AVHRR Imagery Used to Identify Hurricane Damage in a Forested Wetland of Louisiana

Elijah W. Ramsey III, Dal K. Chappell, and Dan G. Baldwin

Abstract

Certain events provide a unique opportunity to test the monitoring capability of AVHRR imagery. On 26 August 1992, Hurricane Andrew passed through Louisiana, impacting a large area of forested wetlands. One response to the widespread defoliation resulting from the hurricane impact was an abnormal bloom of new leaves and new growth in the underlying vegetation between September and October. To capture this atypical phenology, a time sequence of AVHRR images was transformed into a normalized difference vegetation index, NDVI, as an indicator of vegetation changes in the forest impacted by the passage of a hurricane. Using geographic information system functions, three sites in the impacted forest were vectorized as polygons, and the inclusive pixels were extracted for subsequent graphical and univariate statistical analysis. Temporal curves of mean NDVIs for the three sites for before, during, and after the hurricane passage, and aggregate curves of the impacted forest to an undisturbed forest, were compared. These comparisons corraborated the atypical phenology of the impacted forested wetland and directly related the cause to the hurricane passage.

Introduction

Single-date or composite AVHRR images (Eidenshink, 1990) have provided static maps of vegetation (e.g., Stone *et al.*, 1994), forest cover type, and forest inventory (Zhu and Evans, 1994; Ripple, 1994; Teuber, 1990); however, it is the repetitive ability of AVHRR data that has the greatest potential in resource management (Ehrlich *et al.*, 1994). This repetitive ability, or temporal monitoring, allows patterns to be revealed in the data that may be transformed into quantitative determinations of the rates of development of resources, and into qualitative judgments of external affects on these resources (Lulla and Mausel, 1983). To be effective, the procedures used to transform the AVHRR data into products useful to the resource manager must be cost effective, in a form readily implemented in available image processing softwares, and must be verified and calibrated with current operational ground-based measurements (Teuber, 1990). Furthermore, the products produced by the AVHRR analysis must be easily linked to other collateral data sources of finer spatial and spectral resolutions (Nielsen and Werle, 1993) or within a geographic information system (GIS).

Hurricane Andrew

On 26 August 1992, Hurricane Andrew crossed the Louisiana coastline with sustained winds of 209 to 217 km/hr (Kelly, 1993). Wind speeds quickly diminished as the hurricane tracked inland (Kelly, 1993), but over 777 km^2 of cypress-tupelo swamp and bottomland hardwood forests of the Atchafalaya Basin were impacted (Doyle *et al.*, 1995) (Plate 1). Early assessments suggested most forest damage occurred in the northern areas of the basin dominated by hardwoods, while less effect was noticed in the southeastern basin dominated by cypress-tupelo (Kelly, 1993; Doyle *et al.*, 1995). In part, this was associated with the spatial variation of hurricane intensity, with stand density and size, and to a preferential resistance to hurricane damage, the cypress-tupelo being more resistant (Kelly, 1993; Doyle *et al.*, 1995). Overall, Kelly (1993) observed that 10 percent of the live-tree volume was downed, and 63 percent showed some degree of foliage damage.

Responses to the downed trees and widespread defoliation included a sudden growth of underlying vegetation, and the bloom of new leaves one to two months later. Thus, our objective was to test whether a time series of AVHRR imagery could be used to capture this uncharacteristic phenology sequence in the forested wetlands.

Methods

AVHRR Imagery

Imagery was collected as near as possible to immediately before and immediately after Hurricane Andrew, and for similar time periods in 1991 and 1993 (NOAA 11, Table 1). Lower off-nadir view angles (center of study area) and near-anniversary dates were preferred for comparison between images. Cloud contamination was problematic, resulting in half the images with an off-nadir view >30° and requiring non-anniversary dates to be chosen. Careful selection found only ten usable near-anniversary AVHRR images for the period of time between June and November of 1991 to 1993, plus a non-anniversary image for the fall of 1993. Due to persistent cloud contamination, a two-date composite was produced by using the maximum NDVI value generated from the 23 June and 6 July 1992 images. This composite is referred to as the "30 June" image.

Horizontal visibilites were 11 km in all AVHRR acquisitions (Table 1). This consistency implied atmospheric conditions were similar during all acquisitions (Elterman, 1970). Not consistent were the acquisition times (Table 1). Satellite overpasses occurred increasingly later in the day from 1991 to 1993, resulting in lower sun elevations at the times of image acquisitions.

AVHRR images were georeferenced to a conic projection at a 1.1-km resolution and converted to reflectance estimates

E.W. Ramsey III and D.K. Chappell are with the U.S. Geological Survey, National Wetlands Research Center, 700 Cajundome Blvd., Lafayette, LA 70506.

D.G. Baldwin is with the Colorado Center for Astrodynamics Research, Box 431, University of Colorado, Boulder, CO 80309.

Photogrammetric Engineering & Remote Sensing,
Vol. 63, No. 3, March 1997, pp. 293–297.

0099-1112/97/6303-293$3.00/0

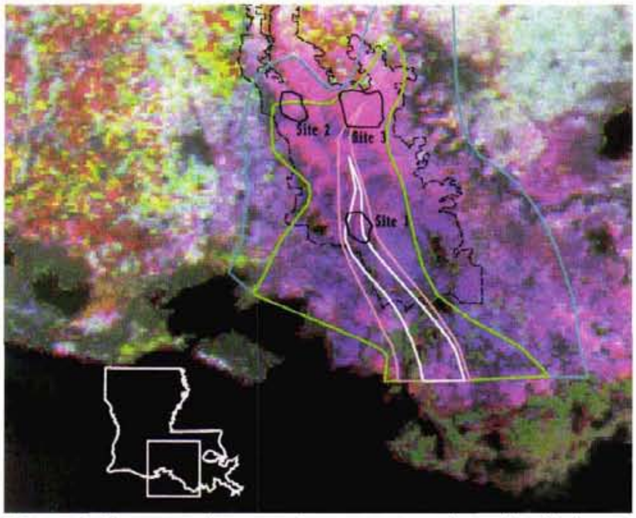

Plate 1. A composite NDVI image centered on the Atchafalya Basin. The dashed black line denotes the forested area and the solid black lines define the test sites referred to in the text. The white, pink, green, and blue lines delineate hurricane impact to the wetland forest: white=severe, pink=moderate, green=light, and blue=scattered light, respectively (Kelly, 1993).

by using software developed at the Colorado Center for Astrodynamics Research at the University of Colorado (Rosborough *et al.*, 1994; Lauritson *et al.*, 1988). Ground control points were incorporated to correct for satellite attitude parameters, and a "nudge" routine was applied. The nudge procedure corrected most remaining offsets by aligning the AVHRR image to a vectorized coastline of the Gulf of Mexico. Image registration accuracies were estimated at about ±1 pixel.

Vegetation Index

The AVHRR image data were next transformed into a normalized difference vegetation index (NDVI) ([near infrared−red]/[near infrared+red]). This index has been extensively used and successfully related to indicators of vegetation biomass, leaf area index (LAI), primary productivity, and active photosynthetically absorbed radiation (e.g., Sellers, 1987; Roughgarden *et al.*, 1991; Chuvieco and Martin, 1994; Ehrlich *et al.*, 1994). Even though studies have shown multitemporal analysis and NDVI are sensitive to atmospheric conditions, view and sun zeniths, and background reflectances (Huete *et al.*, 1985; Deering and Eck, 1987; Duggin *et al.*, 1990), numerous studies have shown NDVI to be a robust and reliable estimator of vegetation trends and status (e.g., Samson, 1993; Andres *et al.*, 1994; Ehrlich *et al.*, 1994). Further, the effects of increased aerosol loadings from the eruption of Mt. Pinatubo (14-15 June 1991) were considered to have minor impact on the derived NDVIs at these lattitudes (~30°) (Kogan *et al.*, 1994). Finally, the NDVI data generated from the AVHRR images were used to identify only areas of change in the wetland forests, not to quantify the relationship to vegetation parameters.

Results

Temporal Analysis

A color composite of three 8-bit NDVI coverages was generated from the 30 June (red plane), 29 August (green plane), and 19 October (blue plane) 1992 AVHRR scenes (Sader and Winne, 1992; Plate 1). Within the forested wetland areas of the Atchafalaya Basin, subtle changes in color were distinguished ranging from pink (high red, lower green, and blue) to purple (high red, lower green, moderately high blue) with the 24-bit true color capabilities and image enhancements (PCI Inc., 1993).

To further examine changes in NDVI from late June to mid October of 1992, three areas of varying shades of pink to purple were delineated by using the on screen vector capabilities (Kruse *et al.*, 1993; Plate 1). Descriptions of the three sites were compiled by examination of videography obtained from the U.S. Forest Service within days of the hurricane passage (Kelly, 1993) and by speaking to Forest Service personnel familiar with the area. From the descriptions, these sites were characterized as Site 1, a fairly open canopy consisting of young cypress/tupelo/willow with a large number of downed trees and widespread defoliation; Site 2, a hardwood area with a more closed canopy than Site 1 and light damage, including some defoliation; and Site 3, a hardwood area with the highest canopy closure and moderate to light damage, including some downed trees and defoliation.

Pixels within each study site polygon were extracted. The means and the 95 percent confidence intervals (±2 standard errors) were plotted (Figure 1b; Kruse *et al.*, 1993; SAS Institute Inc., 1985). Overall, the NDVI curves are similar, mainly differing in magnitude in June and August; however, the forms of the three curves are unusual for a normal forested wetland senescence. Substantiated with post hurricane videography, Site 2 was the least impacted, as demonstrated by the change in NDVI between June and just after the hurricane in August. At the sites with moderate to severe impact, Site 3 and Site 1, respectively, NDVI decreases were nearly identical from before and after the hurricane, even though the beginning and ending absolute magnitudes differed. All sites showed the uncharacteristic trend in NDVI from just after the hurricane passage to mid October. However, recovery differed between sites. Site 2 and Site 3 increased similarly. Site 1 increased more dramatically. NDVI decreased between mid October and November at all sites; however, decreases at Site 2 were higher. Finally, NDVIs decreased to nearly zero by January 1993.

As comparisons, mean NDVI curves are shown of the three areas for the same periods in 1991 and 1993 (Figures 1a and 1c). Mean NDVI of the three sites extracted from near anniversary dates in 1991 showed a steadier decrease in NDVI then those in 1992, with a maximum difference of about 0.10

Table 1. AVHRR Acquisition Parameters

Date	Scan Angle[1] (degrees)	Eastern Standard Time	Sun Elevation (degrees)
29 Jun 91	33.9	1346	76.3
20 Aug 91	32.9	1349	67.3
11 Oct 91	36.2	1351	46.9
09 Nov 91	38.7	1456	30.7
23 Jun 92[2]	42.1	1453	63.8
06 Jul 92[3]	30.5	1426	69.8
29 Aug 92	35.7	1521	50.2
19 Oct 92	17.2	1511	34.3
14 Nov 92	25.7	1459	29.3
30 Jun 93	22.2	1550	51.1
18 Aug 93	21.2	1556	46.4
30 Sep 93	14.5	1536	38.1
10 Nov 93	19.9	1536	24.8

[1]The scan angle was calculated from nadir to the approximate center of the Atchafalaya study area.
[2,3]Due to cloud contamination, the 23 June and 6 July AVHRR images were composited as a single maximum NDVI image. In the text the composite is referred to as the 30 June NDVI image.

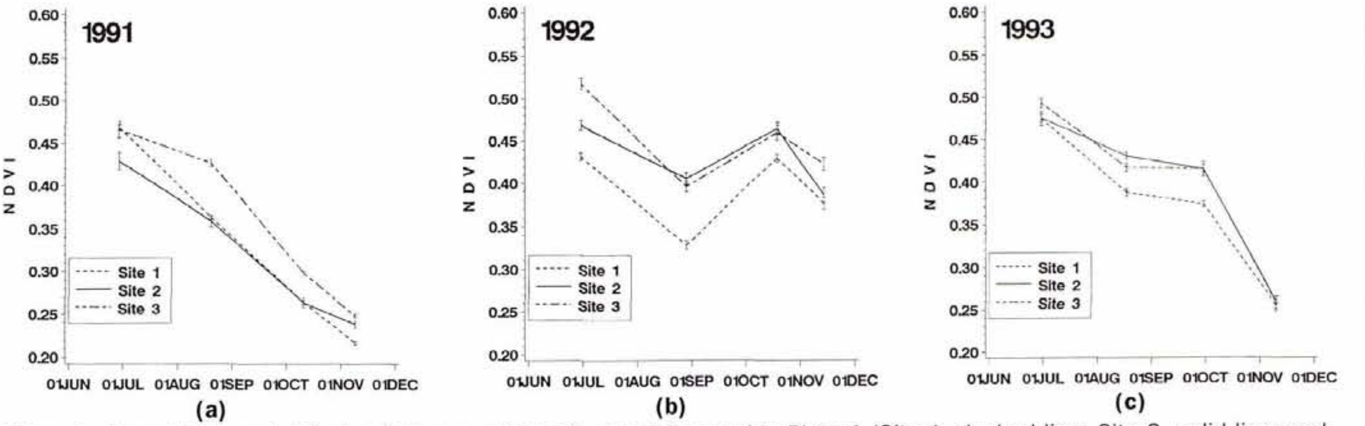

Figure 1. Mean NDVIs and ±2 standard errors for each site delineated in Plate 1 (Site 1, dashed line; Site 2, solid line; and Site 3, long and short dashes). Near-anniversary dates were used during all three years except for the fall date in 1993. In 1992 the sudden drop in NDVI is shown three days after the hurricane passage and the slight decrease to rapid rise in NDVI resulting from the abnormal new leaf bloom in the fall.

between sites in mid August. Because of the earlier date of the fall 1993 AVHRR image, direct comparison to 1991 and 1992 NDVI curves was not possible; however, the 1993 NDVI curves still portray a general decrease from June to November.

As additional confirmation of the 1992 temporal anomaly, NDVI values were extracted from a bottomland hardwood site of similar species composition (especially Sites 2 and 3 in the Atchafalaya) in northern Louisiana, the Tensas National Wildlife Refuge, not effected by Hurricane Andrew. The entire Tensas Forest was integrated as one site. In order to compensate for an unequal number of pixels in the Atchafalaya sites, each pixel NDVI value was weighted by the inverse ratio of the number of pixels included in the associated site. Subsequently, a statistical routine used the individual weights in calculating the mean NDVI and standard errors for each time period during each year in the Atchafalaya Basin (SAS Institute Inc.,1985). Minor NDVI differences between the Atchafalaya and Tensas were expected because of a latitudinal variation in senescence timing and possibly flooding differences; however, curve shape, not magnitude and phase, was the variable of interest.

Mean NDVI curves for the Tensas were similar for shape in 1991 and 1993 and in magnitude for 1993 to mean NDVI curves for the Atchafalaya (Figures 2a and 2c). In 1992, NDVI curves associated with the two areas highly differ in shape and magnitude (Figure 2b). The Tensas 1992 curve showed the same general decrease in NDVI as in the 1991 and 1993 Tensas and Atchafalaya curves, not the more abrupt changes depicted in the 1992 Atchafalaya NDVI curve.

As a final comparison, NDVI curves for all three years were plotted for the Atchafalaya and Tensas Forests (Figures 3a and 3b). The 1992 Atchafalaya NDVI curve was atypical even when compared to the 1993 curve with the non-anniversary fall date. The Tensas curves showed the same pattern in 1991 and 1992, except that 1992 was higher in overall magnitude until November. Even with the earlier fall image in 1993, the NDVI curve decreased faster than usual from June to August, closely mirroring the 1993 Atchafalaya curve.

Discussion

Accurate geo-registration and careful selection of cloudless imagery permitted a time sequence of AVHRR imagery, which was then transformed into an NDVI to identify vegetation changes in a forested wetland impacted by passage of a Hurricane Andrew. Apart from georeferencing, the most critical factor in using the AVHRR imagery to determine change was

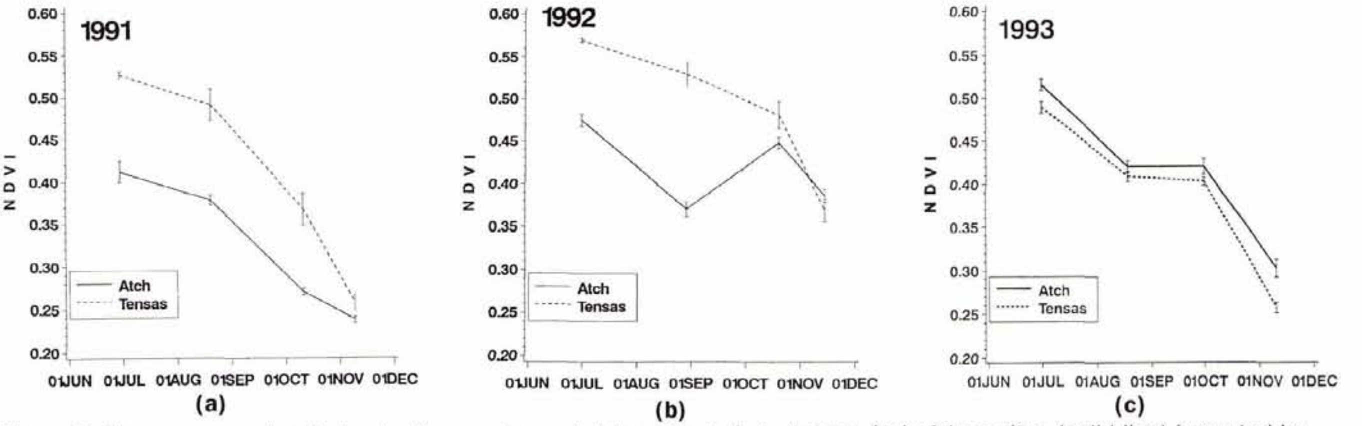

Figure 2. Mean NDVIs and ±2 standard errors generated by aggregating all three Atchafalaya sites (solid line) impacted by the hurricane and combining all pixels making up the Tensas Wildlife Refuge (dashed line).

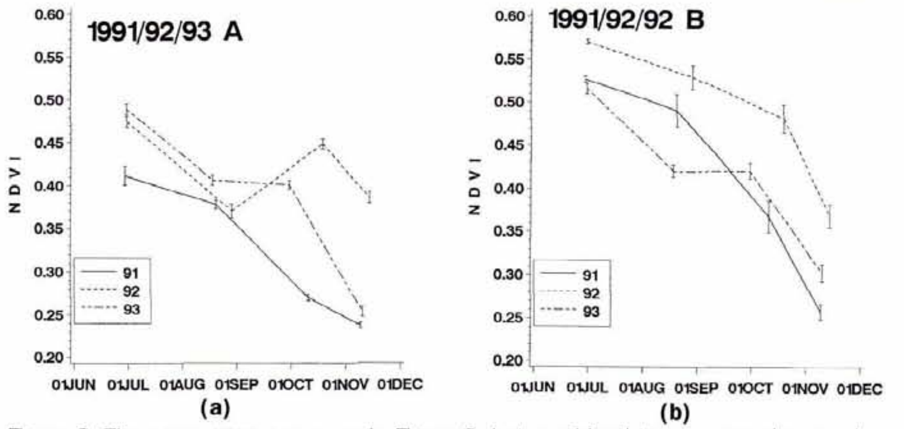

Figure 3. The same NDVI curves as in Figure 2, but combined to compare changes in each site over the three-year period; (A) Atchafalaya, (B) Tensas. The solid line refers to 1991, the dashed line to 1992, and the long and short dashed line to 1993.

cloud contamination. Limited by cloud contamination and excessive scan angles, only three images were found near the time of the hurricane passage: 30 June, 29 August, and 19 October. A color composite of the June, August, and October NDVI transforms of the AVHRR imagery depicted in color the hypothesized progression of NDVI. Pink to purple areas indicated lowered NDVI as an indicator of green biomass three days following the hurricane passage, and a higher than expected NDVI following the artificially induced foliage bloom in fall.

Plots of NDVI values extracted from three sites within the impacted wetland forest corroborated the trend suggested by the color patterns and videography. Mean NDVIs from the three Atchafalaya Basin sites near the time of the hurricane passage in 1992 and from near anniversary dates in 1991 and 1993 documented damage to the forest, but also showed variation between the sites and years. In 1991, a similar magnitude and a near-constant decrease in NDVI throughout mid summer to early winter suggested nearly steady senescence of a comparable green biomass content at all sites. Videography showed canopy type changed as well as canopy closure between sites, suggesting that only the sum of overstory and understory green canopy visible to the AVHRR sensor was similar, not canopy structure.

In 1992, before the hurricane passage, NDVIs were higher than in 1991, and the differences in NDVI magnitude mirrored the suggested trend in canopy closure at each site. NDVI changes also seemed to follow damage severity indicated from the post-hurricane videography; the most impacted site had the highest decrease and increase in post-hurricane NDVIs. The type of damage was not the same at the all sites, possibly suggesting a reason for the difference in immediate post hurricane recovery between sites. Site 3, initially related to the highest NDVIs, had moderate defoliation and little loss of trees, but Site 1 had severe defoliation and loss of trees. The response to defoliation and leaf stress was an abnormal bloom of new leaves in September and October. Another response occurred in areas with dramatic losses in overstory canopy; lower canopy cover flourished for a short time (Doyle *et al.*, 1995). Both responses would induce an atypical rise in NDVI during months of normally green leaf senescence. Presumably, the recovery at Site 1 — beginning with less green biomass and suffering more severe impact — would be a combination of both post-hurricane responses. Sites 2 and 3 would be dominated by the new leaf bloom, and, to a minor extent, by the understory bloom resulting from new openings in the canopy. Therefore, it seems that NDVI variability between sites in response to hurricane impact was dependent not only on the severity of impact, but also on the type of damage.

The same general NDVI trend in 1991 was seen in 1993. If a near-anniversary date had been available for fall, the expected decrease in NDVI from late September to mid October would probably bring the 1993 curves in line with the 1991 curves. Apart from the non-anniversary dates in 1993, differences in mean NDVIs among sites were low. As in 1991, the near equal NDVIs indicate that the green biomass content visible to the AVHRR sensor was similar between sites. Even including the fall NDVI, the trend in 1993 corraborates the 1991 comparison to the 1992 NDVI temporal curves; AVHRR imagery transformed to NDVI captured a change in the Atchafalaya forest phenology uncharacteristic of a more normal senescence trend from mid summer to early winter.

Mean Atchafalaya NDVIs compared to NDVIs extracted from the Tensas forest not impacted by the hurricane substantiated the anomalous phenology of Atchafalaya forest in 1992. The reasons for the difference in NDVI magnitude between forests have not been established, but relative changes in NDVI between years can be examined. In 1991, Tensas and Atchafalaya NDVIs decreased steadily, coalescing to nearly the same value by November. Throughout 1992, Tensas NDVIs were higher than in 1991 and 1993; the increase mirrored a similar increase in the pre-hurricane Atchafalaya mean NDVI. In contrast to Atchafalaya, Tensas NDVI decreased steadily from summer to winter, maintaining the same pattern as in 1991. In 1993, the Tensas NDVI pattern changed. The June 1993 Tensas NDVI was comparable to the 1991 June NDVI, but the August NDVI was lower than the 1991 NDVI (by about 0.07). By fall (accounting for the non-anniversary dates), the 1991 and 1993 Tensas NDVIs were again comparable, and finally decreased to the lowest NDVI of all three years. If not consistent with NDVI patterns in 1991 and 1992, the 1993 Tensas NDVIs were nearly identical to Atchafalaya NDVIs. Part of the reason is because of the slightly elevated Atchafalaya NDVIs in 1993 as compared to 1991; but mostly, the drop in the Tensas NDVI in August caused the nearly identical patterns in 1993 Atchafalaya and Tensas NDVI trends. An explanation for the drop in August will require further analysis. However, comparison of Tensas and Atchafalaya NDVIs over the three years confirmed that the unusual pattern in the 1992 Atchafalaya NDVIs was associated with the hurricane impact, and was not the result of an uncalibrated and uncorrected sensor signal or an undetermined environmental agent or weather anomaly.

Summary and Conclusion

This research showed that AVHRR imagery can provide an early detection system of abnormal disturbance to forested wetland phenology. The impact of Hurricane Andrew on a forested wetland provided an opportunity to use the high temporal frequency of the NOAA satellite carrying the AVHRR sensor to spectrally characterize the impact and recovery of the forest. Besides causing loss of trees and widespread defoliation in the wetland forest, the recovery of the impacted forest included an abnormal bloom in green biomass within one to two months of the hurricane passage. Capturing the short-lived abnormal forest phenology with satellite imagery, however, was not simple. Cloud contamination was problematic, resulting in the use of only a few AVHRR images between June and November for each year before, during, and after the hurricane passage.

Graphical and statistical comparisons of the temporal NDVI curves associated with the three sites (polygons) within the Atchafalaya Basin were made for the years before, during, and after hurricane impact, and for the mean NDVI of the three sites to a non-impacted forest area. The comparisons corraborated the anomalous phenology pattern of all sites in 1992 resulting from hurricane impact, and also documented variable responses between sites to hurricane impact. By using videography and site expertise, the difference in NDVI temporal response between sites to hurricane impact was possibly linked to a combination of forest canopy characteristics, and to the damage severity and type. This suggests that, besides identifying areas of forest damage, information related to forest character, damage type, and damage severity may be associated with changes in the composite NDVI color. However, detailed comparisons await further study.

Acknowledgments

The authors thank Dr. John Kelly and Dr. David Evans of the U.S. Forest Service, Southern Forest Experiment Station, for access to videography of post Hurricane Andrew damage, and for help in associating imagery-derived damage extent to forest and damage types. The authors thank Dr. Emery for providing the AVHRR NAVIGATE software and support in its use. We would also like to thank Dr. Geotz for providing the SIPS software used in characterization of the AVHRR temporal curves, and Ms. Kathy Heidebrecht for help in its use. Finally, we are grateful to Mr. William R. Jones for long hours of help on this study.

The mention of trade names of commercial products in this article does not constitute endorsement or recommendation for use by the U.S. Geological Survey, U.S. Department of the Interior.

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(Received 12 February 1996; accepted 19 April 1996; revised 19 June 1996)