

# MONITORING NORTHEASTERN UNITED STATES FOREST CONDITION USING LANDSAT DATA

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## ABSTRACT

The broad overviews obtained with Landsat data can provide information concerning the location, types, and magnitudes of forest changes not easily obtainable by other means. One of the main goals of the current study is to provide spatial information regarding the more subtle forms of forest change rather than those primarily related to land cover conversion. A forest-dominated area in northern Vermont was selected as the principal study area for this investigation. This region was the site of extensive field and remote sensing investigations of forest decline in the 1980s, when it was discovered that forest decline was pervasive at high elevations and that the declining conditions could be mapped and monitored using Landsat data. A pilot study was conducted to determine the nature and level of spectral changes that have taken place in these high-elevation forests since this time period. Datasets used included Landsat multispectral scanner (MSS) data acquired in 1976 and 1991, Landsat thematic mapper (TM) data acquired in 1991, and Landsat enhanced thematic mapper plus (ETM+) data acquired in 1999. After developing an approach that enabled forest spectral comparison across sensors, it was found that subtle forest changes have occurred throughout much of the region, with the most obvious changes having occurred at the higher elevations. Additional investigation is warranted to determine the reasons behind these subtle changes.

## INTRODUCTION

The status of the Nation's forests is of great interest and concern to many groups and individuals, including resource managers, policymakers, global change scientists, conservationists, and the general public. Changes that occur in forests can have broad implications, affecting natural resource availability, biodiversity, atmospheric composition, and climate. It is important that we assess the current state of the forests and trends that are occurring within them, so that we can provide managers and policymakers with the information required for responsible decisionmaking and sustainable management.

Forests are constantly undergoing changes in response to a multitude of natural as well as anthropogenic factors. These changes range from relatively subtle transitions that occur in response to long-term processes, such as forest community succession and climate change, to wholesale conversion related to logging and urbanization. In general, the changes that are occurring in our forests are not particularly well understood. Landsat data, which have been routinely acquired and archived for the conterminous United States since 1972, can be used to help fill the gap in our knowledge.

The forests of the Northeastern United States were the focus of much research during the 1980s. Much evidence was obtained indicating that the montane forests of this region were experiencing a long-term decline in growth rate and state of health, and increases in levels of tree mortality (Siccama *et al.*, 1982; Vogelmann *et al.*, 1988). Throughout the Northeast, dramatic declines were documented in the density and basal area of red spruce (*Picea rubens*), and less obvious declines were observed for other species. During the same period in Europe, similar declines were noted in Norway spruce (*Picea abies*), white fir (*Abies alba*), and European beech (*Fagus sylvatica*) (Schutt and Cowling, 1985). Although specific causes of the Eastern North American and European forest declines were disputed, various forms of air pollution were implicated as significant contributing factors (NAPAP, 1993).

During the 1980s, a series of exploratory investigations were instigated to determine the applicability of various remote sensing systems for mapping and monitoring forest decline (Rock *et al.*, 1986; Vogelmann and Rock, 1986; Vogelmann and Rock, 1988; Vogelmann, 1988; Lambert *et al.*, 1995). In general, findings indicated that Landsat thematic mapper (TM) data were very appropriate for mapping different levels of forest damage associated with the

decline and that the data were effective in providing regional perspectives on forest health. In addition, a change assessment study using Landsat multispectral scanner (MSS) data (Vogelmann, 1988) showed that decreases in the near-infrared spectral region characterized regions undergoing decline, which was consistent with predicted as well as field/laboratory-derived spectral patterns of decline. This study suggested that satellite-based systems could be used to effectively monitor the forest decline process.

Nearly 15 years have elapsed since these initial remote sensing investigations were conducted. This is ample time for substantial ecological changes to have taken place in these high-elevation forest ecosystems, which in turn could result in spectral changes as detected using remotely sensed data. The objective of this study was to assess the patterns and trends of changes that have taken place in these forests from the 1970s to the present. The study uses a time-series approach using historical Landsat MSS, TM, and enhanced thematic mapper plus (ETM+) data.

## METHODS

### Datasets

Four Landsat datasets were acquired for World Reference System II path/row 13/29, which includes much of northern Vermont and New Hampshire. The northern Green Mountains of Vermont were largely cloud free in all datasets. All images were of excellent quality and largely devoid of obvious haze. Datasets used were acquired on the following dates: August 31, 1999 (ETM+), September 2, 1991 (TM and MSS), and August 22, 1976 (MSS). A part of the study area is shown in Figure 1.

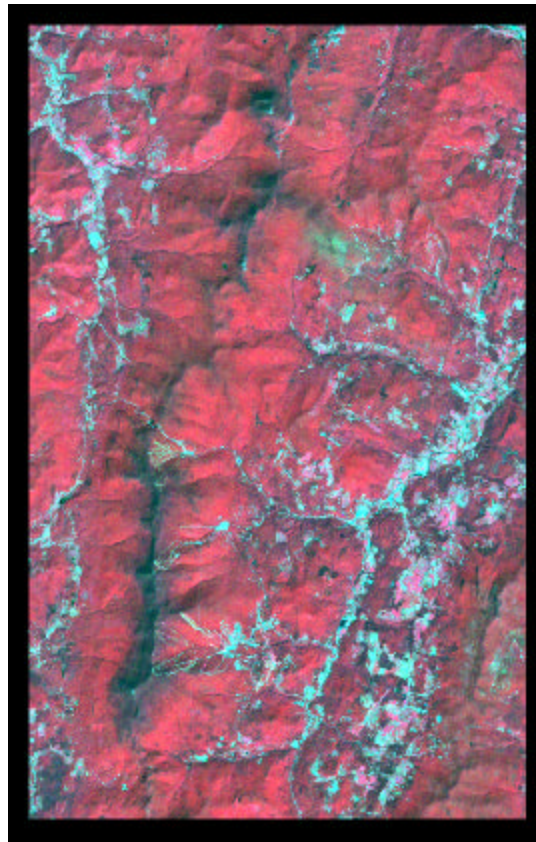


Figure 1. False-color composite produced using ETM+ bands 4, 3, 2 (red, green and blue) for a portion of the Green Mountains of Vermont. Deciduous forest appears red in this imagery, whereas coniferous vegetation is dark.

Concurrent MSS and TM datasets were acquired for the 1991 date to enable cross comparison of MSS and TM/ETM+ data. MSS and TM data were coregistered to the ETM+ dataset (at 30-m pixel sizes) using cubic convolution resampling and an RMS error of about 0.5 pixels. Visual inspection of datasets indicated that they overlaid very well with a minimum amount of misregistration error.

## Pseudoinvariant normalization

A series of pseudoinvariant targets (Schott *et al.*, 1988) were used to normalize 1991 and 1976 datasets to the 1999 ETM+ dataset. This was done in separate steps as outlined below. First, mean digital number (DN) values were extracted from 12 dark and bright targets from 1991 TM and 1999 ETM+ datasets. Large water bodies were used for the dark targets, whereas urban features, such as shopping malls and other large buildings, were chosen for bright targets. For each band, 1991 mean TM DN values were regressed against 1999 mean ETM+ values, and linear regression equations were developed to enable the conversion of 1991 DN values to ETM+ equivalents for each band. Figure 2 shows results for band 4. The  $R^2$  values for these equations ranged from 0.9811 to 0.9962. After the conversion of 1991 to 1999 ETM+ equivalents, calibration coefficients and metadata from the 1999 ETM+ dataset were used to convert both normalized 1991 TM data and ETM+ data to at-sensor reflectance.

The next step was to assess comparability between MSS and TM datasets for the purposes of forest monitoring. Mean DN values were extracted from 20 targets from 1991 MSS and 1991 TM datasets. Because the datasets were acquired simultaneously, a series of forested sites functioned effectively as pseudoinvariant targets. For this part of the investigation, the second MSS infrared band (MSS Band 4) was compared with the near-infrared TM band (band 4), and the second MSS visible band (MSS band 2) was compared with the red band of TM (band 3). Although it is recognized that MSS band 4 is not the same spectrally (or spatially) as TM band 4, it was surmised at the onset of the investigation that the two bands contained comparable information from a vegetative standpoint and that the information content would be highly correlated. Similarly, it was expected that the visible information (MSS band 2 versus TM band 3) would be highly correlated, at least from the standpoint of forest monitoring. Figure 3 shows the degree of correlation between MSS band 4 and TM band 4, and Figure 4 shows the degree to which MSS band 2 correlated with TM band 3. The regression equations were used to convert MSS band 4 DN values to TM band 4 equivalents and to convert MSS band 2 DN values to TM band 3 equivalents. Following this, the equations used to convert TM to ETM+ values described earlier were then used to convert the MSS band 4 and band 2 datasets to ETM+ equivalents. After this, the resultant datasets were converted to at-sensor reflectance using ETM+ coefficients and metadata. Difference data were then produced between ETM+ band 4 and TM band 4, and between ETM+ band 4 and MSS band 4 (Figure 5). Similarly, difference data were produced between ETM+ band 3 and TM band 3, and between ETM+ band 3 and MSS band 2 (Figure 6).

After the 1991 datasets were normalized, the last step was to normalize the MSS 1976 dataset to the other datasets. The first step of this procedure was accomplished by selecting 14 pseudoinvariant targets common to MSS 1976 and 1991 datasets. Only MSS band 4 (second near-infrared band) DN values were extracted from each site. The 1976 mean DN values regressed against the 1991 mean DN values had an  $R^2$  value of 0.927 (Figure 7). A series of forested sites (presumed to have undergone minimal change) were selected, and mean DN values for MSS band 4 were extracted from both 1976 and 1991 datasets and superimposed on the graph depicting the relationship between 1976 and 1991 pseudoinvariant values (Figure 7). The points fit reasonably well with the pseudoinvariant regression line, thus increasing the level of confidence in the validity of the relationship. Once the 1976-91 MSS relationship was established, 1976 band 4 DN values were transformed to 1991 MSS band 4 DN equivalents, and then to 1991 TM equivalents using the 1991 MSS band 4-1991 TM band 4 regression equation, and then finally to 1999 ETM+ equivalents using the 1991 TM band 4-1999 ETM+ band 4 relationship. As a final step, the transformed 1976 MSS data were then converted to reflectance (using August 1999 ETM+ metadata and coefficients).

Difference images were then produced to depict where visible and near infrared reflectance changes have occurred. Images were color coded to represent change in reflectance.

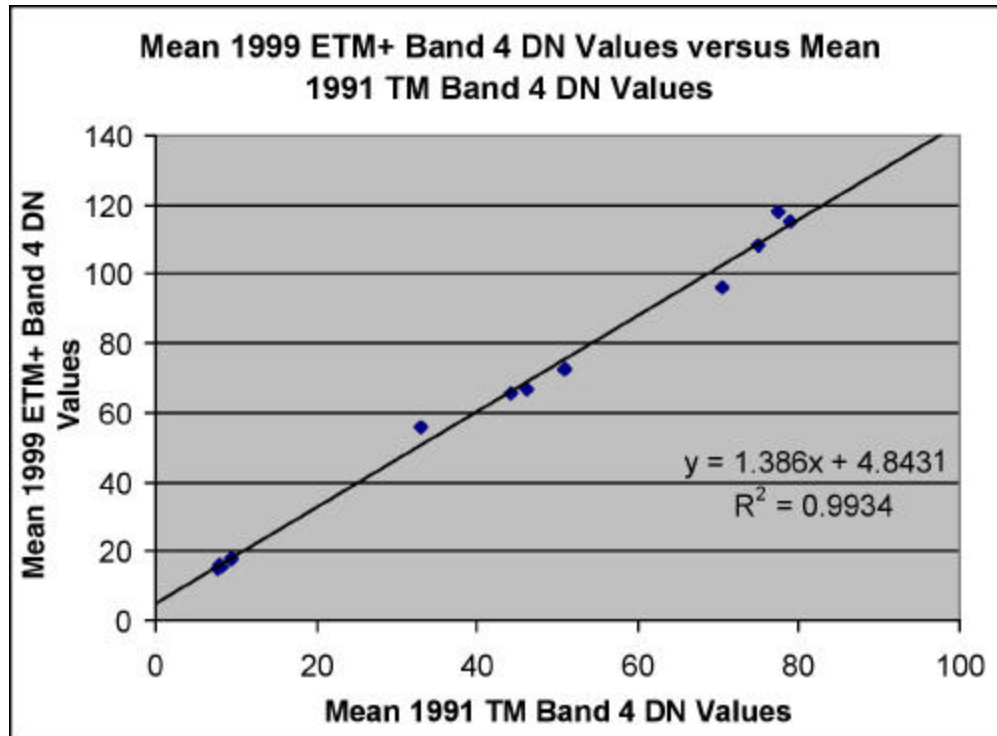


Figure 2. Relationship between ETM+ band 4 versus TM band 4 datasets. Each point represents the mean DN values extracted from a pseudoinvariant target.

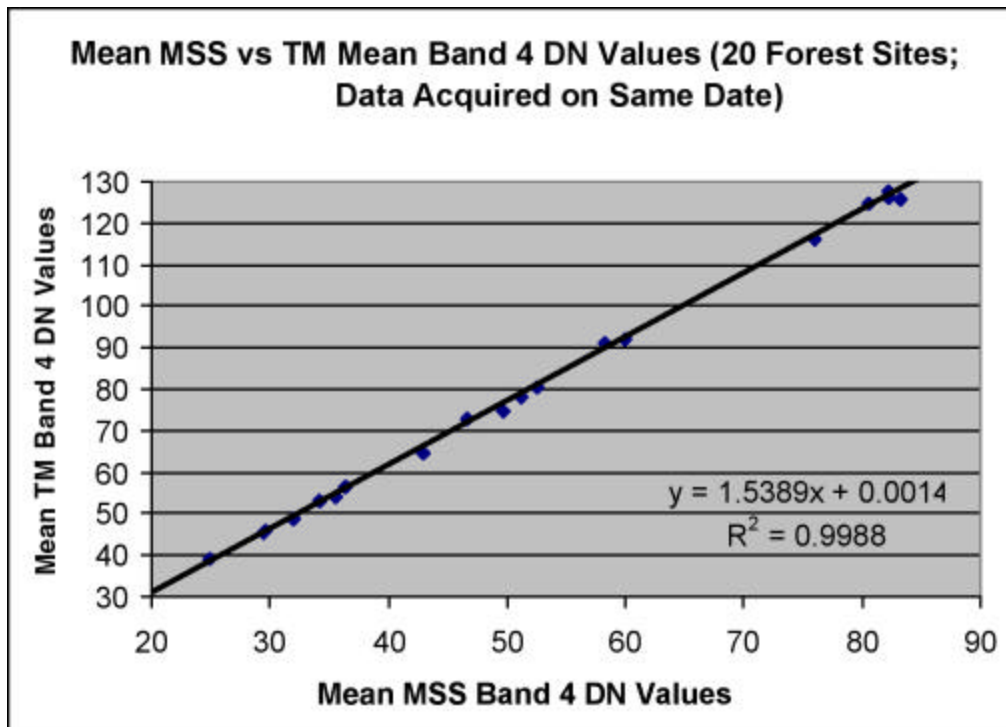


Figure 3. Relationship between TM band 4 versus MSS band 4 datasets. Each point represents the mean DN values extracted from a forested target.

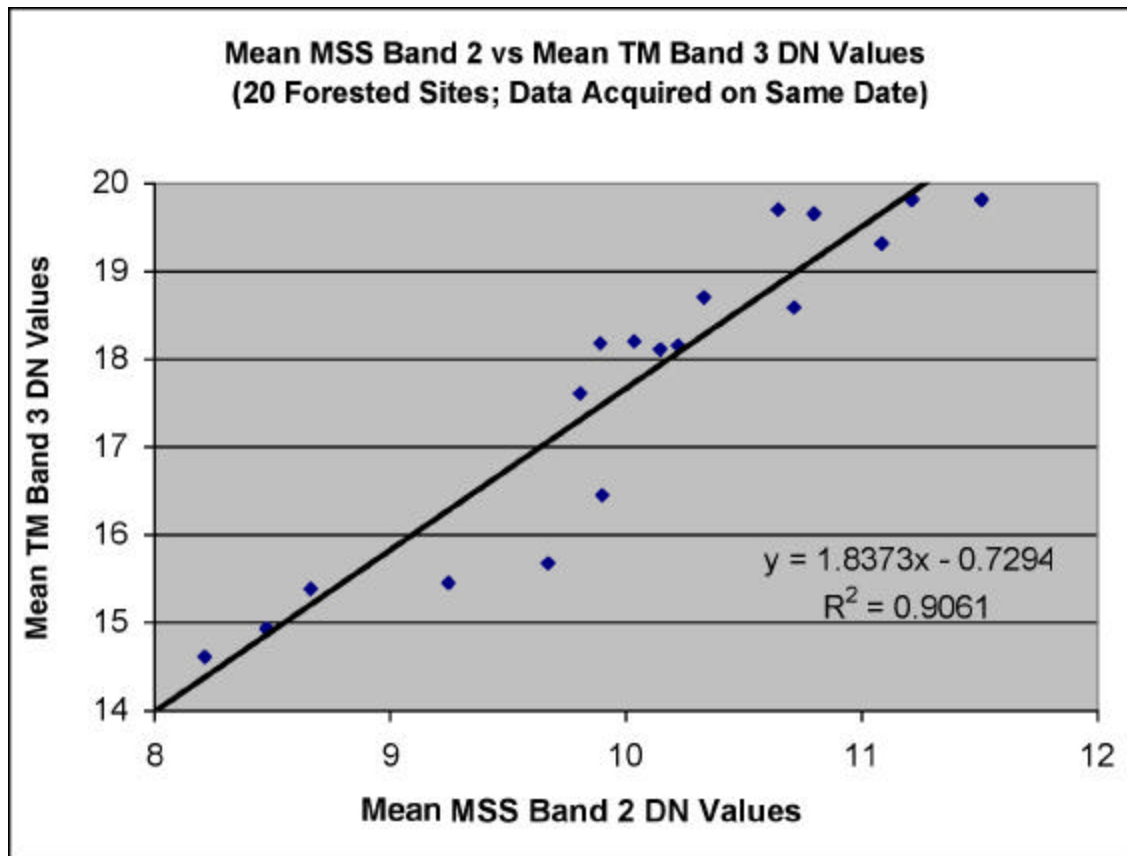


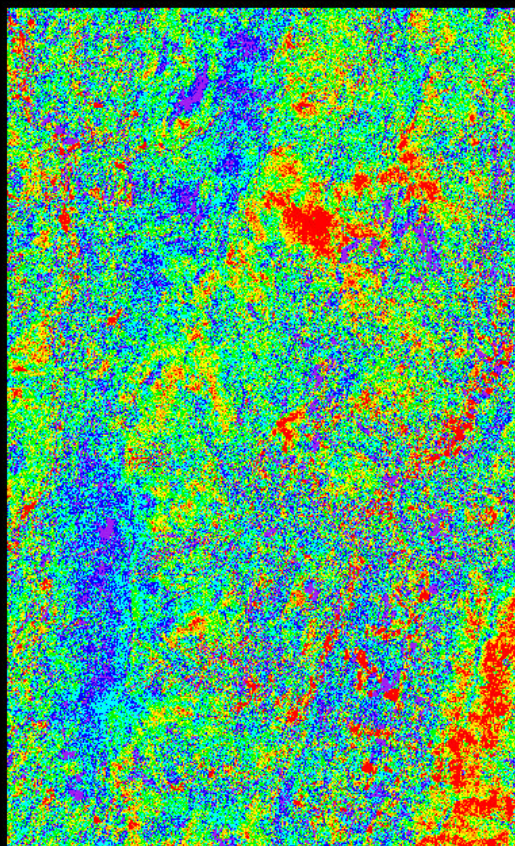
Figure 4. Relationship between TM band 3 versus MSS band 2 datasets. Each point represents the mean DN values extracted from a forested target.

## METHODS ASSESSMENT

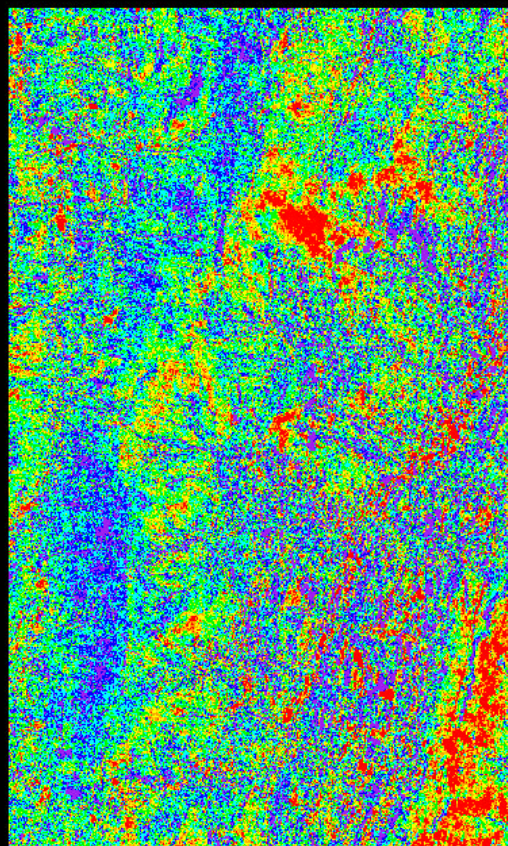
Landsat TM and ETM+ data appear to be highly correlated. This has been described and documented in greater detail in another investigation (Vogelmann *et al.*, 2001). This is certainly an important issue from the standpoint of Landsat data continuity and the appropriateness of using Landsat TM and ETM+ datasets for the purposes of monitoring.

The difference image produced between 1999 ETM+ band 4 data and 1991 TM band 4 data is very similar to that produced between 1999 ETM+ band 4 data and 1991 MSS band 4 data (Figure 5). This is an important finding, because it supports the notion that we can effectively bridge between MSS and TM/ETM+ sensors for forest-monitoring applications. Most other studies using both MSS and TM/ETM+ data for change detection assessments have involved developing classification products for the various datasets used, and comparing statistics of land cover thematic class information from each to generate estimates of change (e.g., Skole and Tucker, 1993; Loveland *et al.*, 2002). Although other techniques, such as principal components analysis and change vector analysis have been successfully used in change detection studies (e.g., Ribed and Lopez, 1995; Byrne *et al.*, 1980; Sohl, 1999) and, at least in theory, could work well for assessing changes across MSS and TM/ETM+ epochs, the current study is unusual in that it seeks to provide MSS and TM/ETM+ change information in units of reflectance. Most investigators have been hesitant to do this for a several reasons, but this study shows that it is indeed possible, using caution and within certain constraints, to provide estimates of MSS to TM/ETM+ change in units of reflectance.

## FOREST CHANGE IN THE NORTHEASTERN UNITED STATES



1999-1991 (ETM-TM)  
Band 4 Difference



1999-1991 (ETM-MSS)  
Band 4 Difference

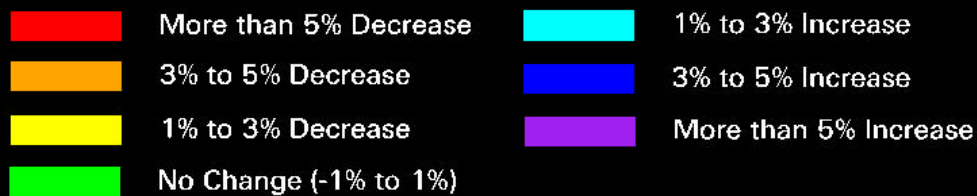


Figure 5. Comparison between difference images produced between 1999 ETM+ and 1991 TM band 4 data and 1999 ETM+ data and 1991 MSS band 4 data. Data have been converted to differences in at-sensor reflectance.

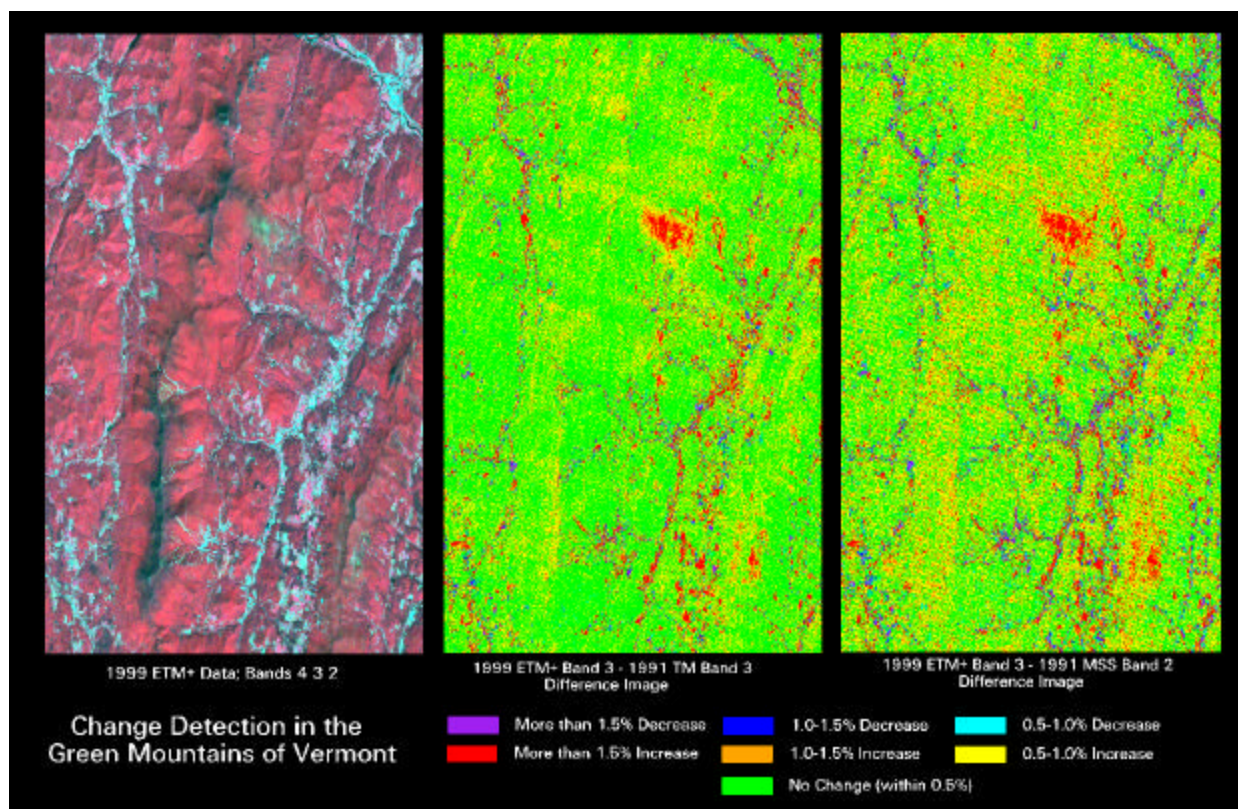


Figure 6. Comparison between difference images produced between 1999 ETM+ and 1991 TM band 3 data, and 1999 ETM+ band 3 data and 1991 MSS band 2 data. Data were converted to differences in at-sensor reflectance.

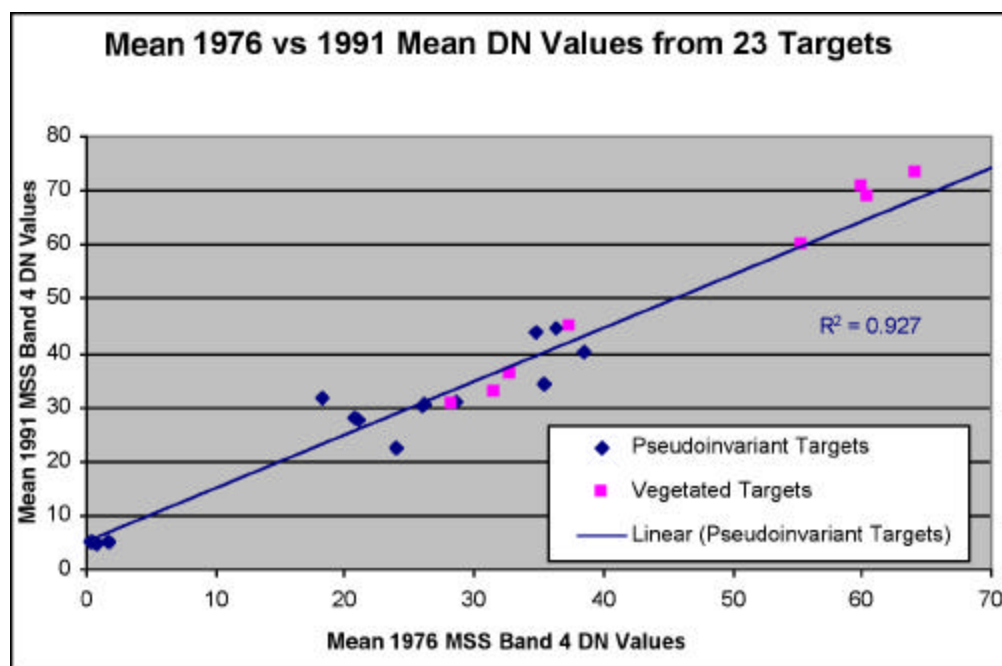


Figure 7. Relationship between 1999 ETM+ band 4 versus 1976 MSS band 4 datasets. Each point represents the mean DN values extracted from a non-vegetated (pseudoinvariant) target (blue) or a forested target (pink).

The difference image produced between 1999 ETM+ band 3 data and 1991 TM band 3 data is reasonably similar to that produced between 1999 ETM+ band 3 data and 1991 MSS band 2 data (Figure 6). It is obvious that both difference images are characterized by instrument noise, as evidenced by the speckling and striping patterns. It is apparent that the difference image produced using the MSS data has more noise than the one produced using the TM data. This is not particularly surprising owing to the striping and speckling patterns noted in the original MSS band 2 data. Nonetheless, it appears that the overall patterns of reflectance changes are similar between the two products and that, at least in the right cases, there is hope for bridging between MSS and TM/ETM+ for monitoring changes taking place in the visible part of the spectrum.

The conversion of 1976 MSS DN values to ETM+ equivalents presents a number of additional challenges and problems. The first is that there are not many pseudoinvariant objects that are large enough to use in the conversion to 1991 MSS DN values (the first step in the conversion process). Many bright targets that work well for normalizing TM/ETM+ data are located in urban areas, at least in the Northeastern United States, and most of these targets are too small to be optimal for use with MSS data. Thus, the relationship between 1976 and 1991 MSS datasets is expected to be less precise than for other conversions (e.g., 1991 TM to 1999 ETM+). Nonetheless, the relationship between 1976 and 1991 MSS band 4 datasets was found to be reasonably strong. A second issue is that some noise is expected to be associated with each stepwise conversion (e.g., 1976 MSS to 1991 MSS; then conversion to 1991 TM equivalents, and then conversion to 1999 ETM+ equivalents).

## ECOLOGICAL DISCUSSION

Forests that undergo decline typically undergo several generic stages of change. Stage 1 relates to an increase in the amount of stressed vegetation and decreased tree vigor. Typical conditions that might characterize Stage 1 include decreases in green-leaf biomass, decreased growth rates, and decreases in chlorophyll content. Expected radiometric changes that accompany Stage 1 include decreased near-infrared reflectance (associated with decreases in green-leaf biomass), and perhaps very slight increased visible reflectance (chlorosis increases visible reflectance slightly). If the decline is severe enough, Stage 2 can occur, which includes sustained declines in growth rates and increases in levels of tree mortality. Expected radiometric changes that accompany Stage 2 include continued decrease in near-infrared reflectance (dead branches and tree trunks have low infrared reflectance compared with green leaves). Visible reflectance may also increase slightly, because brown and dead plant material has higher reflectance in the visible part of the spectrum than living green material. With time, hardy species that are not sensitive to the agents that led to the decline process will replace those species that declined. This is Stage 3, and to the casual observer, it may appear that the forest is “healthy” (some might argue for all the wrong reasons!). Expected spectral changes accompanying Stage 3 include increased near-infrared reflectance and decreased visible reflectance, as compared with Stage 1 and Stage 2 radiometric conditions.

In the case of the high-elevation forests of the Green Mountains, Stages 1 and 2 occurred during the 1970s and 1980s. Although there was evidence that near-infrared reflectance decreased over this time period (Vogelmann, 1988), the changes that were expected in the visible part of the spectrum were too subtle to detect using MSS data. It should be noted, however, that there was evidence of chlorosis in some of the dominant species in the region, and that this was detectable using field, laboratory, and airborne spectroradiometers (Rock *et al.*, 1986; 1988).

There was not much evidence to indicate that Stage 3 had occurred by the 1980s. However, it was conjectured that paper birch would replace the declining conifer species in time, and there were casual observations that the understory vegetation, comprised largely of various species of ferns and broadleaf shrub species, was much more apparent than in years past.

The images in Figure 8 provide information regarding the amount and patterns of change that has taken place in the near-infrared part of the spectrum within the Green Mountains. The upper left image, depicting change between 1976 and 1991, shows evidence of decreasing near-infrared reflectance for a zone (or sometimes a “ring-around-the-mountain”) associated with the mountains at medium-high elevations. This is consistent with field observations that were made over the time period (Vogelmann *et al.*, 1988) and is reasonably consistent with satellite-based observations made between 1973 and 1984 (Vogelmann, 1988). These satellite observations are consistent with the forests having reached Stages 1 and 2. The upper right image depicts near-infrared change between 1991 and 1999. Much of the region, including many areas that show decreased near-infrared reflectance between 1976 and 1991,

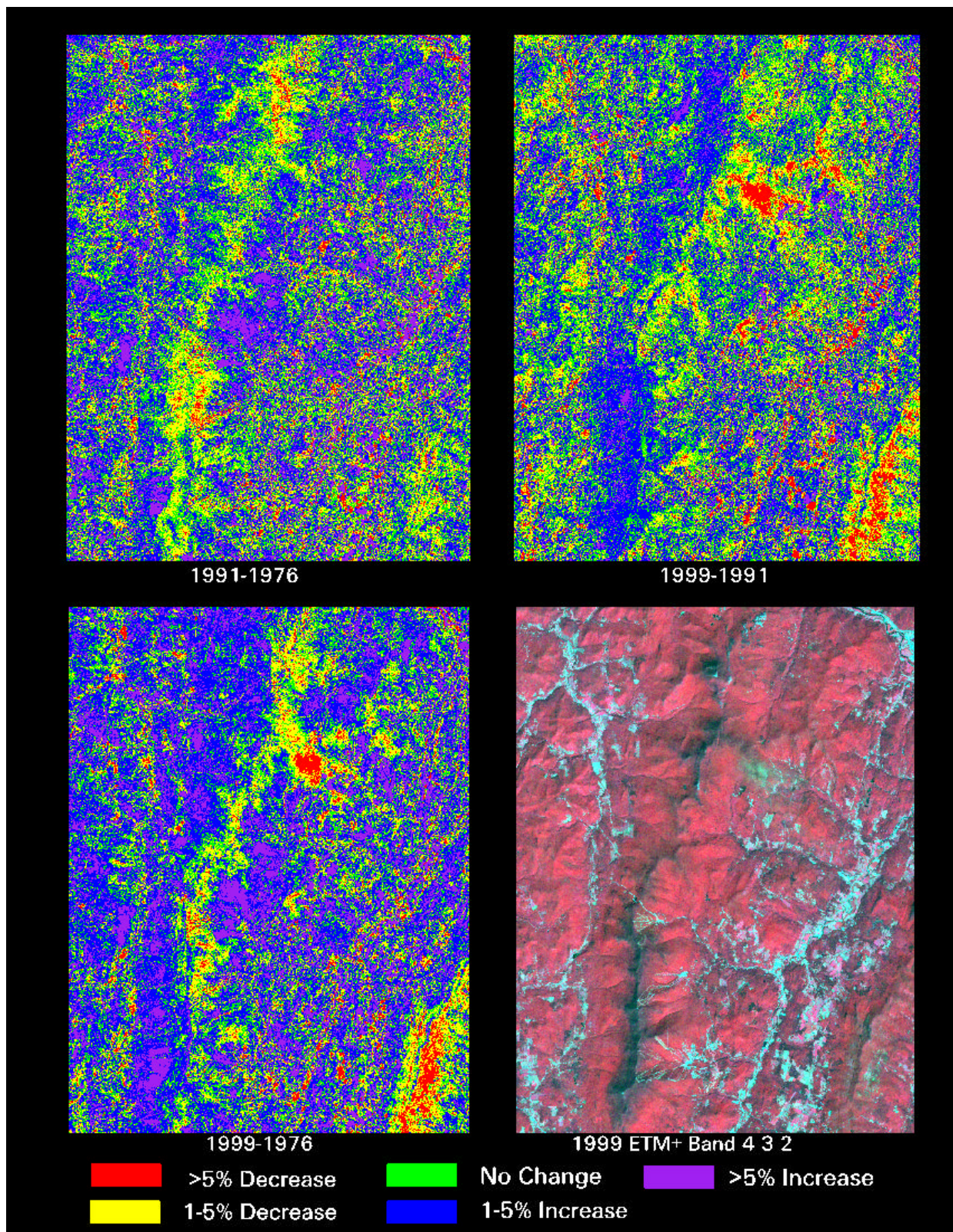


Figure 8. Near-infrared reflectance change in the Green Mountains of Vermont.

showed that increases in near-infrared reflectance occurred between 1991 and 1999. This is consistent with the forest community species changes accompanying Stage 3. It should also be noted that broadleaf vegetation, such as paper birch, tends to have higher near-infrared reflectance than conifer vegetation, and thus the reflectance changes may be especially pronounced owing to replacement of conifer species by broadleaf species. The 1976-99 change image (Figure 8, lower left) is relatively difficult to interpret by itself, in part because some of the near-infrared decreases between 1976 and 1991 were offset by near-infrared increases between 1991 and 1999.

## CONCLUSIONS

Results from this study demonstrate the feasibility of using historical Landsat MSS and TM/ETM+ data for monitoring forest condition. Near-infrared reflectance changes are certainly taking place in these ecosystems and appear to be sensitive to changes taking place within these forests. Although the approach employed is certainly not the only approach that could have been taken, the results are consistent with known ground conditions as well as expected spectral response to the changing forest conditions. Although the study demonstrates the utility of broadband sensors for monitoring the high-elevation forests of the Northeastern United States, a number of questions remain that can only be answered through further study and analysis. A major question remains as to the degree of near-infrared variability from year to year. There is reason to suspect that interannual near-infrared variability may be especially high for deciduous tree species, but this variability is largely undocumented to date. Only through analysis of multiple temporal datasets can this variability become better understood.

Perhaps more importantly, the study presents a test case that illustrates that we can begin understanding how our forests are changing through time across large regions. We need to develop a better understanding of the magnitude of change occurring in our forests and which forest communities are undergoing change. We also need to develop a better understanding as to the nature of the forest changes taking place in a spatial framework. These changes occur in many different forms and include outright clearing, fragmentation caused by urbanization, declines related to natural as well as anthropogenic forces, and forest composition changes related to changes in climate or succession. Finally, we need to develop a better understanding of the rates of forest change, as well as to determine the ramifications of these changes. This information is important for many different groups, including land use planners, the conservation community, foresters, and global change researchers. The analysis provided in this case study represents the first of many similar efforts that should be conducted across the country so that we can provide a holistic understanding of the magnitudes and patterns of changes taking place in our Nation's forests.

## ACKNOWLEDGMENTS

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