Multi-Sensor Examination of Hail Damage Swaths for Near Real-Time Applications and Assessment

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ABSTRACT

Severe thunderstorms occurred across portions of South Dakota, Nebraska, Iowa, and Missouri on 18 August 2011, resulting in several swaths of large hail that caused significant damage to crops toward the end of the growing season. Changes with time in the normalized difference vegetation index (NDVI) and true-color imagery from the Moderate Resolution Imaging Spectroradiometer instrument aboard the National Aeronautics and Space Administration’s Terra satellite identify the damaged area, with corroboration by available radar data. Higher resolution satellite imagery from the public and private sector further identify both damage and NDVI changes within individual fields of planted crops that are susceptible to hail damage. Similar imagery can be developed for near real-time applications seeking to identify crop-damage areas during the growing season.

1. Introduction

Severe weather often leads to crop damage during the growing season, and thus contributes to economic losses. In 2007, combined effects of thunderstorm winds and hail led to over $340M in losses and comprised approximately 30% of the combined property and crop damage that year (NCDC 2007). Detailed ground surveys typically are performed when tornadoes are observed or suspected, but less frequently for damage known to be caused by wind or hail. Satellite remote sensing can play a supporting role with instruments and spectral bands focused on the detection of, and change in, vegetation. Although these applications may not provide detection of damage within urban areas, they can help estimate damage to agriculture during the growing season.

An early example of hail damage detection from satellite remote sensing is provided by Klimowski et al. (1998) who used the visible band of the Geostationary Operational Environmental Satellite-8 (GOES-8) to identify surface damage along a 120-km path of “almost complete vegetative defoliation and destruction” in western South Dakota that was caused by large hail (>5 cm) and severe winds (>50 m s⁻¹), including complete devastation of range grasses, planted crops, and extensive defoliation of trees. Use of the GOES-8 visible band (0.52–0.72 μm) at 1-km spatial resolution allowed for identification of defoliated or wilted vegetation through changes in reflectance from healthy green vegetation to the exposed soil and dead plant material after the event.

Other studies have incorporated satellite sensors with improved spatial and spectral resolution. Bentley et al. (2002) used the Landsat-7 Enhanced Thematic Mapper Plus (ETM+). The ETM+ includes the spectral bands necessary for calculating the normalized difference vegetation index (NDVI):

\[
NDVI = \frac{(R_{NIR} - R_{VIS})}{(R_{NIR} + R_{VIS})},
\]

where \( R_{NIR} \) (\( R_{VIS} \)) represents the near-infrared (red visible) reflectance. Values of NDVI range from −1 to
1 (and are unitless) with healthy vegetation typically corresponding to values of 0.3 and greater. Non-vegetated urban areas, bare soils, and sparsely vegetated regions will tend to produce smaller positive values. Clouds tend to produce negative values, and water is near zero. Bentley et al. (2002) used sequential ETM+ images during the 16-day repeat cycle of Landsat-7 to identify areas of likely vegetation damage by calculating changes in NDVI. Reports of severe thunderstorm winds and large hail occurred within the region of NDVI reduction. Some differences in NDVI change were noted and attributed to a specific type of severe weather event. Defoliation by combined wind and hail contributed to the greatest reduction, whereas strong winds alone may have only toppled the crops and allowed them to survive, resulting in a smaller NDVI change. Pre-storm NDVI values of ≥0.6 were replaced by post-storm values of 0.1–0.25 in areas where damage was clearly attributable to hail. Detailed cloud masking or viewing of single-channel visible imagery also is required to ensure that changes in NDVI are not actually due to changes in cloud cover or shadow effects. Cloud contamination did not permit Bentley et al. (2002) to establish an NDVI change threshold for damage detection.

Although the Landsat-7 ETM+ provides improved spatial resolution, the relatively long 16-day repeat cycle and need for clear skies can make short-term NDVI change detection problematic. The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites offer a compromise. MODIS provides red visible and near-infrared reflectance (thus NDVI) at 250-m spatial resolution along with blue and green visible reflectance at 500-m spatial resolution. The red, green, and blue reflectance can be combined to produce vibrant true-color imagery. Other spectral bands in the near-, mid-, and thermal-infrared are available at 1-km resolution and are useful for identifying cloud cover and other features. The 2330-km swath width of MODIS from either Terra or Aqua provides daytime coverage at least twice per day—once in the morning and again in the early afternoon. The widespread availability of MODIS data has led to several near real-time applications. The United States Geological Survey (USGS) generates week-long composites, referred to as eMODIS (Jenkerson et al. 2010), that have been used to monitor vegetation health and agricultural output. The United States Department of Agriculture (USDA) and the Forest Service use eMODIS composites and differences over multiple years to monitor the health of forested areas along with damage to forests caused by infestations, forest fires, or severe weather (Hoffman et al. 2010). Many users of MODIS data have developed their own compositing techniques tailored to a specific application.

Parker et al. (2005) used 7-day, 500-m resolution composites of maximum MODIS NDVI and differences between consecutive composites to identify hail swaths in North and South Dakota produced by severe thunderstorms on 4 July and 20 July 2003. Repeated views of MODIS allowed for the monitoring of changes in swath characteristics with time. The hail swaths examined by Parker et al. (2005) remained apparent up to six weeks after the event, but included some discontinuities where the predominant vegetation type may have been resistant to hail damage. Hail damaged swaths also created sensible weather effects such as higher air temperature (+0.9°C), lower dewpoint (–0.3°C), and increases in cloud-free, infrared brightness temperatures versus adjacent hail-free areas. Modeling studies confirmed there may be impacts on future convective storms through additional convective initiation, or strengthening of ongoing storms within synoptic or mesoscale environments where the flow is persistent and parallel to the direction of the hail swath. When incorporated within weather forecast models, these narrow swaths also may have impacts on the resulting simulation, but these possible impacts are beyond the scope of this study.

Gallo et al. (2012) investigated hail streaks across northwestern Iowa caused by severe thunderstorms that occurred on 9 August 2009. In locations reporting severe hail, eMODIS NDVI decreases ranged in magnitude from 0.019–0.357. The largest changes in NDVI were limited to vegetated areas, but some locations included in the study were on the fringe of developed (non-vegetated) rural communities or cities where NDVI was small in both the pre- and post-storm composite. The Gallo et al. study also examined relationships between NDVI change and hail size provided by the maximum expected size of hail (MESH) product, which is generated within the Warning Decision Support System—Integrated Information (Lakshmanan et al. 2007) and based upon the National Severe Storms Laboratory (NSSL) Hail Detection Algorithm (Witt et al. 1998; Stumpf et al. 2004). The gridded MESH product compared
reasonably well to available storm reports of hail size and was used to relate hail size to corresponding NDVI change. A recent study determined that MESH output was reasonable and useful in studying the occurrence of hail within the continental United States (Cintineo et al. 2012). Gallo et al. (2012) noted that 77% of cells with nonzero MESH values corresponded to a decrease in NDVI, and that the percentage of NDVI-reduced cells increased when the minimum hail size was increased beyond values used in severe weather warnings (2.54 cm or 1 in). A small but statistically significant amount of the NDVI change was related to hail size. Some minor offsets in the precise location of NDVI change and MESH values were noted and attributed to differences between radar sampling of hail aloft and fallout locations. These offsets likely contributed to a reduced correlation between MESH hail size and NDVI change when values were compared for the same image pixel.

This study provides an additional example of MODIS detection and radar corroboration of crop damage resulting from severe hail, but proposes a new application based upon near real-time MODIS imagery. It incorporates aspects of Bentley et al. (2002) through use of Landsat ETM+ imagery, but identifies other on-orbit sensors capable of identifying hail damage areas at equal or better spatial resolution when ETM+ imagery are not available, outside the ideal viewing (nadir) conditions, or blocked by cloud cover. Use of higher spatial resolution imagery confirms changes observed within the moderate resolution—but more frequent—MODIS composites.

This study focuses on severe thunderstorms that occurred on 18 August 2011 in eastern South Dakota and moved southeastward along the Missouri River. The region was included within the Storm Prediction Center (SPC) day 1 convective outlook issued at 1200 UTC (not shown) and an updated outlook issued at 1943 UTC (Fig. 1). Severe weather began around 1800 UTC with a supercell in Knox County, Nebraska, that produced up to softball-sized hail and then moved to the southeast as other thunderstorms developed in southeastern South Dakota (Fig. 2a). By 2200 UTC, several strong-to-severe thunderstorms were located along the Missouri River and in southwestern Iowa, producing large hail and damaging winds (Fig. 2b). As these storms moved through the Omaha area, reports of softball-sized hail continued, including significant property damage and an injury to a pilot at Eppley Airfield. Severe thunderstorms continued to produce large hail across southwestern Iowa and northwestern Missouri during the late afternoon and early evening (Fig. 2c). Storms crossing the Iowa-Missouri border at 2359 UTC produced long tracks of damaging hail that will be examined in more detail (Fig. 2d). In the wake of this first round of storms, other severe thunder-
storms developed across northeastern Nebraska and followed a similar path. This second round of supercells and bowing segments produced some additional hail across eastern Nebraska, western Iowa, and extreme northwestern Missouri before transitioning primarily to reports of damaging winds across eastern Kansas and central Missouri (Fig. 3).

Figure 3. Preliminary storm reports for 18 August 2011, highlighting the concentration of severe weather reports along the Missouri River, portions of eastern NE, southwestern IA, and northwestern MO. Image courtesy of the Storm Prediction Center.

2. Data and methods

Numerous reports of severe weather were submitted by the public, media, and emergency managers, but for comparison to satellite imagery it is helpful to have a dataset with improved spatial continuity. Herein, this study adopts some techniques of Gallo et al. (2012) by incorporating the MESH product for comparison to MODIS NDVI change. MESH images were acquired from the NSSL OnDemand portal (ondemand.nssl.noaa.gov) for the 24-h period beginning 1200 UTC 18 August 2011 for comparison to SPC-filtered storm reports (Fig. 4). The MESH data identify the numerous streaks of large hail that occurred in northeastern Nebraska, along the Missouri River, and into southwestern Iowa and extreme northwestern Missouri. As in Gallo et al., increases in MESH correspond to increases in reported hail size, subject to some spatial displacements that could be caused by errors in reporting location or differences between radar sampling and fallout location. Given the general agreement between hail reports and MESH, the MESH product is used herein to provide greater spatial coverage and continuity than what is available from individual storm reports.

Figure 4. Terra MODIS true-color image from the morning of 25 August 2011 with overlay of MESH data (contour fill, cm) for the period of 1200 UTC 18 August 2011 through 1200 UTC 19 August 2011. Filtered SPC storm reports of hail size (cm) are provided as color-filled boxes.

a. Use of MODIS data

Archive data were acquired for the Terra MODIS from the NASA Level 1 Atmosphere Archive and Distribution System (ladsweb.nascom.nasa.gov). Although the analysis herein focuses on the use of data from Terra, the same techniques also can be applied to data from Aqua MODIS. Near real-time applications can be developed using MODIS direct broadcast capabilities that provide data over the continental United States. A simple combination of the MODIS red, green, and blue visible reflectance creates a vibrant true-color image. True-color imagery is a straightforward way to identify damage to vegetation, as vibrant greens are replaced with browns when plants wilt or die and the underlying soils are revealed (Fig. 5). Algorithms provided by the NASA Direct Readout Laboratory were used to improve image quality by removing Rayleigh scattering, determining surface reflectance, deriving a mask for cloud features, and calculation of NDVI.

Rapid vegetation change should be detectable almost immediately after the storm and useful products can be developed by focusing on shorter-term composites. In this study, individual 5-min increments of Terra MODIS data were converted to surface reflectance, NDVI, and a supplemental cloud mask.
then projected to a common domain over the continental United States. Single-day mosaics were generated from Terra MODIS clear-sky views and combined to create a maximum cloud-free NDVI composite value during the preceding 14-day period. This ensures that there will be sufficient contrast between the most recent maximum NDVI value and changes resulting from damage to vegetation. This also accommodates clouds and their edges (negative NDVI) or cloud shadows (reduced NDVI) that could be missed by the cloud mask. Daily difference products were created by subtracting the single-day mosaic from the previous 14-day maximum, allowing for the identification of sharp decreases in NDVI associated with storm damage to vegetation. For example, if severe weather occurred on ordinal date 175 and skies were clear enough to observe the damage area on the same day, a clear-sky mosaic on day 175 could be differenced against the 14-day maximum NDVI composite accumulated from days 161 through 174. Clouds will occasionally linger beyond the day of a given severe weather event, but damage to vegetation persists and may become more evident in the days that follow. During cloudy periods, difference images continue to be generated with a cloud mask applied to identify cloud-contaminated

**Figure 5.** Terra MODIS true-color image from the morning of 25 August 2011 (about seven days after the severe storms) when skies generally were clear over the area. Damage scars are apparent as brown streaks generally oriented from northwest-to-southeast, in contrast to green vegetation. Colored boxes highlight the coverage area for segments of other, higher spatial resolution satellite images: (i) a single segment of the Landsat-7 ETM+ in green, (ii) two combined segments of the Advanced Spaceborne Thermal Emission and Reflection Radiometer in red, and (iii) single segments of the Système Pour l’Observation de la Terre (System for Earth Observation) or SPOT-4 (SPOT-5) in yellow (cyan). The white dashed box is a subset region of the aforementioned instruments and is used in Figs. 8, 9, and 10.
areas. Clear portions of the scenes remain useful, allowing for partial detection of damage in areas where tracks are partially obscured by cloud. When skies clear over the damage area, surface damage tracks become apparent in the resulting difference imagery. When post-storm NDVI values and pre-storm composites are differenced, the result is a large, negative value within the damaged area. In this study, resulting difference images were linearly scaled to an 8-bit grayscale color table using light grays to bright white to emphasize NDVI changes of −0.5 or less.

b. Landsat-7 and the ETM+

Sensors with higher spatial resolution provide value through detection of damage at the field scale (Bentley et al. 2002) and linkages to signals in the coarser MODIS data. The ETM+ aboard Landsat-7 provides seven spectral bands in the visible and near-infrared at 30-m spatial resolution, an infrared band at 60-m spatial resolution, and a higher spatial resolution panchromatic band across portions of the visible and near-infrared spectrum at 15-m spatial resolution. Spectral bands of the ETM+ can produce true-color imagery, NDVI, and other false-color composites. Spatial coverage of a single ETM+ scene is 183 km × 170 km. Coverage of individual scenes can provide some overlap on the scene edge, but for best image quality the comparisons of Landsat scenes require the full 16-day repeat cycle. Since late 2003, Landsat-7 ETM+ data have been collected despite a failure of the scan line corrector (SLC), referred to as SLC-off imagery. The loss of the SLC results in missing data near the swath edge for Landsat-7 ETM+ scenes after 31 May 2003. In this study, the area of interest occurs near the center of the swath, and missing pixels from SLC-off data are not an issue. Other hail events in the SLC-off era may be more difficult to assess if they occur near the swath edge. The recent launch of the Landsat Data Continuity Mission (LDCM, now Landsat-8) provides comparable imagery for events beginning in May 2013, but with SLC enabled, allowing for full-resolution imagery throughout the entire swath.

c. The Advanced Spaceborne Thermal Emission and Reflection Radiometer

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an instrument aboard the Terra satellite. Currently, ASTER provides 15-m spatial resolution imagery for spectral bands in the green, red, and near-infrared wavelengths and 90-m spatial resolution in the thermal infrared. Short-wave-infrared bands at 30-m spatial resolution were provided at launch but are not valid for data after April 2008. Although the spectral bands of ASTER do not permit true-color imagery, the instrument provides the bands necessary to calculate NDVI and to produce false-color imagery that approximates the general color palette of a true-color image. False-color imagery helps to discriminate vegetation, vegetation damage, and other land use categories. The ASTER instrument is targetable, so rather than steady and repeated collection of swath imagery, data are produced on demand and often in response to specific research studies or disaster monitoring. Each segment covers approximately 60 km × 60 km, but repeated coverage in a single location is limited. Targeting of the sensor requires some advanced notification, but ideal conditions could allow for image acquisition within three days following an event.

d. Data acquired through private sector and international partnerships

During disaster events, additional satellite imagery can be acquired through commercial sources. To support federal response during the flooding of the Missouri River, the USGS acquired additional imagery from the Système Pour l’Observation de la Terre (System for Earth Observation, or SPOT) satellites originally designed by the Centre National D’études Spatiales (the National Center of Space Research for France, or CNES). Images from SPOT-4 and SPOT-5 are used here to evaluate hail damage. Spectral bands of SPOT-4 and SPOT-5 are similar to ASTER (Table 1) and created additional views of the area when either ASTER or Landsat-7 were not available. Although SPOT-4 has been decommissioned, other SPOT satellites will continue to provide similar data.

Table 1. A summary of the satellite sensors used in this study, products shown here, and spatial resolution.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Product</th>
<th>Resolution</th>
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<tbody>
<tr>
<td>Terra MODIS</td>
<td>NDVI</td>
<td>250 m</td>
</tr>
<tr>
<td></td>
<td>True Color</td>
<td>500 m</td>
</tr>
<tr>
<td>Landsat-7 ETM+</td>
<td>NDVI</td>
<td>30 m</td>
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<tr>
<td></td>
<td>True Color</td>
<td>30 m</td>
</tr>
<tr>
<td>Terra ASTER</td>
<td>NDVI</td>
<td>15 m</td>
</tr>
<tr>
<td></td>
<td>Natural Color</td>
<td>15 m</td>
</tr>
<tr>
<td>SPOT-4</td>
<td>NDVI</td>
<td>20 m</td>
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<td>SPOT-5</td>
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<td></td>
<td>Natural Color</td>
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e. False-color imagery and derived products

MODIS and the Landsat-7 ETM+ provide the spectral bands necessary for true-color imagery. Interpretation of true-color imagery is straightforward as it provides an image similar to what would be seen by the human eye. Although the ASTER, SPOT-4, and SPOT-5 imagery lack the required true-color bands, a false-color technique has been developed to approximate the general color characteristics of a true-color image. Referred to here as natural color (K. Duda, personal communication, 2012), this product uses combinations of visible and near-infrared bands to create a final image where vegetation appears as shades of brown to green, water appears in blue shades, and urban areas in shades of gray to white. Natural color is similar enough to true-color imagery that interpretation of the scene is straightforward. Equations for derivation of the red, green, and blue color intensities of each pixel are as follows:

\[
red = R_R, \\
green = (0.75 \times R_G) + (0.25 \times R_{NIR}), \\
blue = (0.75 \times R_R) - (0.25 \times R_{NIR}).
\]

where red, green, and blue correspond to the color intensity for each pixel, \(R_R\) corresponds to the red visible reflectance, \(R_G\) corresponds to the green visible reflectance, and \(R_{NIR}\) corresponds to the near-infrared reflectance. Although each sensor is slightly different in the spectral bands representing the red, green, and near-infrared components, time of day when the observations are made, and viewing angle, the equations are applied to each of the surveyed instruments. Despite these slight differences, the color characteristics of the resulting images are generally consistent. Final values of red, green, and blue are determined and mapped to 8-bit values (0–255) and then enhanced as appropriate to adjust the brightness of the final 24-bit image.

Vegetation changes inferred from either the natural- or false-color product can be confirmed by examining NDVI data from each instrument. For Terra ASTER, Landsat-7 ETM+, SPOT-4, and SPOT-5, NDVI was calculated from top of the atmosphere reflectance based upon Eq. (1) with a grayscale enhancement selected to identify less-vegetated (heavily vegetated) areas in dark shades (white shades). Although differences in viewing angle, time of day, and sensor characteristics preclude a quantitative comparison between the instruments, individual images still capture the damage swath evident in NDVI and natural-color imagery.

3. Analysis and discussion

Rapid changes in NDVI can be used to identify potential areas of damage, but a combination with MESH constrains the imagery to focus on likely hail damaged areas. Other severe weather events such as strong winds also contribute to vegetation loss or change (Bentley et al. 2002), but composites of radar-estimated wind speeds are not currently available. Tornadoes also create damage scars evident in satellite imagery (Yuan et al. 2002; Jedlovec et al. 2006; Molthan et al. 2011) and could be related to storm rotation tracks information provided by NSSL, but that is beyond the current focus of this study as significant, long-track tornadoes were not reported in the area of interest. It is assumed here that defoliation by large hail contributes to the majority of the NDVI change. Given the colocation of many storm reports for both wind and hail (refer back to Fig. 3), strong winds likely occurred within the region of MESH-indicated hail and also may have contributed to vegetation damage. However, wind-blown crops that retain their greenness and rebound will retain most of their pre-storm characteristics. Larger changes in NDVI will be shown to correlate to increases in hail size, resulting from longer-term wilting or greater devastation to the plant material. The MESH product is used to identify the greatest contributor to vegetation damage (hail), but it is also assumed that strong to severe winds may contribute to NDVI change within the same area.

To determine appropriate thresholds for a MESH constraint, changes in NDVI were examined within size bins of MESH hail size. A box-and-whiskers plot of NDVI change and hail size (Fig. 6a) indicated that the median NDVI progressively decreased for hail sizes of at least 1.27 cm (0.5 in), 1.27–2.54 cm (0.5 in to 1 in), and >2.54 cm (1 in). A joint histogram of hail size and NDVI change, normalized across each hail-size bin, confirmed that there was an increased frequency of large NDVI decrease with increase in hail size (Fig. 6b). Negative correlations between NDVI change and selected hail-size thresholds of 1.27 cm (0.5 in; \(r = -0.28\)), 2.54 cm (1.0 in; \(r = -0.37\)), and 5.08 cm (2.0 in; \(r = -0.31\)) were statistically significant.
at the $\alpha = 0.05$ level. Changes in NDVI were relatively small for hail sizes less than the 2.54-cm (1.0 in) severe thunderstorm threshold, but NDVI decreases were larger as hail size increased. These results are similar to Gallo et al.’s (2012) correlations between MESH size and NDVI change, subject to small spatial displacements between radar-estimated hail and vegetation damage. However, the frequency of extremely large hail is quite low. For example, the frequency of days with hail of at least 1.9 cm (0.75 in) is approximately 25% across the study area, and the size of an average hailstone during any hail event ranges from 0.51–0.76 cm (0.2–0.3 in; Changnon et al. 2009).

Based upon comparisons of hail size and NDVI change, a 2.54-cm (1 in) MESH threshold was selected to highlight likely hail damaged regions as it also corresponds to the current National Weather Service severe thunderstorm threshold. To reduce false returns in the NDVI change imagery, cloud mask features were identified, in addition to major river channels and other water features. Water features contributed short-lived but large changes in NDVI during this study owing to the ongoing flooding of the Missouri River and upstream sources. In the final composite, areas with large NDVI decreases and MESH larger than 2.54 cm (1 in) were featured in dark red to bright white while preserving the grayscale NDVI change product elsewhere (Fig. 7). This helped to identify the major damage swaths in portions of Nebraska, Iowa, and Missouri while correctly excluding the damage area in northeastern Kansas that was attributed to hail on 19 August. The intent of the final composite product was to combine information from both radar and satellite while preserving the context necessary for an analyst to make their own inference regarding the source of any NDVI change. This allows an analyst to focus on suspected or known hail damage areas while excluding other sources of rapid NDVI change that could result from frost or freeze, harvest, or fires.

To demonstrate supporting images provided by ASTER, Landsat-7 ETM+, SPOT-4, and SPOT-5, a subset of each scene was extracted within the coverage area of the Terra MODIS NDVI change and MESH products (refer back to Fig. 5). Nearest-neighbor interpolation was applied during reprojection to preserve the relative coarseness of the MODIS and MESH fields in comparison to other sensors. Based
Figure 7. Terra MODIS NDVI difference based upon data on 25 August minus the maximum NDVI for the 14-day period ending 24 August. Applied grayscale image enhancement is constrained so that values < –0.5 are bright white, and changes of 0 to –0.5 are in shades of light gray. Cyan pixels indicate areas where the cloud mask indicated cloud cover on 25 August. Note that the cloud mask failed to detect cloud cover in east-central KS and an arc of thin clouds in SD and MN. The white inset box identifies NDVI change associated with a separate event evident in MESH data for 19 August. Rivers are masked in blue. Red to white shading identifies large NDVI changes that are coincident with MESH estimates of hail > 2.54 cm (1 in).

upon the MESH hail sizes (Fig. 8a), the strongest decrease in NDVI and most significant damage was expected to run from northwest-to-southeast through the frame, although estimates of 2.54 cm (1 in) or greater occurred throughout the zoomed area. This corresponds well to the MODIS NDVI change images (Figs. 8b, 9a, and 10a) where a corridor of large NDVI changes corresponded to the area of largest hail.

Changes in the true- and natural-color images over time (Fig. 9) provided a qualitative view of the vegetation color and a higher resolution view than provided by MODIS (Fig. 5), while temporal change in NDVI among the various instruments confirmed the vegetation damage, as shown in Fig. 10. An example of the Landsat-7 ETM+ true-color image prior to the event is shown in Fig. 9b, providing a clear picture of the area on the morning of 18 August prior to the severe thunderstorms that would occur later that afternoon. Corresponding images of high NDVI values from Landsat-7 are shown in Fig. 10b, with some variation between planted fields and other vegetation. Natural-color images from other instruments substitute for days within the 16-day repeat cycle of Landsat-7. Individual satellite sensors cannot be directly compared in a quantitative time series since they vary in the characteristics of their spectral bands, viewing geometry, time of day, calibration uncertainty, and other characteristics, but the damaged areas are apparent in the individual images. A SPOT-5 natural-color image from the early afternoon of 19 August—the day following the event—is shown in Fig. 9c. Within the corridor of greatest Terra MODIS NDVI change and largest MESH hail size, the images have browned slightly, corresponding to changes in red and near-infrared reflectance from damage to the surface vegetation. The color variation is non-uniform, likely due to variations in hail size, intensity, duration, any accompanying winds, and the susceptibility to hail damage for each affected type of vegetation. Crops that were more resistant to the severe weather would not be expected to present a large decrease in NDVI. Tree-lined creeks and streams may not have been affected as they would need to be extensively defoliated or toppled to expose the reflectance of the underlying surface. In general, discolorations in the natural-color images correspond to initial decreases (graying) in NDVI (Fig. 10c). Although the natural-color and NDVI images are derived based in part upon the same channels, natural-color images offer a quick, easily interpreted visualization that corresponds to quantitative information provided by NDVI.

Nine days after the storms, damaged vegetation continued to wilt, and some fields may have been harvested in order to minimize losses. Natural-color images from SPOT-4 clearly depict a brown discolor-
Figure 9. Evolution of true- and natural-color images for a hail damaged area in southwestern Iowa. a) Terra MODIS NDVI change product with grayscale enhancement as in Fig. 8b, featuring the inset area shown in Fig. 5. Dashed lines outline the general corridor of greatest NDVI decrease. b) Landsat-7 ETM+ true-color image during the morning of 18 August, a few hours prior to the severe weather event. c) Natural-color image from SPOT-5 on 19 August. d) Natural-color image from SPOT-4 on 27 August. e) Natural-color image from ASTER on 10 September. f) Landsat-7 ETM+ true-color image on 19 September.

Figure 10. Evolution of grayscale NDVI images for a hail damaged area in southwestern Iowa. a) Terra MODIS NDVI change product with grayscale enhancement as in Fig. 8b, featuring the inset area shown in Fig. 5. Dashed lines outline the general corridor of greatest NDVI decrease. b) Landsat-7 ETM+ grayscale NDVI image during the morning of 18 August, with vegetation in shades of light gray to white and damaged vegetation in darker shades. c) Grayscale NDVI image from SPOT-5 on 19 August. d) Grayscale NDVI image from SPOT-4 on 27 August. The area of significant damage is dark gray to black. e) Grayscale NDVI image from ASTER on 10 September. f) Landsat-7 ETM+ NDVI image on 19 September.
ration within the MODIS-estimated damage area (Fig. 9d). These browned areas correspond to a decrease in NDVI along the center of the MODIS-estimated damage area (Fig. 10d). Some of the inferred damage areas are confined to rectangular regions corresponding to individual fields where crops were especially susceptible to hail. As mentioned by Parker et al. (2005), detection of damage through remote sensing requires the colocation of susceptible vegetation and severe weather impacts. Crop susceptibility also can be modified by other vegetation features or arrangements such as adjacent tree lines or row spacing that can mitigate hail damage (Changnon et al. 2009). Therefore, areas less susceptible to widespread damage remain relatively green, but higher resolution imagery provides greater spatial detail than coarser MODIS observations.

Given the 16-day repeat cycle of Landsat-7, ETM+ images would have been available again on 3 September, but the region of interest was obscured by cloud cover. Images from ASTER were available on 10 September but partially obscured by cloud cover and corresponding cloud shadows (Fig. 9e). Cloud cover and shadows resulted in a slightly darker appearance to the scene and a mottled texture in the southwestern quadrant. Despite partial cloudiness, ASTER data also identified reductions in NDVI due to continued loss of green vegetation, particularly in the northwestern-most and generally cloud-free portion of the domain. Comparisons of SPOT-4 images and ASTER images also highlight some fields that likely were harvested based upon the sharp change in NDVI and the shape of the areas affected.

On 19 September, skies were clear and the Landsat-7 ETM+ obtained an additional true-color image (Fig. 9f). Harvesting activities likely were ongoing based upon typical harvest dates (USDA 2010) and appear as sharp changes in field characteristics that were well outside the primary MODIS-detected damage. Although the month-long latency of this ETM+ image and ongoing harvest make it difficult to apply the image toward damage assessment, comparisons to NDVI are helpful to understand the range of expected values and how they would relate to field characteristics. Natural vegetation remains green in portions of the ETM+ image on 19 September and corresponds to relatively bright areas in the NDVI image (Fig. 10f, high values), whereas harvested fields appear much darker (lower values).

a. Feasibility of developing near real-time products and applications

The preceding discussion focused on the use of a variety of satellite sensors for identifying vegetation damage associated with severe hail events. Satellites can provide an efficient means of estimating damaged areas or identifying areas requiring a detailed ground survey. Whereas some studies, such as Parker et al. (2005) and Gallo et al. (2012), used MODIS NDVI composites from sources aggregating over multi-week periods and used multiple, lengthy composites for change detection, NDVI change-product latency can be reduced by leveraging near real-time MODIS data sources via direct broadcast. The recent launch of the Suomi National Polar-Orbiting Partnership (S-NPP) also provides additional information via the Visible Infrared Imaging and Radiometer Suite (VIIRS), which includes red visible and near-infrared spectral bands at a spatial resolution similar to MODIS (375 m; Hillger et al. 2013). Combinations of MODIS and VIIRS will provide near real-time products for monitoring vegetation changes that are likely related to severe weather. Given the repeat coverage of Terra, Aqua, and S-NPP, NDVI change-detection products will be available on a daily basis to support severe weather damage assessment. It is envisioned that MODIS and VIIRS-based products can serve as a rapidly acquired, quick-look capability to be supplemented by less timely, but more detailed, imagery.

Some higher resolution instruments, such as Landsat-7 ETM+, are acquired as a standard observation over the United States and will be supplemented by the recently launched LDCM (Landsat-8). Others, such as the Terra ASTER, SPOT, and commercial instruments not examined in this study (e.g., Ikonos, Worldview, GeoEye, and others) can be acquired in partnership with the USGS Earth Explorer (earthexplorer.usgs.gov) or the USGS Hazards Data Distribution System (hdds.usgs.gov/hdds2), which can acquire commercial datasets following significant severe weather events. Although products from these instruments have varying degrees of latency, their higher resolution images can refine damage detection to finer spatial scales. Vegetation damage may persist for several days (Parker et al. 2005), so these images continue to provide information well beyond conclusion of a specific severe weather event.
4. Conclusions

Severe thunderstorms on 18 August 2011 caused significant hail damage to vegetation in eastern Nebraska, western Iowa, and northwestern Missouri. Although it is not standard practice for field survey teams to assess this type of severe weather impact, satellite remote sensing offers a unique opportunity to efficiently detect and assess significant damage to vegetated areas during the growing season. This study focused on the following objectives:

- demonstrating the feasibility of developing MODIS NDVI compositing and differencing techniques using data nearer to the event, which reduces latency over the use of other NDVI composite products aggregated over longer time periods;
- determining that the MESH size thresholds and corresponding NDVI change in this event were similar to those of Gallo et al. (2012), reinforcing the value of combined radar–satellite information for identifying possible hail damage to vegetation; and
- identifying additional, higher resolution satellite sensors that improve the detection of field-scale damage while also confirming the signals apparent in more readily available MODIS imagery.

Given the continued availability of Terra and Aqua MODIS data and the S-NPP VIIRS instrument, future work will include development of near real-time NDVI change products for assessment of hail damage during the growing season. Likely customers include meteorologists responsible for storm damage survey teams and regional disaster assessment teams focused on agricultural impacts. Products from MODIS and VIIRS will be developed for near real-time applications following significant weather events and to support end users interested in characterizing the affected areas. Additional events will be used to better understand relationships between hail occurrence, NDVI change, and vegetation type. Meanwhile, continued collaboration with the USGS will improve the availability of other high-resolution sensor products for use by those performing damage assessments.

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