ASSESSING TORNADO DAMAGE VIA ANALYSIS OF MULTI-TEMPORAL LANDSAT 7 ETM+ DATA

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ABSTRACT

On June 18, 2001 a powerful (F-3) tornado struck the village of Siren and other parts of Burnett County in northwestern Wisconsin, leaving a 25 million dollar swath of destruction more than 40 km long through a heavily forested area. This storm resulted in three deaths, eight serious injuries, complete destruction of 180 homes and businesses and damage to 270 others. Very shortly after the tornado, investigators at the University of Wisconsin-Madison obtained Landsat-7 imagery (from May 18 and June 19, 2001) and used a multitemporal principal components analysis (PCA) technique to produce change maps of the areas affected by the tornado. The Landsat imagery from both dates, along with the change-assessment data, were reprojected and processed to suit the needs of the state and local emergency management team. Results were quickly distributed to emergency management staff over the Internet.

Four days after the tornado, 1:10,000 normal color photographs were also acquired over the entire damage path. These have been used as reference data to assess the nature and accuracy of the damaged areas delineated by the above change detection methods. The satellite-based analysis has proven to be remarkably accurate and in many respects superior to information extracted from the aerial photography, in large measure due to the importance of the mid-IR ETM+ Band 5 data used in the multitemporal analysis. Thus, Landsat-7 data proved to be a very effective means of documenting the tornado damage and in aiding recovery efforts.

BACKGROUND

During the evening of June 18, 2001, a powerful (F-3) tornado with winds up to 330 km/hr touched down in Burnett County, Wisconsin, leaving a swath of destruction more than 40 km long. Known locally as "The Siren Tornado," this twister began its destruction west of Alpha, Wisconsin east of the Minnesota/Wisconsin border and continued easterly through the heart of the village of Siren, and finally left the ground just to the west of Spooner, Wisconsin (Figure 1).

The structural damage in the village of Siren was extensive, with many homes and businesses being completely leveled or severely damaged (Figure 2). It is extremely fortunate that the death toll was not larger than the three people tragically killed by the storm, and that less than a dozen were seriously injured. In fact, many people had little warning that the storm was approaching because the village's emergency siren was inoperative at the time. The siren had been struck by lightening approximately a month earlier and, ironically was scheduled for repair during the week after the tornado struck.

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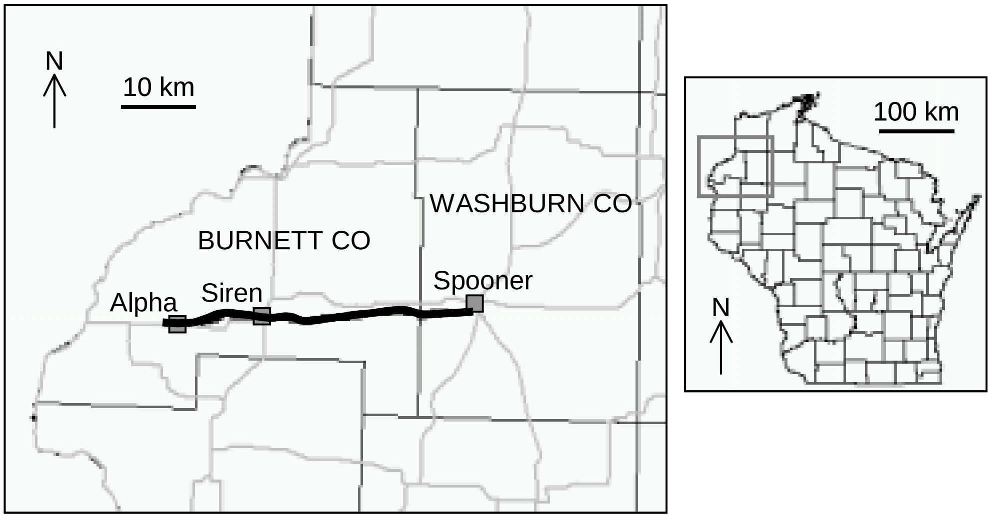

Figure 1. Map of Wisconsin showing the location of Burnett County and the approximate path of "The Siren Tornado."

Figure 2. Typical damage along center of tornado swath through village of Siren, Wisconsin.
(Image from Wisconsin Emergency Management website.)

The path of the tornado outside the area of Siren proper traversed a rural landscape dominated by a mix of forested areas, lakes, wetlands, low intensity agriculture, and rural homesteads. The major forest types present in the area include mixed northern hardwoods: northern pin/red oak (*Quercus ellipsoildalis/rubra*), aspen (*Populus tremuloides*), sugar/red maple (*Acer saccharum/rubrum),* birch (*Betula papyrifera*), basswood (*Tilia americana*), as well as jack pine (*Pinus backsiana*), white pine (*Pinus strobus*), and red pine (*Pinus resinosa*) in natural stands and plantations. The soils in the area are very sandy and the topography is relatively flat with local areas of moderately rolling terrain.

LANDSAT-7 COVERAGE OF THE TORNADO PATH

As news about the tornado broke, researchers at the University of Wisconsin Environmental Remote Sensing Center (ERSC) began inventorying potential sources of satellite imagery covering the damage path. It so happened that nearly cloud free Landsat-7 ETM+ data were acquired over the site the day after the storm (on June 19, 2001). The EROS Data Center (EDC) posted the browse image associated with this acquisition (path 27/row 28) on June 20, 2001. This image was analyzed in comparison with a previous acquisition for the same path and row made approximately one month earlier (on May 18, 2001). Even at the relatively coarse spatial resolution (300m) of these browse images, the presence of the general tornado damage track was evident (Figure 3). Given the potential usefulness of this image pair for damage estimation and recovery planning, an expedited order was placed with EDC to process these scenes as soon as feasible. This order was placed mid-day on June 20, 2001 and the processed imagery was made accessible via FTP the next business day (June 21, 2001).

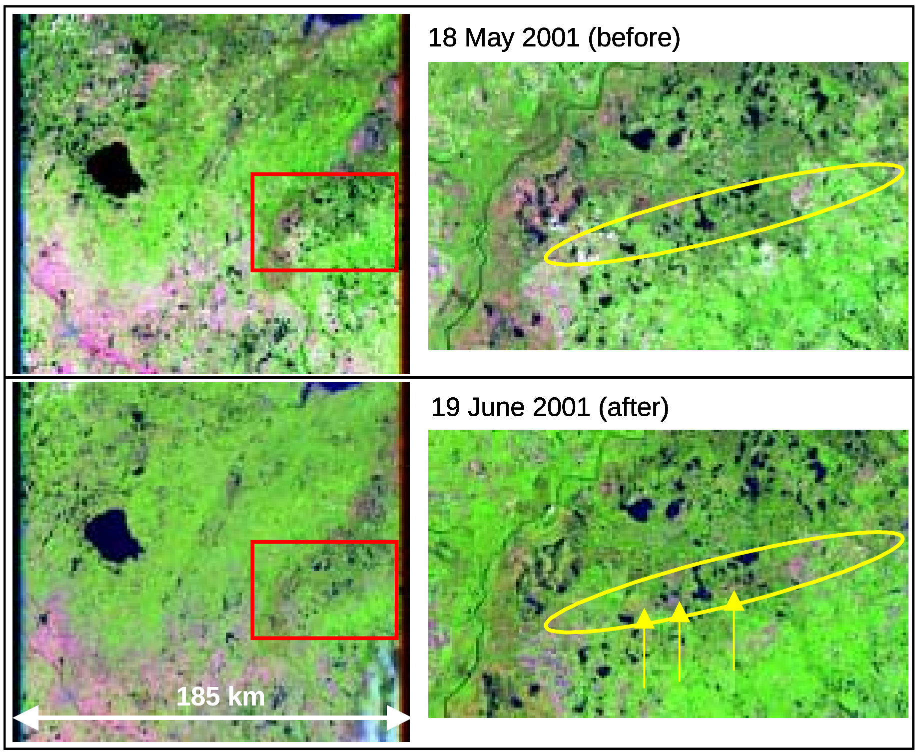

Figure 3. “Before” (May 18, 2001) and “After” (June 19, 2001) browse images of the tornado damage track.

IMAGE PROCESSING OBJECTIVES AND APPRAOCH

Our overall object in obtaining and processing the ETM+ images was to determine if, and to what extent, the data would be useful for damage assessment and recovery planning. Our initial efforts were self-motivated and speculative in nature. That is, no specific individual or group had requested such an analysis and we had little preconceived notion as to what, if any, value the ETM+ data would afford to the damage assessment and recovery process, but our goals included disseminating any pertinent findings quickly to aid the recovery effort. The initial evaluation of change was performed under a time restriction. In six hours, two Landsat images, each comprising 550 megabytes, were downloaded from a remote ftp site, imported into ERDAS Imagine formats, viewed and analyzed and then the results of our analysis were placed on a publicly accessible web site. Due to time constraints, initially, we only processed the first five optical bands and the panchromatic band.

Visual Interpretation

We began the image analysis process by comparing the “After” (June 19, 2001) image with the “Before” image (May 18, 2001) on a band-by-band basis. This initial analysis confirmed that the path of the tornado could be tracked by evaluating these satellite images. The information content of the tornado damage in the “After” image by band follows:

- Band 1 (blue): The path of tornado was definitely noticeable but there was a slight haze throughout this band due to atmospheric scattering.
- Band 2 (green): This band showed the tornado’s path clearly and was the best band to view the westernmost portion of the damage (see Figure 4a).
- Band 3 (red): The contrast of the tornado’s path to the rest of the image was far less than in band 1 and 2.
- Band 4 (near IR): Only vaguely could the middle portion of the tornado’s path be discerned (see Figure 4b).
- Band 5 (mid IR): The portion of the tornado’s path east of Siren could be clearly identified; however, the portion west of Siren was not as clear as in band 1 and 2 (see Figure 4c).
- Band 7 (mid IR): Due to time constraints this band was not evaluated until after the first products were disseminated; however, this band displayed the tornado’s path with a bit more clarity than band 5, especially west of Siren.
- Band 8 (Panchromatic): There was virtually no evidence of the tornado.

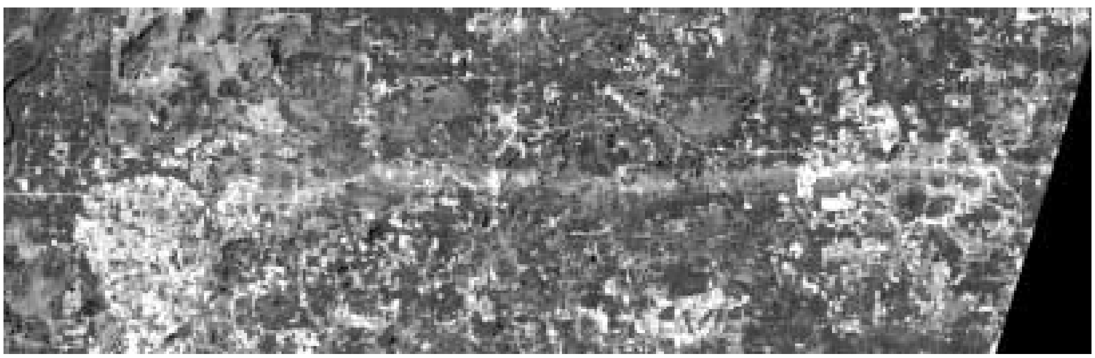

Figure 4(a). June 19, 2001 (1 day after tornado) - Landsat ETM+, Band 2 (green).

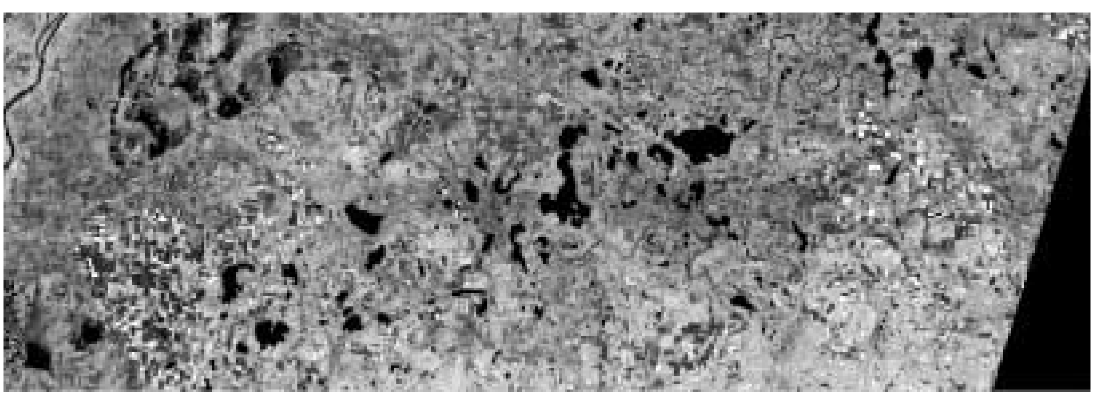

Figure 4(b). June 19, 2001 - Landsat ETM+, Band 4 (near-infrared).

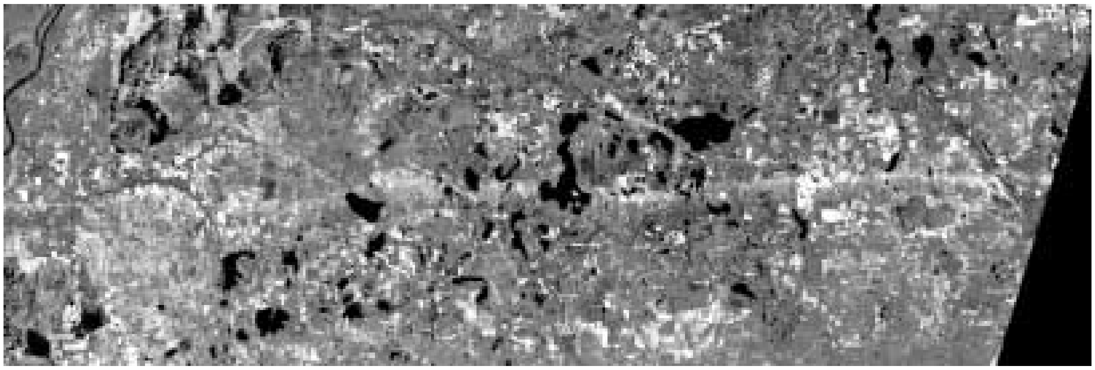

Figure 4(c). June 19, 2001 - Landsat ETM+, Band 5 (mid-infrared).

We prepared a number of three-band composites on the "After" image. Two three-band composites that showed the path of the tornado quite well emulate a color and a color infrared photograph (see Figure 5a and 5b respectively). However, we found the three-band composite that most clearly displayed the tornado's path was band 5 combined with bands 1 and 2. We determined that displaying band 1 as blue, band 2 as green, and band 5 as red produced an image whose hues looked similar to a color infrared photograph and therefore could be easily interpreted (see Figure 5c).

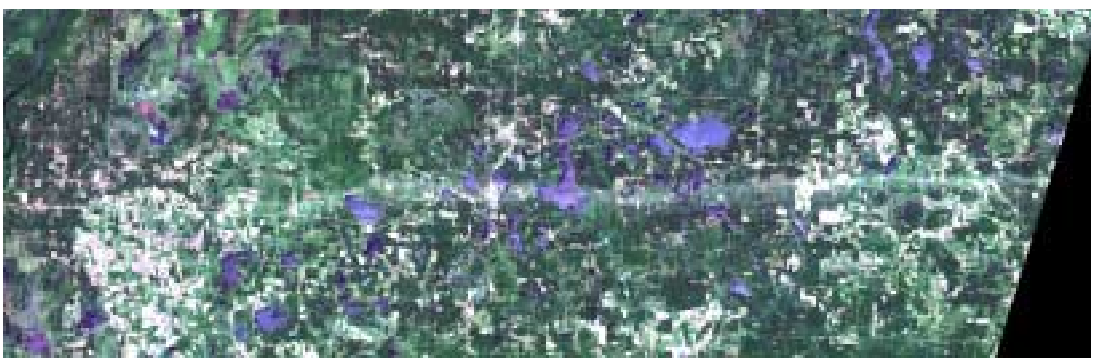

Figure 5(a). June 19, 2001 – Color Composite (red-band 3, green - band 2, blue – band 1).

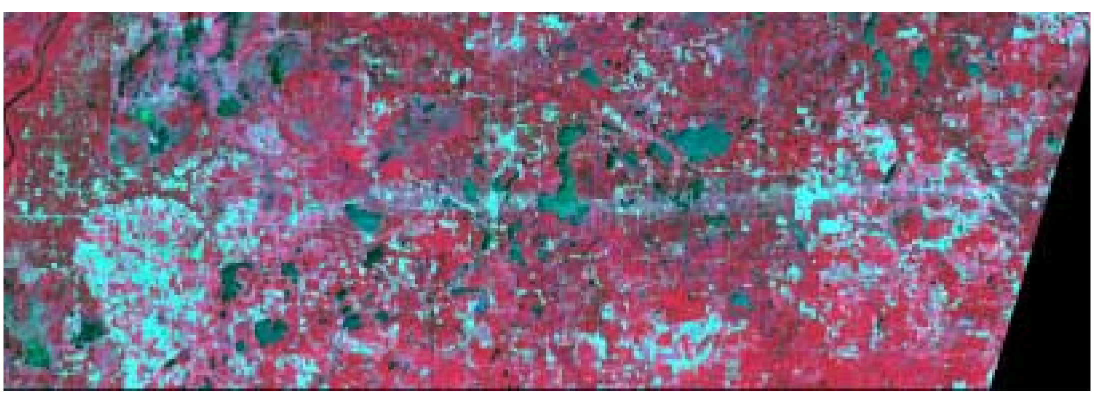

Figure 5(b). June 19, 2001 – Color Composite (red - band 4, green - band 3, blue – band 2).

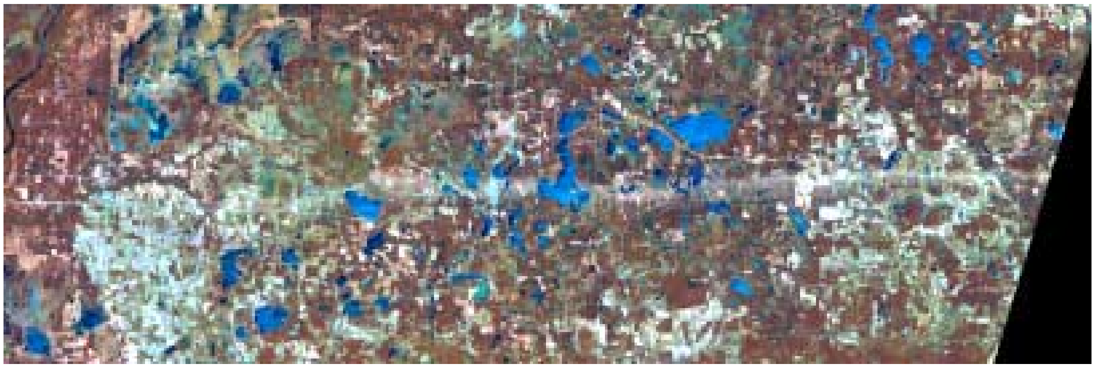

Figure 5(c). June 19, 2001 – Color Composite (red - band 5, green - band 2, blue – band 1).

We attempted to enhance these three-band composites by using the higher resolution panchromatic band via a "pan-sharpening" technique. A "pan-sharpening" process would effectively maintain the multispectral resolution of the three band composite while improving the apparent spatial resolution from 30 meters to the 15 meters of the panchromatic band. We used an Intensity-Hue-Saturation method that involved first linearly transforming the original red, green and blue (RGB) bands into intensity, hue and saturation (IHS) components. Then the panchromatic band was substituted for the intensity component and the image was transformed back to a RGB composite. Unfortunately, this "pan-sharpening" technique actually degraded the clarity of the tornado's track. Most likely this degradation was due to the fact that the path of the tornado was not captured well in the panchromatic band (see Figure 6).

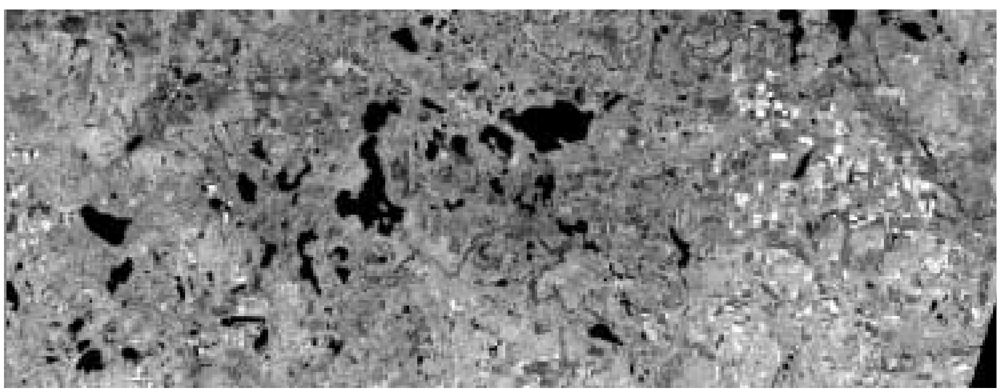

Figure 6. June 19, 2001 – Panchromatic band, 15 meter spatial resolution.

Change Detection Analysis

We experimented with a number of change detection techniques to further enhance the extent of damage caused by the tornado. We first tried a change detection method that incorporated a vegetation index. These methods are known to successfully enhance changes in vegetated landscapes. Since the tornado caused damage primarily to forested and agricultural lands, we reasoned that this sort of technique would work well. These methods involve first performing a vegetation index on the "Before" and "After" images and then subtracting the results of the index images from each other. For our analysis we used the Normalized Difference Vegetation Index. The result of this change detection method was poor, which on further reflection was not surprising because vegetation indices depend on the red and infrared bands (bands 3 and 4) and the tornado's damage was not clearly visible in these bands.

We then tried the simple band-subtraction change detection method. This technique requires only that a single band from one image be subtracted from the corresponding band in the second image on a pixel-by-pixel basis. A resultant gray-level image is produced and changes between the two dates appear either very dark or very light. We tested this change detection method on two different bands, the green band (band 2) and the mid-infrared band (band 5) subtracting the "Before" image from the "After" image and producing a resultant gray-level image where the tornado's damage appeared very light and contrasted well with the background pixels. The differencing between band 5 values gave different but clearer results than these associated with band 2.

Since the individual band-subtraction methods gave different results, we next tried a principal component change detection method that captures change from a multiple number of bands and we hoped would place the majority of change into a single output component. For this principal component analysis (PCA) we used bands 1, 2, and 5 from both dates. These bands were the ones where the damage was visually well defined. The results were very good and the cumulative damage from the tornado was captured in the second principal component (see Figure 7).

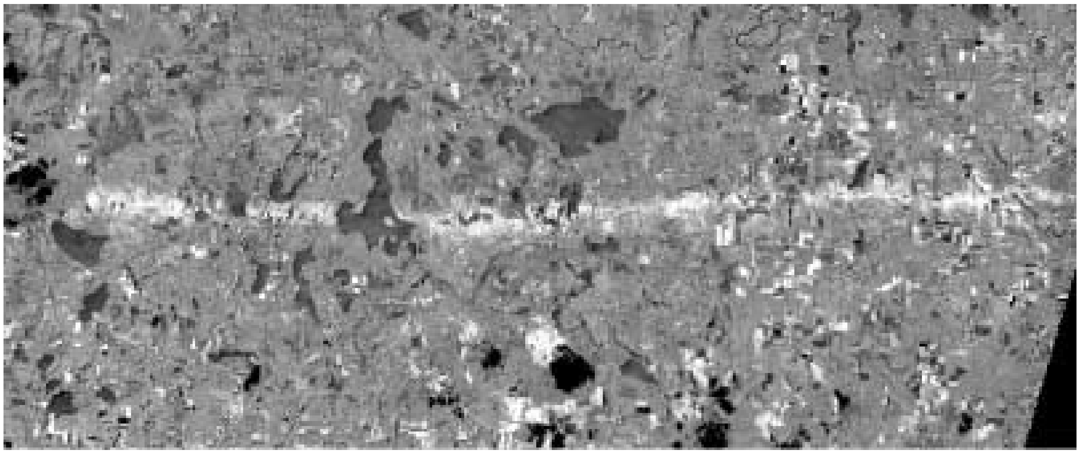

Figure 7. June 19th (1 day after tornado) and May 18th – Second PC using bands 1,2, and 5.

Later, we experimented with a number of other PCAs, and found that the best results were produced when using bands 1,2,5 and 7 from both time periods. Again, most of the damage caused by the tornado was best expressed in the second principal component. We also experimented with PCA using all the bands from both the "Before" and "After" images. With this analysis the third principal component showed the tornado's path the best, but we felt that the path was not as well delineated as in the images from the previous analysis. It is also interesting to note that when based on the eigenvectors from these two PCA analyses (see Tables 1 and 2), the bands that contributed the most to the principal component that captured the change were the mid-infrared bands, bands 5 and 7. Furthermore, the near-infrared band contributed the least information to this component that contained the most change.

Table 1: Principal component analysis using bands 1,2,5 and 7.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Band 1 – Before	0.1673	-0.3600	0.2660	0.5494	-0.0623	-0.0263	0.6812	0.0366
Band 2 – Before	0.2046	-0.3070	0.1056	0.5742	-0.0435	-0.0345	-0.7204	-0.0317
Band 5 – Before	0.6341	-0.1727	-0.5811	-0.0961	0.3788	-0.2665	0.0815	0.0068
Band 7 – Before	0.5273	-0.3177	0.3527	-0.4985	-0.3691	0.3298	-0.0532	-0.0181
Band 1 – After	0.0631	0.0739	0.3231	-0.0276	0.4989	0.0999	0.0116	-0.7915
Band 2 – After	0.1075	0.1386	0.2740	0.0332	0.6142	0.4306	-0.0449	0.5731
Band 5 – After	0.3891	0.6664	-0.1918	0.3263	-0.2957	0.3900	0.0635	-0.1326
Band 7 – After	0.2883	0.4202	0.4897	-0.0499	-0.0300	-0.6862	-0.0374	0.1578

Table 2: Principal component analysis using all reflected bands.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8…
Band 1 – Before	0.1564	-0.0995	-0.2957	0.2896	-0.3206	-0.2793	-0.0091	-0.0253
Band 2 – Before	0.1932	-0.0301	-0.2775	0.2880	-0.2438	-0.1903	0.0283	-0.1191
Band 3 – Before	0.3112	-0.2176	-0.3028	0.1981	-0.3258	-0.0446	-0.0414	0.0547
Band 4 – Before	0.1761	0.5878	-0.0542	0.6206	0.4215	0.0876	0.1484	0.1207
Band 5 – Before	0.5829	0.0637	-0.1876	-0.3542	0.4378	-0.2091	-0.4440	-0.2468
Band 7 – Before	0.4766	-0.2211	-0.1579	-0.2083	0.0678	0.5271	0.4994	0.2918
Band 1 – After	0.0557	-0.0878	0.1313	0.1457	-0.0574	0.2095	-0.3129	0.1130
Band 2 – After	0.0976	-0.0592	0.1770	0.1320	-0.1188	0.2253	-0.4649	0.3575
Band 3 – After	0.1536	-0.1870	0.3109	0.2851	-0.0453	0.3637	-0.3175	-0.1736
Band 4 – After	0.1090	0.6826	-0.0515	-0.2988	-0.5493	0.2965	-0.0800	-0.1774
Band 5 – After	0.3581	0.1351	0.5536	-0.0998	-0.1784	-0.4895	0.1268	0.4581
Band 7 – After	0.2590	-0.1139	0.4759	0.1440	-0.0679	0.0118	0.3025	-0.6399

INITIAL FIELD EVALUATION OF THE ETM+ DAMANGE ASSESSMENT PRODUCTS

Approximately one week after the ETM+ damage assessment products had been released, ERSC researchers began an initial assessment of the accuracy and utility of these products in the field. This field evaluation consisted of visiting selected segments of the entire 40 km long damage path. A total of 31 north/south transects were made across the damage path in order to evaluate qualitatively the extent to which the “image change” product was correctly delineating actual damage areas on the ground. Errors of omission and commission were both of interest and the locations of all transects were determined via GPS. Travel across much of the damage path was still very difficult at the time of these field surveys but we were successful in transversing the damage path at intervals spaced approximately 1.3 km apart. Numerous ground photographs were also taken to document the type of damage present at various locations.

The initial field evaluation of the accuracy of satellite-based damage products was extremely positive. The image data very clearly delineated the field-observed boundaries of damage areas as well as areas of minimal or no damage within these boundaries. While we expected this to be the case in heavily forested areas, the image-based products also appeared to detect structural damage (and debris) with great accuracy. Even “subtle” damage in agricultural fields and wetlands was well delineated with few errors of omission or commission (false positives) noted. As described below, this preliminary field evaluation was then supplemented by a follow-up analysis of aerial photography of the entire damage path.

DETAILED FOLLOW-UP ANALYSIS OF AERIAL PHOTOGRAPHIC REFERENCE DATA

Four days after the tornado (on June 22, 2001) Burnett County officials contracted for the acquisition of aerial photography of the entire damage path. This coverage took the form of 1:10,000 normal color photography, which consisted of a three flight line block, with each flight line containing 62 photographs. Figure 7 shows the 186 photos needed to cover the study area.

Figure 8**.** The 186 photos needed to cover the study area.

The objectives of the visual analysis were: 1) Verify the start and end points of the tornado path on the aerial photos. 2) Characterize the nature and range of damage with regards to different tree species. 3) Investigate and verify the extent to which the damage area delineated by the TM imagery corresponded to that visible in the photography.

All 186 analog aerial photographs were viewed both individually and in stereo pair combinations. The evidence of the damage was quite clear with either method. The full range and extent of the damage, from start to stop, narrowest to widest points were visible. All tree species in the path were damage to some degree. Of particular note, was the difference between even-aged red pine plantations and other hardwood forested areas. The even-aged red pine plantations were toppled in domino form with the trees breaking off at the base. The damage in the hardwood areas took the form of a more jagged appearance with break levels ranging in heights. In addition, there were areas directly in the path, where a ring of trees surrounding a lake were left standing while in other areas they were blown over into the water.

The full length of the damage path indicated on the TM imagery was compared visually on-screen with the aerial photography. The TM imagery was displayed showing the 6 non-thermal bands individually and in combination. In addition, the final TM change image was also viewed. The three broad areas of generally different cover type, rural forested, rural agricultural, and urban were in the path of damage. The damage in all three types was readily identifiable and followed the outline of damage indicated on the aerial photographs down to the pixel.

IMAGE PROCESSING APPROACH REVISITED

For our initial analysis we were very fortunate to acquire a very clear Landsat scene within hours after the tornado passed through the Siren area. Two coincidences made this image acquisition possible; the clarity of the weather the following day and the orbiting cycle of the Landsat-7 satellite. The satellite passed over Burnett County around 11:30 am the morning following the tornado. Thus, we questioned whether the success of our analysis was due merely to the timing coincidence of the imagery acquisition. In other words would the tornado's path be as noticeably using Landsat images captured at later dates? Also, how much differently would the tornado's damage be captured by images obtained at a later date?

To answer these questions two additional Landsat ETM+ images were obtained. The later dates included scenes acquired 10 and 17 days after the storm, June 28 (from adjacent path 26/row 28) and July 05, 2001, respectively. Visual interpretations of each image were performed as well as principal component change detection analysis over a number of different band combinations on each of these additional dates of imagery.

Visual Interpretation

- Band 1: The tornado's damage is clear, and similar in appearance on all dates.
- Band 2: The tornado's damage is clear, and similar in appearance on all dates.
- Band 3: The evidence of the tornado becomes slightly less clear as time progresses.
- Band 4: Each date shows approximately the same slight evidence of the tornado.
- Band 5: The tornado's path is clear, and similar in appearance on all dates.
- Band 7: The tornado's path is clear, and similar in appearance on all dates.
- Band 8: There is virtually no evidence of a tornado.

The results of the three band composites on these later dates were analogous to the initial composites performed on the original "After" image of June 19th. Also a number of PCAs were performed on the June 28th and July 5th images and these analyses gave very comparable results with our initial analysis using the June 19th data. For example, we performed a separate PCA using bands 1,2,5 and 7 on the "Before" image with each of the different "After" images (June 19, 28 and July 5) and in each of these PCAs the second principal component captured most of the change due to the tornado damage (see Figures 9a, 9b and 9c).

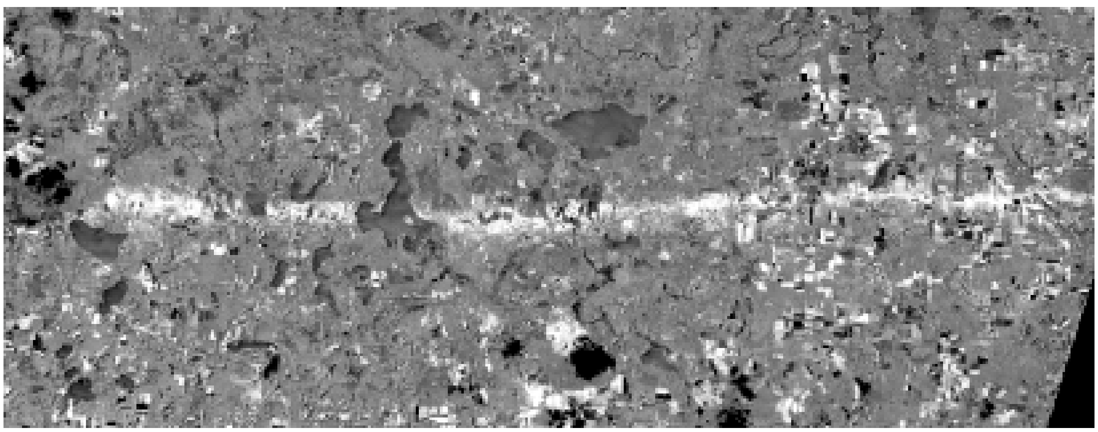

Figure 9(a). June 19th (1 day after tornado) and May 18th – Second PC using bands 1,2,5 and 7.

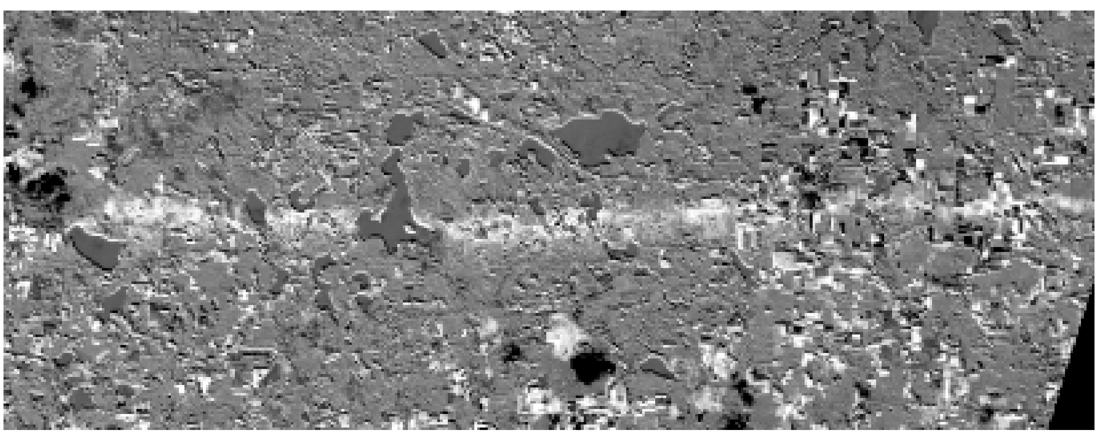

Figure 9(b). June 28th (10 days after tornado) and May 18th – Second PC using bands 1,2,5 and 7.

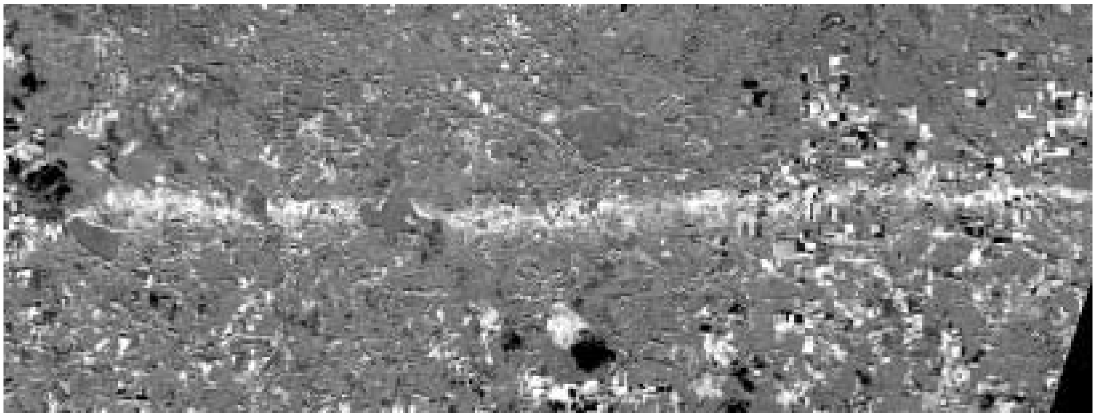

Figure 9(c). July 5th (17 days after tornado) and May 18th– Second PC using bands 1,2,5 and 7.

CONCLUSIONS

Based on both field evaluation and the analysis of comparative aerial photography, we established that the Landsat ETM+ imagery was very useful for tracking the damage and aiding the associated recovery efforts. The particularly useful bands were the visible and mid-infrared bands. Somewhat surprisingly, we found that the panchromatic and near-infrared bands gave very little information about the tornado's path. To further enhance the tornado's path PCA could be used and seemed to work best when analysis was performed on those bands wherein the damage could best be interpreted visually. We also found that the tornado's damage could be tracked similarly with imagery acquired from the next day and through to at least two and a half weeks after the tornado had struck. Finally, Internet delivery of the imagery proved to be extremely helpful in providing damage assessment in a timely manner.

ACKNOWLEDGEMENTS

Like the tornado that occasioned it, the project reported herein "came right out of the sky." On very short notice, many people had to work together to provide a useful product in a very short period of time. Personnel at the EROS Data Center, particularly Bruce Quirk and Rose Tyrrell, are recognized for their help in expediting the delivery of the Landsat ETM+ data used in this project. Many people associated with Burnett County or the WI Department of Natural Resources helped in the provision of information or data required to accomplish this project. Kathy Swingle, Pete Engman, Greg Rich, Paul Cook, and Douglas Crane were particularly helpful in this regard. This work was supported, in part, by the Upper Midwest Regional Earth Science Applications Center under NASA grant NAG 13-99002 and by the NASA Affiliated Research Center Program.

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