8.0 FINDINGS AND CONCLUSIONS

The primary thrust of this study has been the application of remote sensing imagery to detect stresses to the tree canopy over longwall mining areas. Three study sites at each of three mines in Washington and Greene counties, Pennsylvania were selected for collection of imagery. At each mine, one of the selected study sites had been undermined in the 1995-99 timeframe, one had been undermined more than 10 years ago, and one had not been undermined. The latter study site at each mine was selected for control purposes.

The primary source of remote sensing data was airborne multispectral scanning imagery provided by SenSyTech. These data were supplemented by satellite (IKONOS I) color infrared imagery and scanned color infrared photography provided by BAE Systems ADR, Inc. The airborne multispectral scanning imagery was obtained on June 30/July 2, 2000, and the additional satellite color infrared imagery and aerial photography from BAE Systems ADR was obtained for dates between July 20 and September 22, 2000.

The multispectral scanning imagery was analyzed using the IMAGINE 8.4 Software developed by ERDAS. Approximately 70 areas of potentially stressed tree canopy (field sites) were identified from the imagery. Some of the field sites were subsequently eliminated because they were located outside the study site boundaries. Ground truthing was planned at the remaining 48 field sites for the purpose of determining the field condition of the tree canopy observed on the imagery. Accordingly, from the large study site areas of generally healthy forestland, the imagery was used to identify field sites with potential canopy stress that represented only a small portion of each study site area (Table 9).

The ground truthing effort was conducted between August 29 and September 28, 2000. The field reconnaissance team, lead by Dr. Davis, visited 32 of the 48 field sites identified within the study areas. At some of the larger field sites, more than one tree survey was performed. In total, 42 field tree surveys were performed.

In addition to surveying field sites of potential canopy stress identified from the imagery, the D'Appolonia field team also evaluated some areas where subsidence effects were observed or predicted. These included:

- Pools created by subsidence and the segments between the pools along Enlow Fork at study site A-1;
- Longwall mine panel boundaries (where high tensile strains were predicted) at each of the three mines; and
- A property near study site D-1 where the owner reported subsidence damage to trees.

8.1 USE OF REMOTE SENSING IMAGERY TO DETECT TREE CANOPY STRESS

The multispectral scanning imagery, satellite color infrared imagery and aerial color infrared photography were used to identify locations of potentially stressed tree canopy. The multispectral scanning imagery proved to be the most useful for tree canopy stress detection because of the multiple types of images provided, the orthorectification of the images, the clarity of the images and the lack of interference from clouds.

The image analysis was performed by simultaneously scanning enlarged portions of the various types of multispectral images (e.g., natural color, color infrared, NDVI, day and night thermal) using the IMAGINE 8.4 software. Areas of stressed tree canopy tended to be green or gray on the color infrared images and pinkish on the natural color images. Some grayish areas were identified on the color infrared and natural color images; these areas were determined to be related to stressed tree canopy by the ground truthing effort. On the color infrared images, the gray areas appear to be precursors to green areas, while on the natural color images the gray areas were generally found to correspond to dead trees.

The stressed tree canopy showed up as medium dark gray areas on the NDVI images. The night thermal images were helpful in identifying roads and streams that were obscured by the tree canopy during the day, as well as revealing areas of diminished transpiration function in the tree canopy. The day thermal imagery was useful for detecting conditions such as branch dieback, but was less useful for detecting leaf browning and defoliation caused by insects.

Additional satellite and aerial photographic color infrared imagery collected at three different periods over the growing season indicated the development and expansion of identified areas of potential canopy stress. The expansion of distressed canopy areas is consistent with the seasonal progression of stresses such as insect infestations.

The potentially stressed tree canopy locations identified from the imagery are summarized in Table 10. The table provides topographic position, soil classification, tree types and a description of the observed canopy stress. These locations tended to be on the mid- to upper slopes of hillsides and were found with all orientations (most frequently east- and west-facing slopes and less frequently north-facing slopes). Soils at these locations are typically shallow and characterized as silt and silty clay loam, consisting of colluvium and residual soil (weathered from shale, siltstone and limestone) and are moderately well to well drained.

The multispectral images for the mine study sites were systematically traversed in order to identify areas with stressed tree canopy that might align with the predicted distribution of tensile and compressive strains over the longwall panels. Table 11 summarizes the predicted subsidence settlement and tensional strain at the field site locations selected based on the imagery, along with locations of predicted or observed subsidence effects. Areas of potentially stressed tree canopy were found in all types of predicted strain zones, including zones of high tensile strains at magnitudes (5 to 10 x 10^{-3} ft/ft) estimated to cause potential damage to woodlands. However, locations of potentially stressed tree canopy identified on the imagery were not associated with high tensile strain conditions any more frequently than with zones of compression or transition strain. No linear or geometric features or patterns that aligned with locations of high strains or subsidence were detected from the imagery.

If geometric patterns were to be found, the most likely locations for tree canopy stress would have been along the high tensile strain zones around the perimeters of longwall panels (Section 4.0). As discussed in Section 7.0, tree canopies were characterized as generally healthy at the locations of high tensile strain, where cracks and other evidence of subsidence on the ground were detected. Distinctive evidence of canopy distress associated with longwall mine panel boundaries was not detected on the imagery.

8.2 ANALYSIS OF IMAGERY AND TREE SURVEY DATA FROM FIELD SITES

8.2.1 General

Insect infestation and defoliation, impacting black locust and elm trees, were the most frequently detected stresses at field sites. Branch dieback of oak, aspen and maple was also detected on the imagery. The branch dieback of oaks is likely related to past insect defoliation such as the gypsy moth damage that occurred in the area in 1996 (Section 2.4.2 and Figure 3). The dieback of aspen is believed to be a natural phenomenon, considering their short-lived characteristics.

Distinctive spectral response was associated with insect defoliation, particularly where leaf browning occurred. The average vigor ratings assigned for tree canopies at field sites in August/September when insect damage was confirmed were typically between 2 and 4, as indicated in Table 12. These values reflect conditions of light decline (foliage discoloration present in 10 to 25 percent of the tree crown) to severe decline (foliage discoloration present in more than 50 percent of the tree crown). Considering the progression of insect damage indicated by the satellite color infrared imagery, the extent of decline was likely less at the time of the acquisition of AMS imagery on June 30/July 2. Accordingly, the AMS was likely capable of detecting vigor ratings of 2 (light decline) in black locust and elm trees due to insect infestation.

Branch dieback had a less distinctive spectral response than insect infestation and defoliation. Oak and aspen trees observed at the field sites were in severe decline to dead based on the average vigor ratings (typically 4 to 5 as indicated on Table 12) determined during the ground truthing. No progression of branch dieback areas was observed in the satellite and airborne color infrared images. Generally branch dieback that was detected by the AMS was associated with larger trees in an advanced state of decline.

8.2.2 Comparison of Tree Health at Undermined and Control Study Sites

A comparison of tree survey data at undermined and control sites is provided on Figure 41. The figure shows the distribution of vigor ratings for the six tree types most frequently found at field sites at the three mines and presents a comparison between conditions at undermined and control study sites. Vigor was evaluated in accordance with the criteria presented in Table 8, where 1 is healthy and 5 is dead.

In general, the plots of vigor rating do not indicate significant differences between undermined and control study sites. A summary of data is also presented in Table 12, which shows average vigor ratings for the three types of study sites for various tree types and canopy stresses. It should be noted that this study was not intended as a large-scale tree survey and the numbers of some trees are not large enough for conclusions relative to data trends to be relied upon. Also, because insect infestations were frequently detected on the imagery, the occurrence of black locust trees in the data is out of proportion to their overall presence and importance in the total tree population.

It does not appear that there is any significant difference in the health of black locust and black cherry trees observed at undermined and control study sites. Elm trees and maple trees surveyed were less healthy on control study sites. There were no data for oak trees at control study sites, and oak trees at sites undermined prior to 1990 were slightly less healthy than oak trees at study sites undermined between 1995 and 1999. Insufficient data were available for aspen trees to make any comparisons. Overall, no meaningful difference in the distribution of vigor ratings was detected for the most frequently encountered tree types at the three types of study sites.

8.2.3 Comparison of Imagery at Undermined and Control Study Sites

A comparison of canopy stress conditions observed on the imagery for the three types of study sites is provided on Figures 32, 33 and 34. Figure 32 shows a comparison of insect infestation stresses on primarily black locust and elm trees at study sites A-1, A-2 and A-3. The actual field sites were A-1-4, A-2-3 and A-3-2. As shown on the figure, the observed stresses appear similar for the three types of study sites.

Figure 33 shows a comparison of insect infestation stresses on primarily black locust trees at study sites B-1, B-2 and B-3. The actual field sites were B-1-1b, B-2-1a and B-3-3. As noted above, the observed stresses are similar at the three types of study sites. Note that the stresses are difficult to detect on the day thermal images.

Figure 34 shows a comparison of branch dieback on aspen, oak and red maple trees at study sites D-1, D-2 and D-3. The actual field sites were D-1-4, D-2-4 and D-3-4. Note that the branch dieback shows up as purplish on the natural color imagery for all three study sites. The branch dieback also consistently shows up as a light area on the day thermal imagery.

8.3 EVALUATION OF OBSERVATIONS AT SUBSIDED AREAS

In addition to the analysis of imagery and subsequent evaluation of identified areas of stressed tree canopy in the field, a number of areas with known or predicted subsidence effects were evaluated in the field in order to determine if impacts were present in the tree canopy.

8.3.1 Enlow Fork Pools

Several days were spent evaluating conditions at the subsidence pools and the areas between these pools along Enlow Fork at the Bailey Mine. As would be expected, it was observed that soils were wetter around the pools as compared to the areas between pools. The relative health of a number of tree species growing along Enlow Fork was evaluated for both the areas around the pools and the areas between pools. It was found that species that were relatively tolerant of increased soil moisture such as sycamore, black locust, boxelder and elm had similar percentages of healthy trees in pool and between-pool areas. On the other hand, species such as black walnut and maple that are more sensitive to soil moisture conditions had lower percentages of healthy trees around the subsidence pools.

A comparison of data from tree surveys at subsidence pools and the stream segments between pools is presented in Figure 42. The figure shows the distribution of vigor ratings for the nine most abundant tree species found along Enlow Fork. The distribution of vigor ratings is shown in bar graph form as a percentage in each vigor-rating category (Table 8). For most trees, the results for pool areas and between-pool segments are similar. Most notably, the results for sycamore, elm and boxelder show similar distributions for pool areas and between-pool segments. Maple shows somewhat better tree health for between-pool segments and black walnut shows better tree health for between-pool segments. However, only a small percentage of all trees along the pools appeared to be affected.

As discussed in Section 7.0 and the preceding paragraph, the field reconnaissance team observed some minor canopy stresses associated with some types of trees around the Enlow Fork pools. As the data indicate, the overall effect on the tree canopy from the pools is minor and limited to less moisture tolerant trees such as maple and black walnut (only a few trees with vigor ratings greater than 2).

The remote sensing imagery for the area around the pools at Enlow Fork was further reviewed following the ground truthing effort. However, review of the imagery did not reveal conditions around the pools that could be distinguished from conditions in nearby areas at study site A-1. It should be noted that the presence of the stream increases the difficulty of detection because it tends to mask data in the vicinity of the pools. The tree survey area around the pools was limited to a narrow strip about 10 feet in width, and the distressed black walnut and maple trees represented a small fraction of the total trees along Enlow Fork.

8.3.2 Mine Panel Boundaries

The areas between longwall mine panels can be regions of high tensile strain at the ground surface, and cracks and slides are sometimes observed in these areas. Based upon the analysis of strains and subsidence discussed in Section 4.0, areas of high tensile strain along panel boundaries were selected at each of the three mines. The field reconnaissance team subjectively evaluated the selected areas in order to determine subsidence effects on the tree canopy. Observed ground disturbance associated with subsidence, predicted subsidence and strain magnitudes, and predominant tree species at locations along the selected mine panel boundaries are presented in Table 11. Generally, slides and associated scarps were observed and some effects including root damage and inclination of trees (sometimes severe) were observed. However, tree canopies were generally characterized as healthy.

The remote sensing imagery along longwall panel boundaries was carefully reviewed. However, no areas in the imagery were found that indicated the presence of distinctive canopy stress along alignments of high strain.

Enlargement of the imagery for study site A-1 at the Bailey Mine indicated scattered points of potential canopy stress, perhaps consisting of one stressed tree, on a background of healthy vegetation throughout the study site. Some canopy stress of this type was detected on the imagery along the panel boundaries, but the images in these areas are consistent with other areas of study site A-1.

Similarly, a review of the imagery for the panel boundary evaluated in the field at study site B-1 (Figure 38) did not indicate canopy conditions that were different from canopy conditions away from the panel boundaries (consistent with field observations). Note that a portion of this panel boundary passes through field site B-1-1, a large area with numerous black locust trees that were affected by insect infestation.

A review of the panel boundary at study site D-2 (Figure 39) provides no indication of canopy stress along the mine panel boundary, which is consistent with the observations of the field team.

It should be noted that there are differences among the three mine sites that affect the ease of detection of very localized areas of tree canopy stress. As discussed above, the imagery for the Bailey Mine showed scattered points of canopy stress while the imagery for the Humphrey No. 7 Mine did not exhibit this condition. However, in neither case could conditions along mine panel boundaries viewed on the imagery be distinguished from conditions away from the panel boundaries where lower strains were predicted.

8.3.3 Lee Property

The Lee property is a former open field that is in the early stages of reverting to a forest. The property exhibited wetness and ground disturbance related to subsidence, including slides and scarps, hummocky terrain, tree root damage and leaning trees. Ash dieback and dead ash trees were observed on the property. While other ash trees in the area also exhibited dieback, the effects were more severe on the Lee property.

The Lee property is located just east of the eastern boundary of study site D-1, as shown on Figure 40. The longwall mine panel that has affected the Lee property is shown on the figure. A bare area associated with a slide is clearly visible on the imagery. Blown-up natural color and color infrared images of the Lee property are also provided on the figure. There are indications of minor areas of canopy stress at the eastern end (corresponding to the end of the longwall panel) of the enlarged images. This is most noticeable on the color infrared image as small greenish areas. On the natural color image there are some purplish tinges that appear to correspond to the greenish areas on the color infrared image.

Ash dieback and dead ash trees were the tree stresses most commonly found by the field reconnaissance team on the Lee property. The effects observed on the imagery are consistent with branch dieback observed at other study sites (the natural color and color infrared images for field site D-2-4 shown on Figure 40 exhibit similar effects). It should be pointed out, however, that the effects found on the imagery for the Lee property were difficult to detect and likely would not have been found if the Lee property had not been reported as having subsidence damage to trees.

8.4 CONCLUSIONS

8.4.1 Field Sites Identified from the Imagery

The field sites identified from the remote sensing imagery were generally found to have anomalies resulting from one of the following: insect infestations, branch dieback, and logging slash.

Ground truthing revealed that insect infestations of black locust and elm trees were the cause of areas of canopy stress at the majority of the field sites, both at undermined and control study sites. Branch dieback of oaks was detected at undermined field sites, but could not be compared to conditions at control study sites because oaks were not represented at field sites associated with control study sites. In Dr. Davis' experience, branch dieback in oak frequently occurs in the years following a gypsy moth infestation. A gypsy moth infestation covering most of Greene County including the Blacksville and Humphrey No. 7 mines occurred in 1996. Decline of aspen, encountered only at one undermined field site, is believed to be associated with its short-lived characteristics. The logging slash observed on the imagery was not associated with tree canopy stress.

None of the conditions of canopy stress observed at the field sites identified from the imagery were attributed to the longwall mine panels at the undermined study sites. Other causal factors, generally related to insects were implicated. There was no evidence of a correlation of observed stress in the tree canopy with ground disturbance associated with subsidence or predicted subsidence effects at these field sites.

8.4.2 Subsidence Areas Observed in the Field

Longwall mining subsidence has the potential to cause damage to the forestland through several mechanisms. One mechanism would be settlement over collapsed longwall panels resulting in the creation of "basins" where drainage is affected and soil moisture is increased, resulting in damage to moisture-sensitive trees. This is unlikely to occur in steep terrain, but can be a factor in relatively flat areas. Another possibility, in areas of steep terrain, is that cracks, slides and resulting scarps can cause damage to trees through tearing of the roots, leaning of trees, or even localized changes to the groundwater table. The D'Appolonia field reconnaissance team observed instances of such subsidence effects at panel boundaries (Section 7.2) and at the Lee property (Section 7.3).

However, while damage to the trees resulting from subsidence was observed in the field, it was also evident that this damage was relatively minor and that the trees affected were generally resilient. The tree canopy condition was evaluated as generally healthy throughout such areas regardless of whether the mining occurred relatively recently (between 1995 and 1999) or prior to 1990.

Ponding of streams due to subsidence may be responsible for adverse impacts to some moisture sensitive trees (i.e., black walnut and maple), as was observed adjacent to the pools along Enlow Fork at Bailey Mine. Other tree types at this site (i.e., sycamore and boxelder) had not suffered observable impacts. Trees observed in the vicinity of the pools may eventually die, but the effect on the tree canopy at the time of observation was relatively minor. No canopy stress conditions associated with subsidence pools at Enlow Fork were detected on the imagery.

At the Lee property near study site D-1, a slide with associated wet ground conditions and other subsidence features was observed in the field, and branch dieback and some mortality were observed in a stand of ash. The resulting canopy stress was detected on the imagery, but would not have been detected if conditions at this site had not been observed in the field.

The ability to detect branch dieback on the remote sensing imagery is a function of the severity of the branch dieback and forest type. Severe decline and mortality were difficult to detect on the AMS imagery in a young stand of mostly ash trees (Lee property), while at some field sites severe dieback was detected at stands of larger hardwoods, such as oaks and maples.