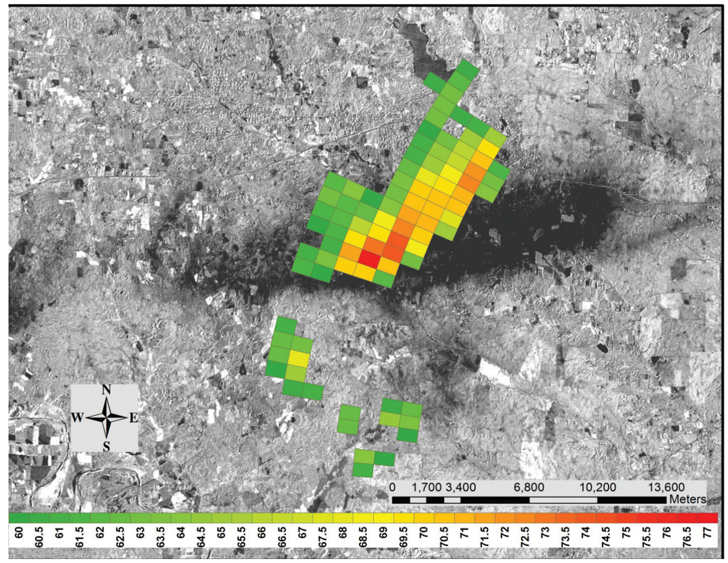

Fig. 9. Overlay of KFWS WSR-88D data from 2338 UTC over the NDVI Differencing image. WSR-88D dBZ values are on a scale along the bottom of the image.

Fig. 10 (a)

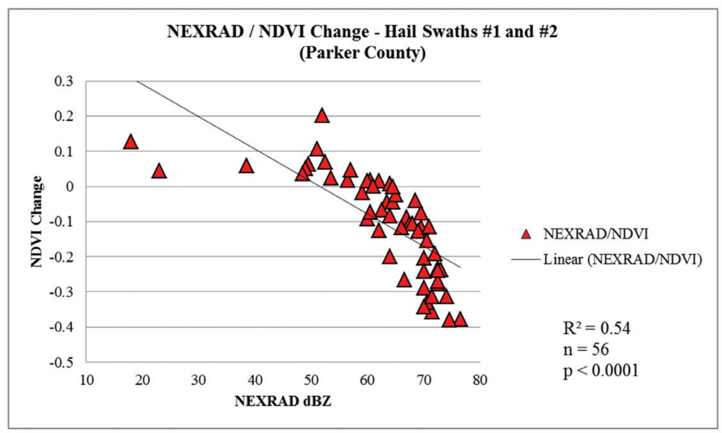

Fig. 10 (b)

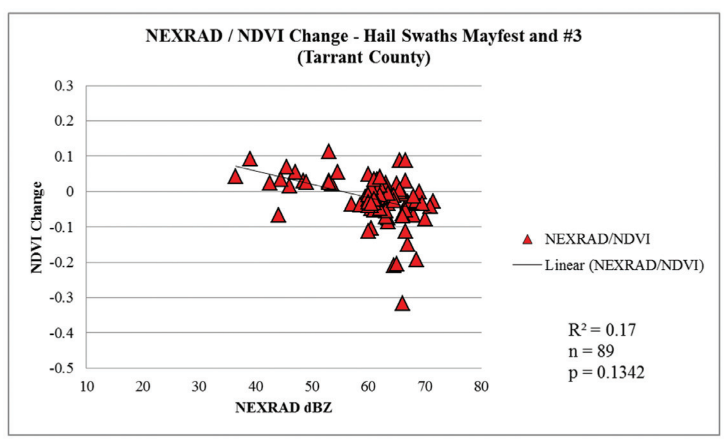

Fig. 10. Scatter plot diagrams for WSR-88D and NDVI Differencing comparisons. Both plots indicated a negative linear correlation.

NDVI difference. A weak negative linear relationship is seen. Statistical correlations for the comparisons show R^2 (i.e., correlation coefficient squared or the percent of the total variance) values for Parker at 0.54 ($p < .0001$), and for Tarrant at 0.17 ($p = 0.1342$), indicating statistical significance for the comparisons in Parker County.

Figure 11 shows the 0019 UTC FWS WSR-88D scan, taken 1 minute before the official reports of 8.9 cm hail at the Mayfest celebration. At this point, reflectivity values are at a maximum of 71, with corresponding NDVI differencing values of -0.04. Although the highest radar return is in the vicinity of the Trinity Park area, the highest returns do not correlate to the highest NDVI indicated damage. This is an indication that the spatial accuracy of the NEXRAD data is limited by several factors, including beam angle and height (Junyent et al. 2010). This is also a possible indication of the temporal problems of using NEXRAD data to derive actual damage locations, in that the radar data is a "snapshot" of the storm, limited to intervals of about 5 minutes.

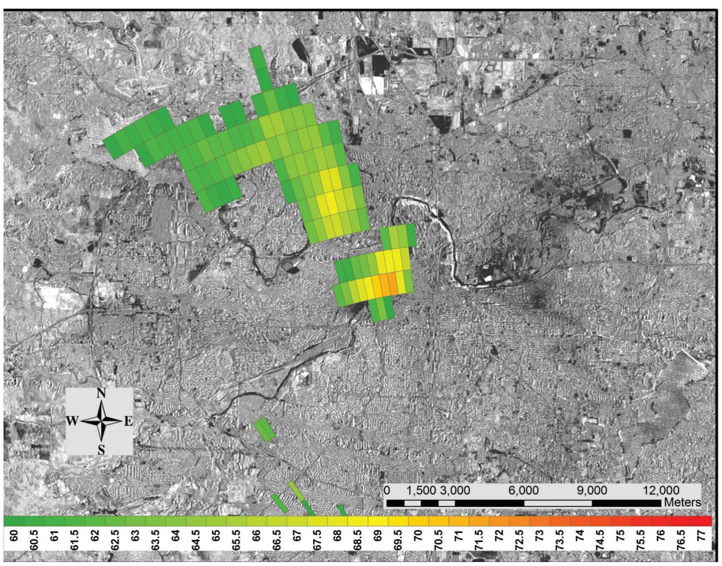

Fig. 11. Overlay of KFWS WSR-88D data from 0019 UTC over the NDVI Differencing image. Trinity Park is located beneath the highest dBZ values from this scan. WSR-88D dBZ values are on a scale along the bottom of the image.

6. Discussion

For the purpose of this study, it is assumed that the May 5th, 1995 hail event caused massive destruction to vegetation, as is evidenced by storm reports from that day. Hail has been shown to totally destroy vegetation, thereby reducing or eliminating near-infrared reflectance (Klimowski et al. 1998). Wind damage causes some vegetation damage, but the plants will often recover to some extent within a few weeks. The time frame of the images used for this study allow for some re-growth of vegetation that may have sustained wind damage, as opposed to vegetative hail damage, which would continue to be evident without massive cleanup and replanting efforts. Parker et al. (2005) showed that hail damage swaths are often the most detectable using NDVI methods from approximately five days to a month after the storm event.

The hail damage for the relatively rural Parker County is visually apparent in NDVI differencing images. This makes classification of these features seemingly straightforward. Comparisons with the KFWS WSR-88D time series for the storm event confirm the locations of the identified hail swaths are valid. In-situ storm reports from the time of the event also provide validity to the location of the NDVI identified hail swaths.

The ease of identifying hail swaths over Parker County contrasts with the somewhat difficult nature of hail swath identification for Tarrant County. In-situ reports indicate that the largest hail from the storm event fell in parts of Tarrant County. With the exception of the Trinity Park/Fort Worth Botanical Garden area and eastern Forth Worth, hail swaths are not obvious on the NDVI differencing image. However, radar returns from Tarrant County do not indicate the same storm organization as the returns from Parker County. This could be due to the proximity of the storm to the FWS radar site, the presence of ground clutter, and the vertical angle of the radar sweep for the base reflectivity data used in this study. Despite these potential error inducers, WSR-88D returns for Tarrant County still indicate that hail was present in the storm up to 0100 UTC.

Results of the WSR-88D/NDVI differencing image comparison indicate that NDVI change detection is an excellent technique to determine rural and/or highly vegetated areas which have experienced hail damage. Although the NDVI technique allows for some visual interpretation of hail damage paths in urban areas, the method suffers from the lack of vegetation. Evidence of this is the lack of NDVI change for downtown Fort Worth, which experienced significant hail damage. Remote sensing methods that use principle component analysis (PCA) may be a better option for dense urban areas (Yuan et al. 2002). PCA has an advantage in that it does not utilize change detection methods; therefore, only one image is needed for analysis.

Another possible explanation for the lack of distinct hail swaths in Tarrant County is reported hail size and density. In general, hail that was smaller in size but more intense in spatial density, was experienced in Parker County. Tarrant County experienced very large hail, with less spatial density. "Hail drifts" were observed in Hail Swath 2 in Parker County, and had the highest negative NDVI differencing values over the greatest overall area.

This hail swath was also the easiest to visually interpret on the NDVI differencing image. WSR-88D radar returns are also consistently higher and showed a more organized pattern for Hail Swath 2, when compared to returns for Tarrant County. Results from this study lead to the conclusion that hail density (and not necessarily size) results in the greatest overall damage to vegetation and the most organized radar returns are associated with dense hail falls.

Results from this study are hindered by the lack of consistency for storm reports. The times of the reports do not match the timing of the storm as interpreted from WSR-88D imagery. This may be due to a lag time from when the actual event was observed to the time the event was reported. It is obvious that several reports used in this study were not recorded during the actual event, but were based on observations of storm damage after the storm had passed. This is especially true for Parker County, where the population density is relatively low and therefore fewer "eyes" to see the storm. In Tarrant County, news media provided live coverage of the event as it occurred and recorded video of the hail fall (KXAS 1995). The population bias for observing severe weather events indicates that remote sensing techniques may not be needed to a great extent for dense urban areas, where storm damage is well documented. NDVI change detection techniques perform best in rural areas, where there is often a lack of in-situ storm reports and documentation of damage.

No attempt was made to directly relate storm dynamics with features defined on the NDVI differencing image. Further interpretation of the "V" shaped feature seen on the eastern edge of Hail Swath 2 could lead to a better understanding of the dynamic "pulses" of intensity within a supercell hail producing thunderstorm. The effects of dense urban areas and high-rise buildings on storm intensity and movement may help in part to explain the turning of the May 5th storm to the northeast after it moved through downtown Fort Worth.

Use of Landsat Thematic Mapper data in storm damage assessment is hindered by the temporal resolution of the data. The interval between consecutive overpasses of the Landsat satellite is 16 days. An alternative is the Moderate Resolution Imaging Spectroradiometer (MODIS), which has the advantage of a much shorter temporal resolution of 1 day, although the spatial resolution is courser at 250 to 500 square meters in the bandwidths of interest (NASA 2011). Although the course resolution of MODIS data is not as effective in NDVI analysis as Landsat TM data, single band and composite imagery has been used successfully to detect and verify severe storm damage (Jedlovec, Nair, and Haines 2006; Molthan, Jedlovec, and Carcione 2011).

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