Using Landsat to Identify Thunderstorm Damage in Agricultural Regions

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Remotely sensed data are used to supplement other techniques to identify the extent and estimate the cost of damage to crops from hail and wind in western Illinois.

About 20 000 severe thunderstorms occur in the United States annually, primarily during the warm season months of May–July (Schaefer and Brooks 2000). The resulting loss of property and agriculture from severe thunderstorms ranges from \$1 to \$3 billion annually. The frequency of damaging thunderstorm wind gusts greater than 33 m s^{-1} is concentrated in the central plains and Corn Belt regions of the United States, agriculturally important areas (Kelly et al. 1985). On a monthly basis, the greatest frequency of damaging thunderstorm wind gusts occurs in May, June, and July, the primary growing season (Golden and Snow 1991). Occasionally, individual thunderstorms evolve into an organized complex or mesoscale convective system (MCS; Zipser 1982). These systems can produce damaging wind swaths over large regions and also are most common throughout the Great Plains during the warm season (Bentley and Mote 1998). Since severe thunderstorms produce significant damage to agriculture, it is important to identify the areal extent of this damage in order to accurately estimate losses.

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Spatial mapping of agricultural damage could be utilized by farmers, insurance companies, and even meteorologists examining storm morphology and downburst severity. However, for spatial mapping to be useful in these endeavors high-resolution imagery must be acquired for accurate storm damage detection and areal estimation. Due to the frequency of storm damage in the Great Plains and Midwest during the warm season, terrestrial approaches for damage assessment have several major disadvantages. They can be time consuming, costly, and incomplete when large areas are affected, and the generation of adequate maps for the affected area can be difficult due to a lack of equipment and personnel. Another alternative that has been employed with some success is aerial photography (Pain and Stephens 1990). However, this approach is also not optimal due to the following restrictions:

- the planning and execution of airborne campaigns can be time intensive,

- the flight(s) must be done during good weather conditions,
- aerial photography acquisitions can be expensive, and
- there is a general lack of personnel trained in photogrammetry.

The National Climatic Data Center's (NCDC) publication *Storm Data* is often used by meteorologists and climatologists in locating areas of storm damage produced by significant weather events. The data are useful in this capacity; however, it is impossible to accurately identify the spatial extent of a storm's impact using these data. Storm reports are primarily obtained from the emergency services disaster agency (ESDA) coordinators/spotters during an event (M. Byrd 2001, personal communication). Additionally, the National Weather Service Office makes phone calls to coordinators and spotters the following day to further identify severe weather reports. If there are several reports from one county for the same type of phenomena, verified by looking at archived radar data, they are grouped as one report and labeled "countywide" with a beginning time and an ending time (M. Byrd 2001, personal communication). While this locates where storm damage has occurred, it does not provide useful information regarding the areal extent of the damage. Therefore it is necessary to examine other alternatives for accurately assessing storm damage that do not rely on terrestrial, airborne, or *Storm Data* reports.

Few formal investigations into spaceborne techniques useful for identifying storm damage have been performed. Klimowski et al. (1998) used the *Geostationary Operational Environmental Satellite-8* (*GOES-8*) to identify rangeland grass and crop damage from a severe hailstorm in South Dakota. Their findings suggest that for such an event to be identifiable on GOES visible satellite imagery the hailstorm must have occurred over an area with similar surface characteristics and be of sufficient magnitude to devastate the ground cover (Klimowski et al. 1998).

A recent study of the Oklahoma City tornadoes on 3 May 1999 utilized *Landsat-7* multispectral data to identify storm damage (Magsig et al. 2000). Results suggest that *Landsat-7* data could be useful for storm damage detection provided that land cover characteristics are such that this damage can produce a signature in the imagery (Magsig et al. 2000). The Minnesota Department of Natural Resources (DNR) routinely utilizes Landsat data to map Minnesota land cover and as a way to detect changes in land cover over long periods of time (Minnesota-DNR 1999). On 4 July 1999, a derecho swept across the Boundary Waters Canoe Area Wilderness and blew down hundreds of thousands of trees (Minnesota-DNR 1999). Since this is a very remote location in the arrowhead of Minnesota, Landsat imagery before and after the derecho was utilized along with aerial photography to assess the extent of the damage. It was found that by using change detection methods, short-term land cover changes could be accurately identified by high-resolution satellite imagery (Minnesota-DNR 1999).

This investigation examines the utility of Landsat imagery for assessing storm damage to crops in Illinois. During the evening hours of 12 August 1999, an MCS moved over several counties in west-central to south-central Illinois. This thunderstorm complex produced severe straight-line winds and several short-lived tornadoes that downed much of the corn plants in the region (NCDC 1999). The MCS first affected Schuyler County, leveling numerous trees and power lines (NCDC 1999). Additionally, thousands of acres of corn were laid down by the winds. The New Holland Fire Department in Logan County reported 38 m s^{-1} winds sustained for nearly 2 min as the storm passed (NCDC 1999). As the system continued moving to the southeast, major crop damage was reported in Mason, Menard, Cass, Morgan, Scott, and Macon Counties (NCDC 1999). Initially, crop damage was estimated at over \$52 million in these eight counties.

Six days later on 18 August, two severe thunderstorms moved over Schuyler and Cass Counties. Hail ranging from 44 to 70 mm in diameter was reported in Cass and Schuyler Counties and caused another \$4 million in damage to corn and soybeans (NCDC 1999). Additionally, hundreds of cars and houses also sustained damage due to the large hail. Damage from both events is evaluated with the goal to provide an areal estimation of the number of acres damaged from both the wind and hail events and also the severity of the damage.

DATA. *Study area.* The area selected for this investigation is in the western part of Illinois, covering an area of approximately 21 123 km^2. The study area consists of all or portions of 14 counties: Hancock, Adams, McDonough, Schuyler, Brown, Pike, Fulton, Cass, Morgan, Scott, Tazewell, Mason, Menard, and Sangamon (Fig. 1). Corn and soybeans are the primary crops in the region with several counties ranking in the top 10 harvesting statistics for the state of Illinois (Illinois Department of Agriculture 1999). In 1998, Illinois was second in the nation in total corn

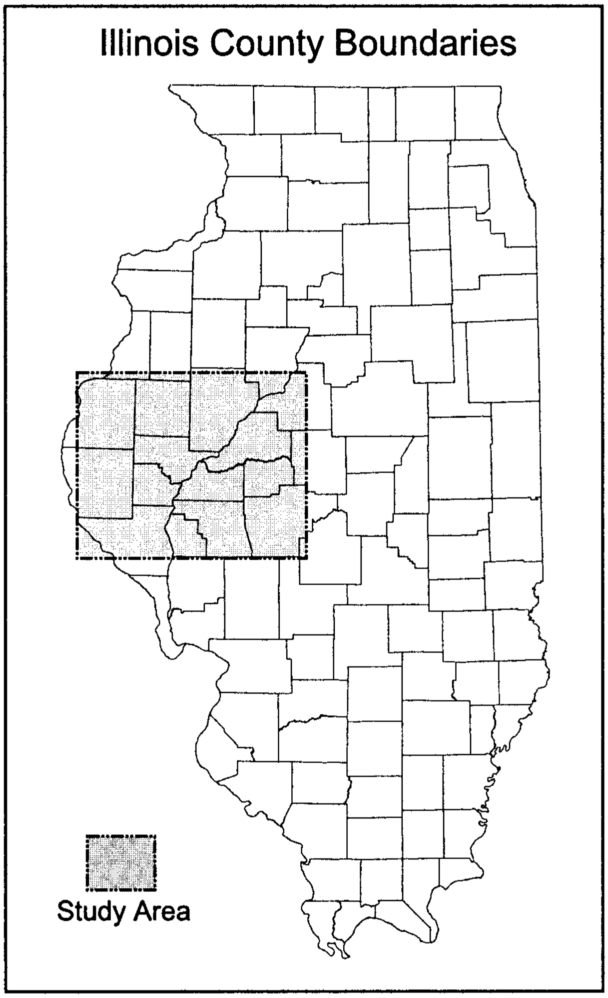


Fig. 1. West-central Illinois region of significant crop damage on 12 and 18 Aug 1999 [after Illinois State Geological Survey (1984)].

acreage (Illinois Department of Agriculture 1999). This underlines the importance of agriculture in this region that is also prone to severe thunderstorms during the growing season.

Characteristics of Landsat-7 ETM⁺ data. The high-resolution multispectral data employed in this investigation were acquired by the Earth Resources Observation Systems (EROS) data center near Sioux Falls, South Dakota. The *Landsat-7* data were in FAST-L7A format (NASA 1998) and the systematic errors were corrected. The satellite orbits at an altitude of 705 km above the mean terrain.

The Enhanced Thematic Mapper Plus (ETM^+) onboard *Landsat-7* replicates the capabilities of the Thematic Mapper instrument on *Landsats-4* and *-5*. The ETM^+ includes features for land cover monitoring and assessment, large area mapping, onboard 5% absolute radiometric calibration, and thermal IR channel with 60-m spatial resolution (NASA 1999). Landsat bands 1–5 and 7 were resampled to 25-m resolution, band 6 was resampled to 30-m resolution, and the panchromatic band to 14.25-m resolution.

The *Landsat-7* data employed in this investigation were in universal transverse Mercator coordinate (UTM) zone 15, covering 14 counties in western Illinois. Two sets of *Landsat-7* data for the same area were examined in the analysis. The "before" image was obtained on 11 July 1999, and the "after" image was obtained on 28 August 1999 (Figs. 2 and 3). As will be shown in the methodology section, the normalized difference vegetation index is computed using data from bands 4 (near-infrared) and 3 (red). The data from band 5 (midinfrared) is employed to aid image interpretation. The characteristics of the *Landsat-*

Table 1. The specifications of the *Landsat-7* ETM^+ data. [From NASA (1999).]

Channel	Bandwidths (μm)	Nominal spectral location	Ground resolution (m)	Resampled data resolution (m)
1	0.45–0.515	Blue	30	25
2	0.525–0.605	Green	30	25
3	0.630–0.690	Red	30	25
4	0.750–0.900	Near-infrared	30	25
5	1.55–1.75	Midinfrared	30	25
6	10.40–12.50	Thermal infrared	60	30
7	2.09–2.35	Midinfrared	30	25
Pan	0.52–0.90	Visible	15	14.25

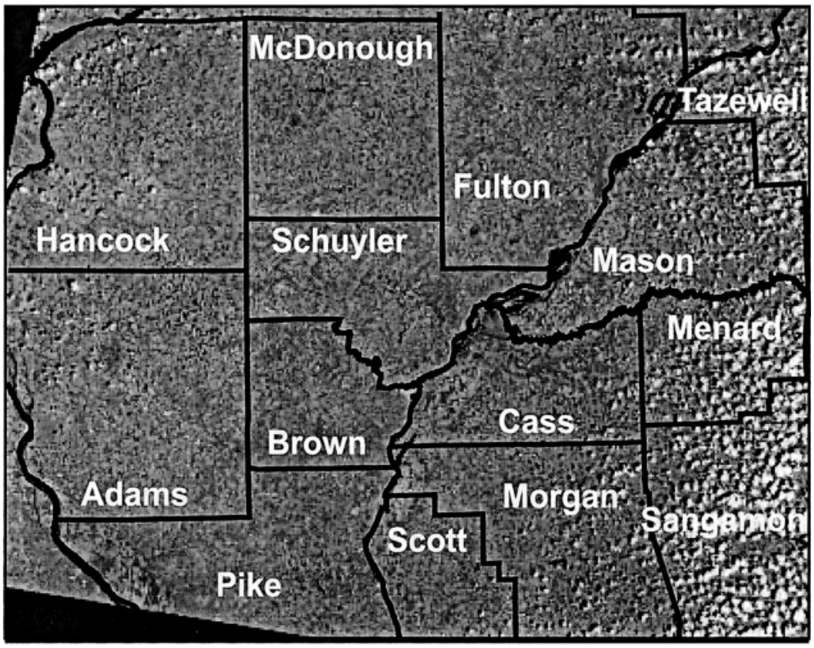


FIG. 2. *Landsat-7* grayscaled image (band 5), 11 Jul 1999. This band makes vegetation appear as darker shades of gray. Light gray to near-white regions indicate urban areas while near-black regions indicate cloud shadows and water bodies.

7 ETM+ data are illustrated in Table 1. ETM+ band 3 (red) is designed for detecting chlorophyll absorption in vegetation. ETM+ band 4 (near-infrared) data are ideal for detecting near-IR reflectance peaks in healthy green vegetation and for detecting water–land interfaces. The two mid-IR bands 5 and 7 are useful for vegetation and soil moisture studies and for discriminating between rock and mineral types. Band 5 was also found useful in delineating crop damage due to increases in ground reflectance after the crops were damaged or destroyed (Fig. 3).

NCDC storm reports (12 and 18 August 1999). To examine the spatial patterns of vegetation damage due to severe thunderstorm winds and hail, storm reports were overlaid on the Landsat data (Fig. 3). This facilitated the analysis by illustrating the orientation of damage swaths produced by the storms and also highlighted the shortcomings of storm reports for assessing the areal extent of damage. These reports were obtained from *Storm Data* (NCDC 1999).

METHODOLOGY. Before performing the data analysis, preprocessing of the data is necessary. Preprocessing is the procedure that involves the initial processing of raw image data to correct for geometric distortions, to calibrate the data radiometrically, and to eliminate noise. The error from the data acquisition process can degrade the quality of the data collected, and also has an impact on the accuracy (Meyer et al. 1993). Preprocessing is dependent on the characteristics of the data and the sensor used to acquire them.

The *Landsat-7* data employed in this study have been radiometrically and geometrically corrected by the EROS data center. The distortion between the before and after images was found to be less than 25 m (1 pixel). This is acceptable since this investigation's main focus is in thematic accuracy rather than positional accuracy. Thus, the two images do not need to be registered to correct for data geometry. Generally, registration to within 1 pixel is required for change detection analysis. When misregistration is greater than 1 pixel, numerous errors will result when comparing the images (Lillesand and Kiefer 1994).

The ERDAS Imagine version 8.4 software package was used throughout the image analysis. Since the *Landsat-7* data were in FAST-L7A format, they were converted to ERDAS 8.4 format in order to perform the analysis. The steps and techniques utilized to identify agricultural damage due to severe thunderstorms are described in the following section.

Perform the NDVI calculation. The normalized difference vegetation index (NDVI) is a measure of vegetation vigor computed from multispectral data. The magnitude of NDVI is related to the level of photosynthetic activity in the observed vegetation (Kidwell 1999). It is calculated based on band ratioing between the near-infrared band 4 (0.75–0.90 μm) and the red band 3 (0.63–0.69 μm) as

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

Values for NDVI range from 1.0 to –1.0. Vegetated areas generally yield high values for the NDVI because of their relatively high near-infrared reflectance and low visible reflectance. In contrast, clouds and water have larger visible reflectance than near-infrared re-

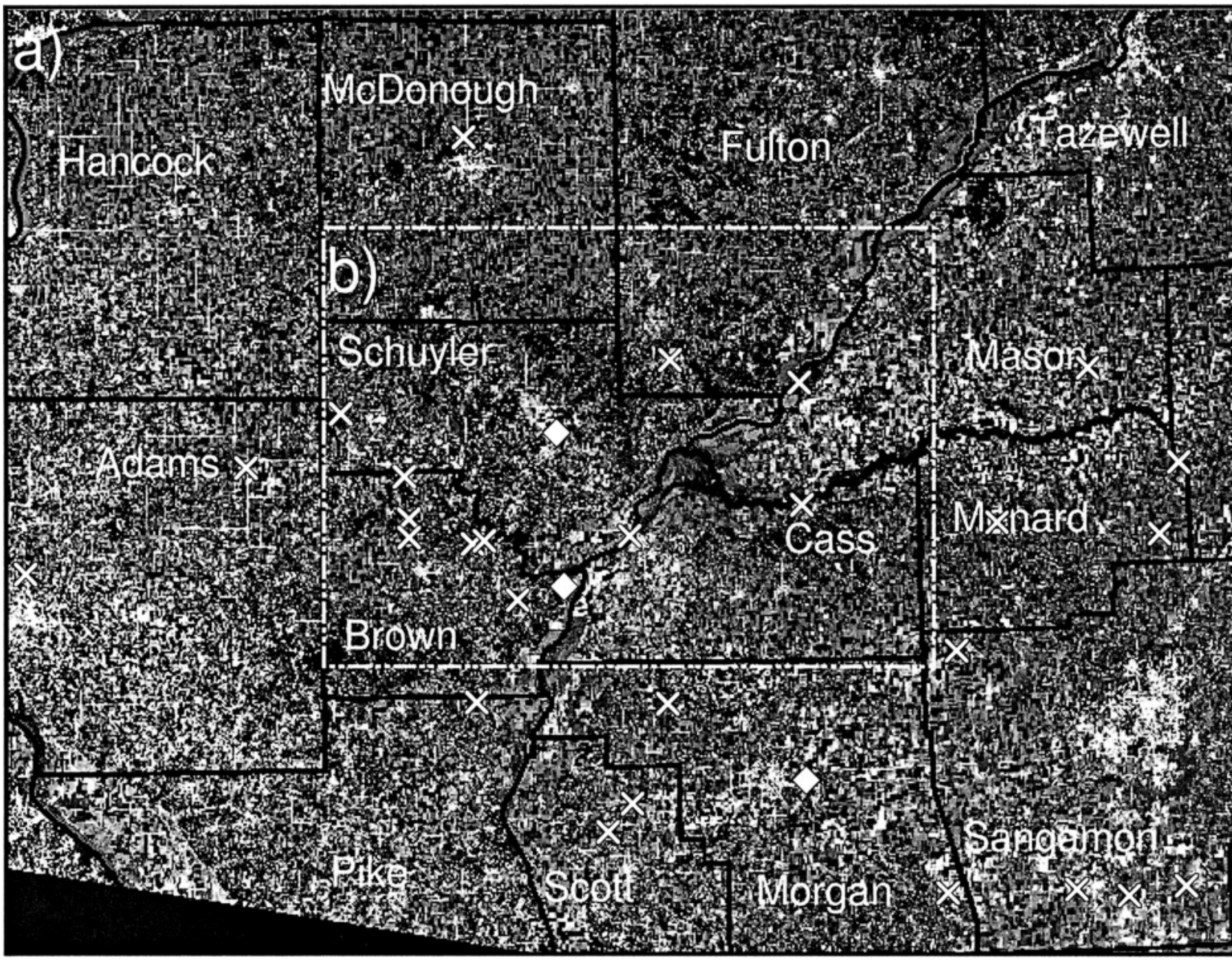
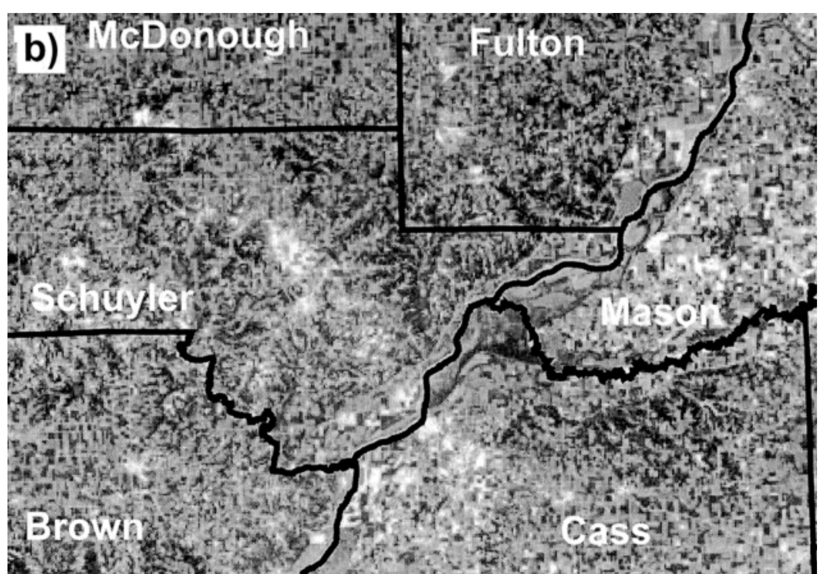


FIG. 3. (a) *Landsat*-7 grayscaled image (band 5), 28 Aug 1999. The high wind reports (Xs) occurred on 12 Aug 1999, while the hail reports (diamonds) occurred on 18 Aug 1999 (NCDC 1999). (b) Enlarged region detailing some of the damaged corn crops. The lighter gray "streak" and patches in this image illustrate damage due to large hail and winds.



flectance. Thus, these features yield negative index values. Rock and bare soil areas have similar reflectances in the two bands, resulting in an NDVI near zero (Lillesand and Kiefer 1994; Sabins 1997). In this investigation, NDVI was calculated on the before and after images in order to extract information about vegetative condition. The NDVI output was reduced down to a single number per pixel that predicted or accessed such canopy characteristics as biomass estimation, productivity, and percent vegetation ground cover. These output images were then employed in further analyses and damage estimation (Figs. 4 and 5).

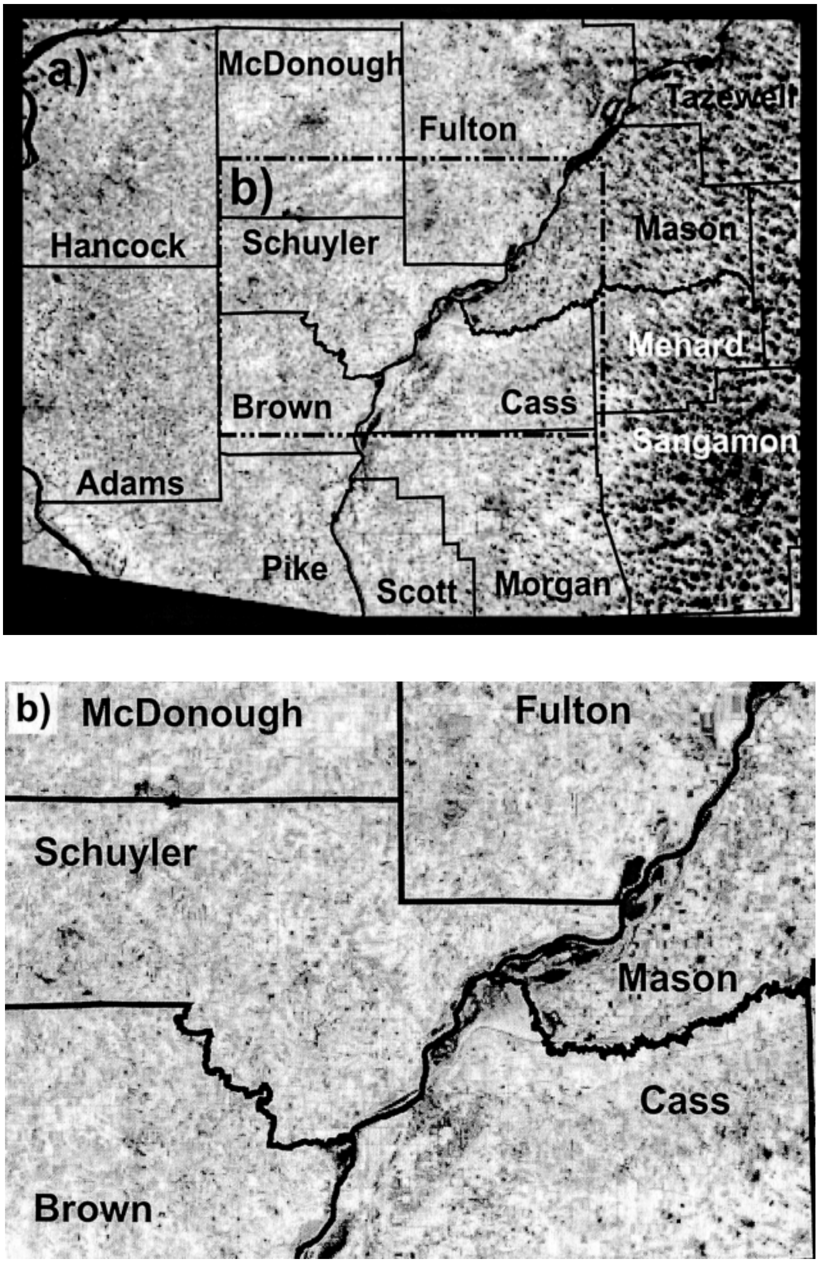


FIG. 4. (a) The NDVI created from the 11 Jul 1999 image. NDVI vegetation values range from a low of 0.10 to a high of 0.66 in this image and are displayed as a grayscale composite. Higher values (lighter gray shades to near white) indicate increasing concentrations of green vegetation, while lower values (darker gray shades to near black) indicate nonvegetated features such as water, urban area, barren land, or clouds and their shadows. (b) Enlarged region where hail and wind damage were evident in the 28 Aug 1999 image.

Change detection procedure. Change detection mapping and analysis can be facilitated through the interpretation of multidated remotely sensed data. Ideally, change detection procedures involve data acquired by the same sensor and recorded using the same spatial resolution, viewing geometry, spectral bands, and time of day. The type of changes that might be of interest can range from short-term to long-term phenomena. The common approach in change detection is temporal image differencing. Image differencing involves subtracting the digital numbers (DNs) of one date from those of the other (Fig. 6). The subtraction results in positive and negative values in areas of radiance change and near-zero values in areas of no change in the new image. The possible values for the differenced image in an 8-bit analysis range from –255 to 255; thus, a constant (i.e., 255) is normally added to transform the image into positive values for display purposes (Lillesand and Kiefer 1994; Jensen 1996). The before and after NDVI images were differenced to show the image changes in the study region from 11 July 1999 to 28 August 1999.

Storm track identification. The storm reports obtained from *Storm Data* (NCDC 1999) were in latitude–longitude coordinates. These data were input as an ASCII file and then imported to ArcView to plot the locations of the storm reports. Next, ArcInfo was utilized to reproject the storm reports to UTM zone 15 in order to overlay on the *Landsat-7* difference image.

Additionally, Weather Surveillance Radar-1998 Doppler (WSR-88D) composite reflectivity data were obtained and used to identify the storm tracks of the two events through west-central Illinois (Fig. 7). These data were received in near–real time and archived for the entire continental United States at the Hydrological Cycle Distributed Active Archive Center (DAAC) located at the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center. Figure 7a illustrates the MCS that produced the damaging straight-line winds on 12 August 1999. As the MCS moved over the study region, its radar signature contained a bowing convective line segment with a prominent rear-inflow notch, indicative of high winds (Fujita 1978). On 18 August 1999, composite reflectivities exceeding 55 dBZ were noted through Cass and Schuyler Counties (Fig. 7b). These regions of high reflectivity on radar were associated with the 40–70-mm diameter hail reported in these counties.

Determination of the areal extent of crop damage. Although change detection is an efficient method of identifying pixels that have changed in brightness value between dates, a careful selection of the "change/no-change" area is required. In this step, the storm reports were overlaid on top of the difference image to identify the general damage region caused by severe thunderstorms. The damage areas were then digitized and the acreage of the damage areas was calculated. Due to cloud contamination, automatic classifying using a threshold value could not be accomplished. When cloud cover contaminates the imagery, the areal extent of damage within a cloudy region will be uncalculable using an automated differencing technique. For example, patchy cumulus clouds were present in east-central Morgan County on 11 July 1999 (Fig. 8a). This region received considerable damage due to high winds on 12 August (NCDC 1999; Fig. 8c). If an automated technique is employed, the NDVI differenced image shows the regions of cloud and their shadows as an area of NDVI *increase*. Therefore, these areas would not be identified as damaged. However, by examining the before, after, and differenced imagery and interpreting manually, a significant drop in NDVI throughout this region is evident between the patchy cloud cover (Fig. 8).

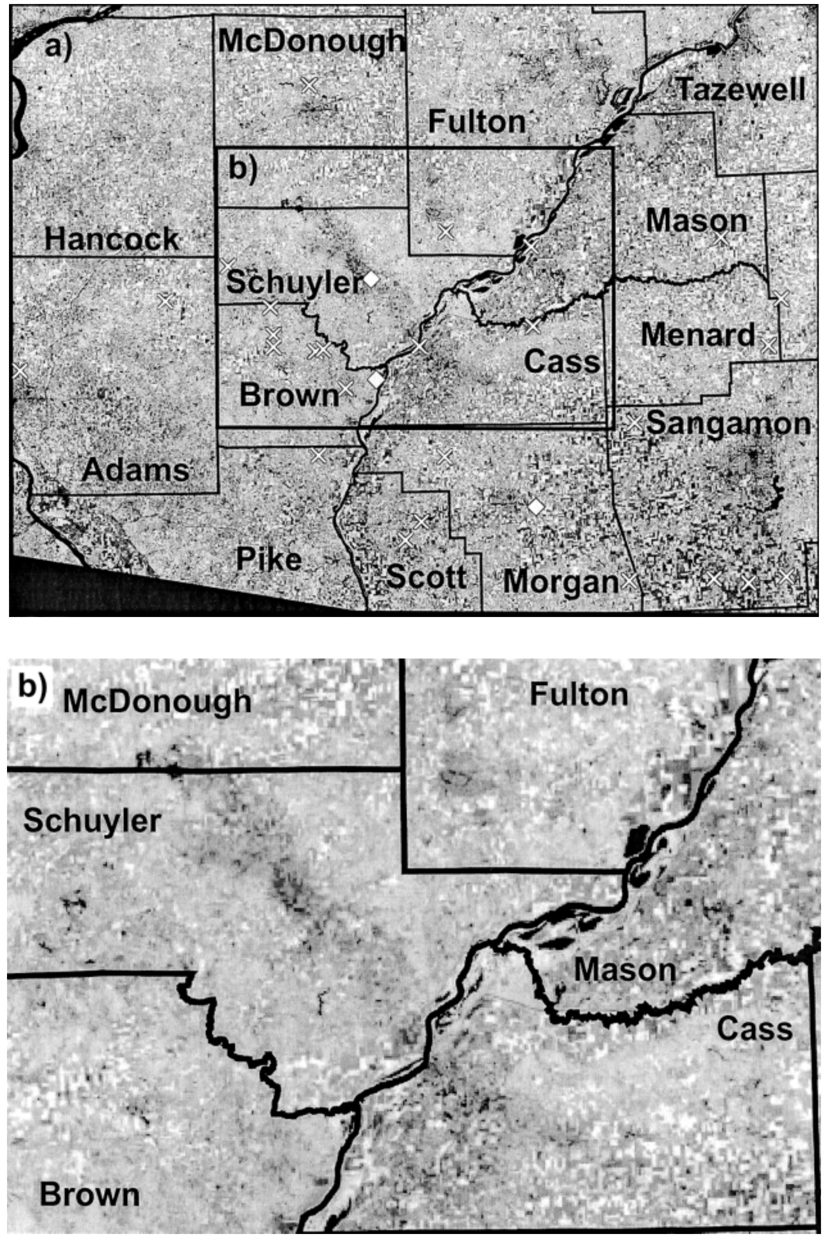


FIG. 5. (a) The NDVI created from the 28 Aug 1999 image. The high wind reports (Xs) occurred on 12 Aug 1999, while the hail reports (diamonds) occurred on 18 Aug 1999 (NCDC 1999). The areas of high concentration of green vegetation have been significantly decreased after the windstorm of 12 Aug and hailstorm of 18 Aug. (b) Enlarged region illustrating the significant decreases in vegetation due to the storm event. The dark streak was produced by the hailstorm, while several patchy regions of decreased vegetation were produced by the windstorm.

Since the before, after, and the differenced images are in the same reference (i.e., map projection, datum, etc.), they can be displayed on separate viewers in ERDAS Imagine and linked together. Therefore, the pixel values of the same position on the three images

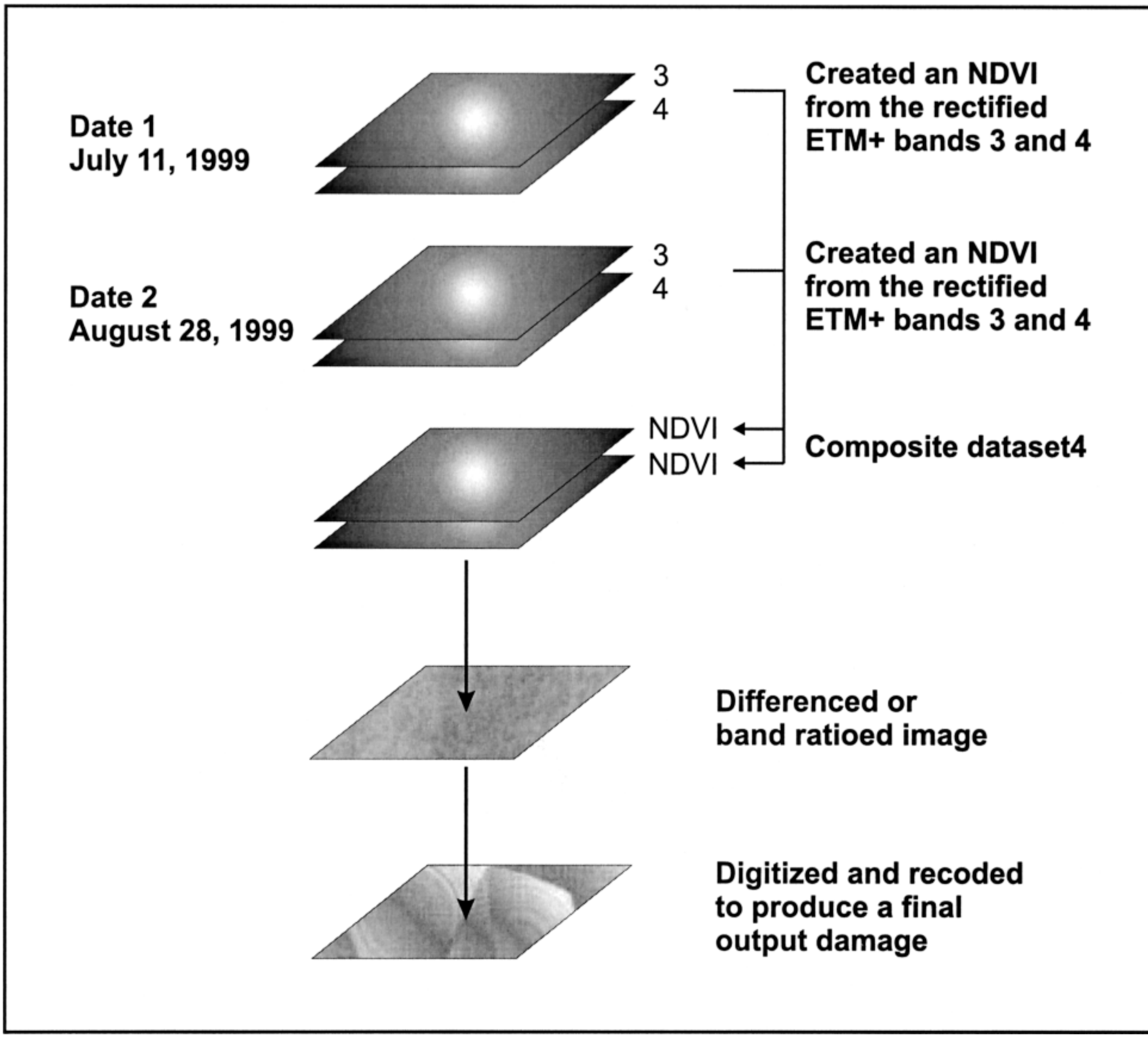


Fig. 6. Diagram of image algebra change detection (after Jensen 1996).

can be determined. The outlines of the damaged areas are visually interpreted and manually delineated based on the pixel values of the difference image. Manual digitization was also employed because one can avoid performing areal estimation on the urban areas and rivers, since the emphasis is on identifying crop damage only.

RESULTS. The NDVI outputs created from the before and after images are shown in Figs. 4 and 5. Examination of these images allows one to identify the location of highly vegetated areas on 12 July 1999 (Fig. 4a) and 28 August 1999 (Fig. 5a). Before the storm, NDVI values ranged from 0.10 to 0.66 (Fig. 4). Much of the region contained corn and soybean plants near maturity, as illustrated by the lighter gray to near-white regions in the image indicating high NDVI values. Portions of western Hancock and Adams Counties yield lower NDVI values since these regions contain greater population and fewer large farms. Another region of lower NDVI values is located on the right side of the image. Although more urbanization is located in this area since it contains Springfield, the main factors contributing to lower NDVI values are clouds and their associated shadows. Figure 2 is a grayscaled image of the study area illustrating the location and number of clouds. Analysis in the eastern sections of the study region will be limited to examination of the 28 August image, when virtually no clouds were evident at the time of the image. By enlarging the image and examining a region that contains Schuyler and Cass Counties, the high spatial resolution of the data is evident, as are the high NDVI values (Fig. 4b).

Overall, NDVI values were lower in the 28 August image when compared to 12 July. Although there still existed pixels with NDVI values of greater than 0.66, these were much less numerous. Much of the image at this time contained values between 0.10 and 0.55 (Fig. 5a). The very low NDVI values located in the lower right of the image are associated with urbanization due to Springfield, Illinois. Low values in the left portions of the image are also due to urbanization in and around Quincy, Illinois, and due to the different vegetation characteristics found along the floodplain of the Mississippi River.

Differences between vegetation on 12 July and 28 August are apparent when comparing the two images. The most notable is a swath of low NDVI values through Schuyler and Cass Counties (Fig. 5b). This is a region of crop destruction due to 45–70-mm diameter hail that fell from isolated thunderstorms on 18 August and caused an estimated $4 million in damage (NCDC 1999). More subtle changes in vegetation are notable in many other portions of the image due to the damaging thunderstorm winds of 12 August (Figs. 5a and 5b). Storm reports from the 12 and 18 August wind- and hailstorms were also plotted in the images in order to highlight regions where NDVI decreased due to storm damage (Fig. 5a). Several areas where NDVI values dropped between the 12 and 28 August images were likely due to the affects of hail and wind damage. Large wind-driven hail is capable of pulverizing vegetation to the point of destruction (Klimowski et al. 1998). Hailstones of 70 mm will defoliate and in some cases break the stalks of crops, greatly reducing their near-infrared reflectance. In contrast, damaging downburst winds will blow over crops. If these plants are not completely uprooted they will be damaged but survive. Since crops sustaining wind damage are more likely to survive, they will also yield higher near-infrared reflectance and NDVI values. The windstorm of 12 August blew over the crops but most were not uprooted and in fact were able to be harvested (S. R. Turner 2000, personal communication).

The county that sustained the greatest dollar amount of crop damage was Mason (NCDC 1999). Although clouds contaminate portions of the before image, Mason County appears to be highly vegetated with NDVI values greater than 0.66 (Figs. 4a and 4b). This is in contrast to the 28 August image where NDVI values fell significantly throughout the county to less than 0.10 in the southwest near the Sanganois Recreation Area where an individual in a car was trapped by fallen trees (Figs. 5a and 5b; NCDC 1999). The lower NDVI values are also found across the county line in northern Menard County (Fig. 5a). Another county sustaining a large amount of crop damage due to downburst winds is Morgan. On 12 July, much of Morgan County was highly vegetated yielding NDVI values greater than 0.66 (Fig. 4a). However, on 28 August there was a considerable drop

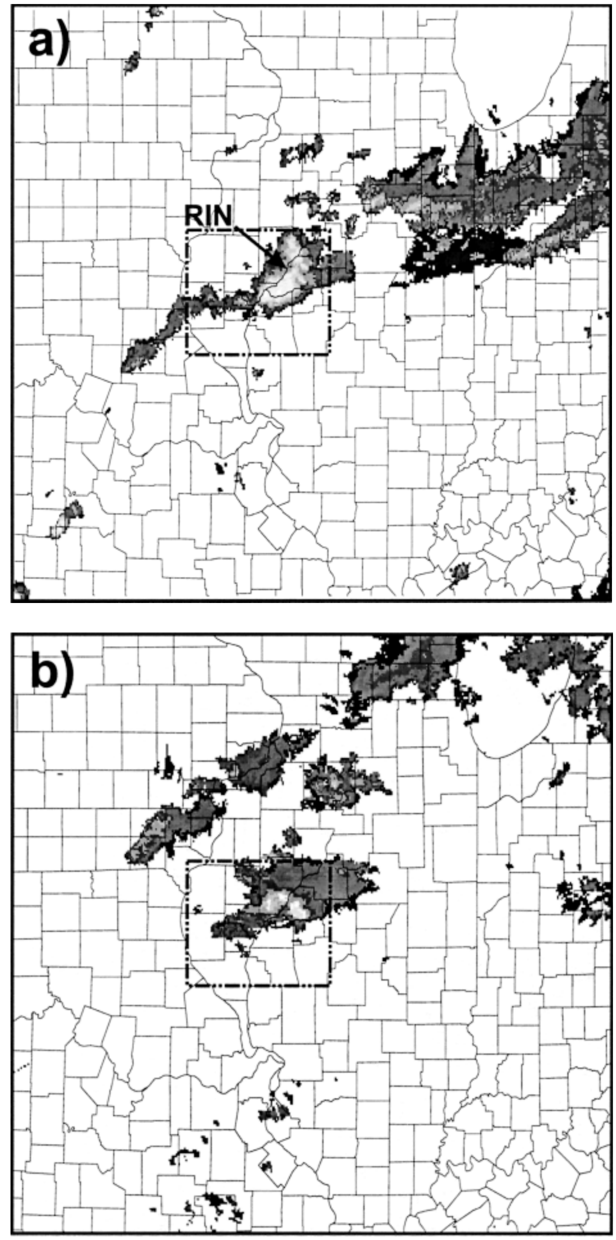
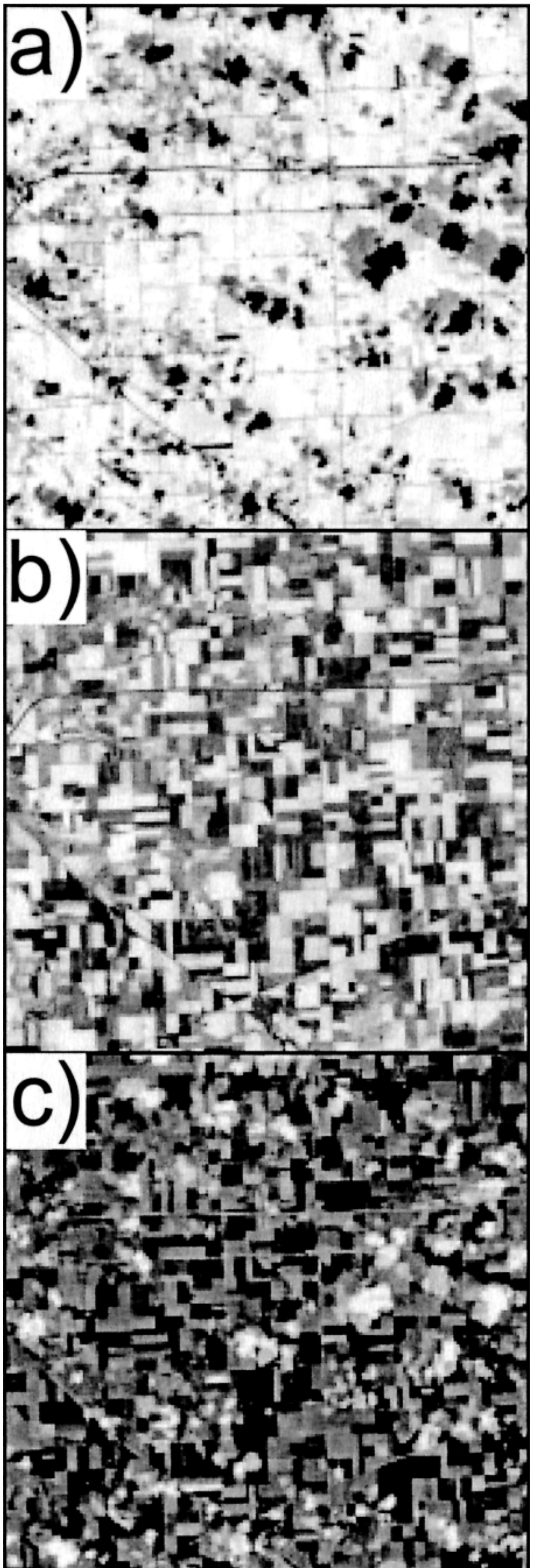


Fig. 7. (a) WSR-88D composite reflectivity (2-km resolution) for 0100 UTC 12 Aug 1999. Lighter shades indicate higher reflectivity values and the boxed area illustrates the study region. "RIN" denotes a rear-inflow notch, a radar signature indicative of damaging straight-line winds. (b) Same as in (a) except at 0330 UTC 18 Aug 1999. Lighter shades indicate higher reflectivity values and the boxed area illustrates the study region.



in near-infrared reflectance, signifying a decrease in vegetation vigor. NDVI values ranges from 0.52 to nearly 0.10 throughout the county. A visual inspection of the before and after images indicates the greatest changes are located in the east-central part of the county and move into Sangamon County, west of the city of Springfield (Fig. 5a). As shown, Cass County sustained damage from both the 12 August windstorm and 18 August hailstorm, although there were no storm reports for the hailstorm (NCDC 1999; Figs. 7a and 7b). The greatest crop damage occurred between Beardstown and Arensville located in the west-central part of the county. This is verified by the large number of pixels with NDVI values between 0.10 and 0.25 located in this region (Figs. 5a and 5b). Scott County was also hard hit, with NDVI values dropping to near 0.10 in many areas of the county; however, the central and western portions of the county appear hardest hit by damaging thunderstorm winds (Fig. 5a).

Several other counties contained damage reports, but no crop damage estimates. There was an F1 tornado reported in Brown County along with four other reports of damaging winds (NCDC 1999). The NDVI was shown to decrease from greater than 0.66 to approximately 0.30 in the 28 August image in many regions of the county (Fig. 5a). Adams County also contained two storm reports with the greatest decrease in NDVI occurring in the northeastern portions of the county (Fig. 5a). Only one storm report was located in McDonough County near the city of Macomb; however, much of the county showed a significant drop in NDVI values ranging from 0.40 to 0.66 in the before image to 0.25 on 28 August. Pike County also contained some damage in the northeastern portions of the county; however, the

Fig. 8. (a) The NDVI created from the 11 Jul 1999 image of east-central Morgan County. Lighter shades indicate higher NDVI values, while clouds and their associated shadows are dark gray to black. (b) The NDVI created from the 28 Aug 1999 image of east-central Morgan County. Significant decreases in NDVI are evident when compared to the before image. Extensive wind damage occurred throughout this area on 12 Aug (NCDC 1999). (c) The NDVI difference image of east-central Morgan County. Darker gray shades indicate greater decreases in NDVI between images while lighter gray shades illustrate less significant changes in vegetation vigor between the 11 Jul and 28 Aug 1999 images. Clouds and their shadows are also depicted as light gray to near-white spots indicating an increase in the NDVI.

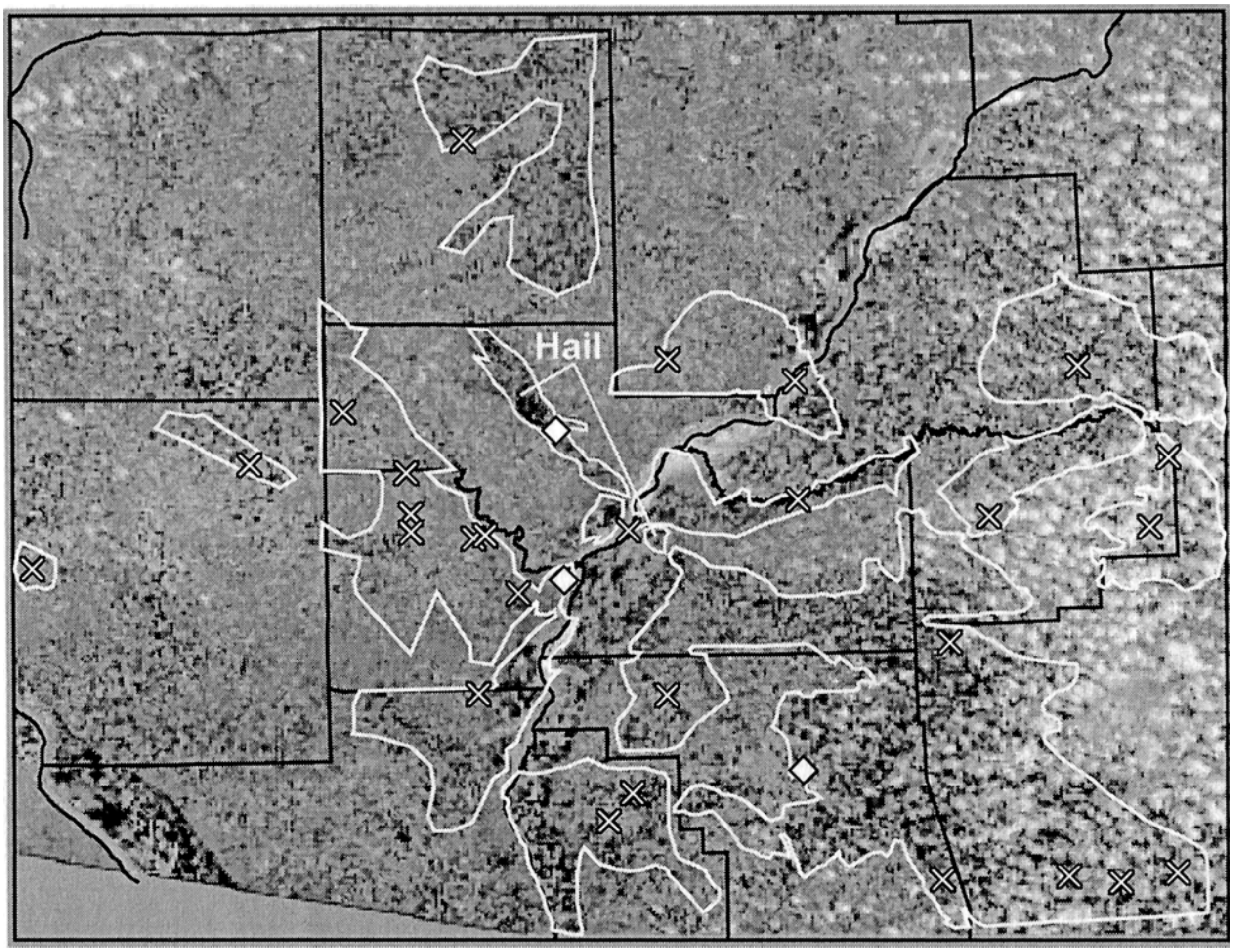


FIG. 9. The NDVI difference image with the digitized areal extent of high wind damage (12 Aug 1999) outlined in white and areal extent of hail damage (18 Aug 1999) also annotated. The high wind reports (Xs), hail reports (diamonds), and county boundaries were overlaid on top to aid image interpretation. Darker gray shades indicate greater changes in NDVI between images while lighter gray shades illustrate less significant changes in vegetation vigor between the 11 Jul and 28 Aug 1999 images. Clouds and their shadows are also depicted as light gray to near-white spots in the lower right of the image.

damage was found to be widely scattered (Fig. 5a). Although Sangamon County contained a significant amount of cloud cover on 12 July, changes in NDVI are still between the clouds. NDVI values appeared to drop from greater than 0.66 to only 0.10 after the windstorm (Figs. 4a and 5a). Fulton County damage appeared concentrated in the south with the NDVI decreasing from greater than 0.66 to 0.52 on 28 August.

To derive an areal estimation of corn damage, the 12 July and 28 August images were overlaid and the pixel values of NDVI were subtracted in order to produce a differenced image (Fig. 9). This image identifies decreases in NDVI, illustrating regions where vegetation was damaged. Using the differenced image along with the 12 July and 28 August NDVI and the reports of storm damage, the areas of significant vegetation degradation were manually digitized. As shown, Sangamon County yielded the greatest areal coverage of vegetation damage from NDVI with Morgan, McDonough, Cass, and Brown Counties all containing damage regions greater than 100 000 acres (Fig. 9, Table 2). It is interesting to note that the two counties with crop damage estimates greater than \$10 million did not contain the greatest areal coverage of damage (Fig. 9, Table 2). This points out the limitations of *Storm Data* reports. For example, although the after NDVI and differenced images (Figs. 5 and 9) indicated that the 18 August hailstorm damaged crops in Schuyler (31 007 acres) and Cass (9225 acres) Counties, damage was only reported in Schuyler County (NCDC 1999; Table 3). The Cass

Table 2. The estimated areal extent of crop damage and dollar losses from severe thunderstorms on 12 Aug 1999. Also, *Storm Data* damage estimates included where applicable.

County	Total area (acres)[a]	Estimated damaged area (acres)[b]	Corn acreage 1999[c]	1999 corn yield[c]	Estimated damage at 35% loss and $1.94 per bushel	*Storm Data* damage estimates ($)
Adams	548 286	21 324	119 000	122	1 766 448	
Brown	195 647	106 824	39 400	128	3 263 817	
Cass	240 639	113 769	79 500	152	6 909 504	6 800 000
Fulton	554 046	56 056	152 000	154	5 861 558	
Logan	395 647	44 934	175 000	158	4 820 575	8 300 000
Mason	344 959	85 272	114 600	146	8 453 336	12 300 000
McDonough	377 151	117 227	134 000	157	12 496 739	
Menard	201 151	96 744	77 800	163	8 293 713	6 000 000
Morgan	364 031	164 073	125 000	147	13 834 625	11 800 000
Pike	531 390	65 699	135 000	124	5 531 610	
Sangamon	555 710	255 569	202 000	145	17 007 592	
Schuyler	280 191	57 679	60 600	133	5 208 853	6 000 000
Scott	160 639	86 045	50 600	122	4 569 534	2 800 000

[a] The data are from the National Association of Counties (2000).
[b] The estimated damaged area calculated from the classified Landsat data.
[c] Illinois Department of Agriculture (1999).

County Farm Service Agency verified that there was hail damage in Cass County on 18 August (S. R. Turner 2000, personal communication).

To calculate corn damage from the areal estimates determined from the NDVI differenced image, corn acreage, yield, and price information were obtained. Discussions with Farm Service Agency employees in the region allowed us to determine an initial yield loss estimation of 35% for wind-damaged corn and 45% for hail-damaged corn (S. R. Turner 2000, personal

Table 3. The estimated areal extent of crop damage and dollar losses from hail on 18 Aug 1999. Also, *Storm Data* damage estimates included where applicable.

County	Total area (acres)[a]	Estimated damage area (acres)[b]	Corn acreage 1999[c]	1999 corn yield[c]	Estimated damage at 45% loss and $1.94 per bushel	*Storm Data* damage estimates ($)
Cass	240 639	9225	79 500	152	1 224 121	
Schuyler	280 191	31 007	60 600	133	3 600 192	4 000 000

[a] The data are from the National Association of Counties (2000).
[b] The estimated damaged area calculated from the classified Landsat data.
[c] Illinois Department of Agriculture (1999).

communication). Due to prevailing soil conditions and the ability of farmers to modify harvesting equipment, the actual losses from the severe wind event were only approximately 10% (S. R. Turner 2000, personal communication). Although blown down, most of the corn plants were able to remain rooted and harvesting equipment was modified in order to pick up the corn laying near the ground (S. R. Turner 2000, personal communication). This minimized the actual losses in this particular event. However, the dollar amount estimates calculated using the *Landsat-7* imagery compare favorably with the *Storm Data* estimates, which were obtained from the Agricultural Extension Offices located throughout the region (M. Byrd 2001, personal communication; Tables 2 and 3). To determine the relationship between the estimated total storm damage due to hail and wind from *Landsat-7* and that from *Storm Data* damage reports, several statistics were computed (Table 4). Seven counties contained damage estimates from *Landsat-7* and *Storm Data* and these were ranked and then correlated by calculating the Spearman's rank correlation coefficient (Table 4). The Spearman's rank correlation coefficient provides a measure of correlation between ranks with a perfect positive correlation being 1 and a perfect negative correlation being −1 (McClave and Dietrich 1988). The correlation coefficient was 0.75, which indicates a significant relationship between the two independent storm damage estimation methods. This evidence also suggests that much of the variability between the county damage estimates was captured. The mean values for the two estimation samples also compare favorably (Table 4). There is only a 2% difference between the calculated means of the two samples.

Table 4. The calculated means of the estimated total storm damage due to hail and winds using Landsat and *Storm Data* reports. Spearman's rank correlation coefficient calculated after ranking the damage estimates. The coefficient is significant at the 0.05 α level.

Variable	Mean	Spearman's coefficient
Landsat estimation	8 130 636	0.75
Storm Data estimation	8 285 714	α at 0.05 = 0.714

Discrepancies between our estimates and *Storm Data* arise from limitations in drive-by estimation of crop damage. Additionally, discrepancies exist due to missing reports of crop damage. University of Illinois Agricultural Extension employees confirm that corn crops were damaged throughout the western portions of Sangamon County (D. J. Robson 2000, personal communication). This is consistent with the NDVI differenced image, which showed vegetation losses in western Sangamon County (Fig. 8). However, *Storm Data* did not contain any crop damage estimates for this county, although it did report three instances of thunderstorm winds knocking down small trees and power poles (NCDC 1999).

DISCUSSION. Overall, the utilization of *Landsat-7* for storm damage assessment over agricultural regions was found to be useful with several important findings obtained from this investigation. First, it can be difficult to visually detect damage produced by thunderstorm winds using the NDVI images. This is due to the fact that much of the vegetation survives, making changes in NDVI between before and after imagery more subtle. In contrast, hail damage is much easier to detect visually since it typically destroys vegetation. To better identify damage produced by severe thunderstorm winds, one approach might be to subset the images to a particular county, create a difference image, and then automate the damage assessment process by determining threshold values for a range of damage severity contained on the difference image. These thresholds could then be used as a primary estimator over the difference image covering the entire region. The only drawback to automating the classification is cloud cover. If cloud cover contaminates the imagery, the areal extent of damage within a cloudy region will not be able to be calculated using an automated technique.

Another important finding centers around the storm reports used to aid damage assessment. Several counties that contained considerable decreases in NVDI, indicative of widespread damage, only had one or two reports of storm damage and no estimated damage to crops. Other counties appeared to have more accurate estimations of overall damage. This brings into question the usefulness of *Storm Data* damage estimates obtained after a significant weather event. The large farms located in this region make drive-by-based identification of the areal extent of damage very difficult. This further complicates the process of storm damage assessment.

As illustrated in this investigation, several counties showing signs of significant damage were not identified in the storm reports. In other counties, storm damage estimates of crop loss were consistent with those calculated from the *Landsat-7* imagery. Although severe thunderstorm wind damage can be difficult to identify even from *Landsat-7* imagery, with proper tools and techniques the assessment of storm damage from remotely sensed data can yield accurate results and could prove useful for farmers, meteorologists, and insurance companies.

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