MAPPING THE DISTRIBUTION OF LEAFY SPURGE AT THEODORE ROOSEVELT NATIONAL PARK USING AVIRIS

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1. INTRODUCTION

Weed invasions are one of the most serious and rapidly accelerating ecological threats to land degradation and long-term environmental health faced by environmental managers. Management of invasive weeds is a top priority for environmental management in the United States. The rapid spread of non-native invasive plant species, including noxious weeds is causing irreparable damage to natural resources. The Bureau of Land Management reports that in just the 11 western states, 70 million acres of private, state, and federal lands are infested with noxious weeds. The problem of controlling and managing invasive weeds has accelerated in recent years. Current estimates indicate that weeds infest 4,600 acres daily in the United States, causing severe economic losses and ecological degradation. One of the most troublesome weeds is Leafy Spurge (*Euphorbia esula* L.), an annual that has invaded rangelands throughout the western states. The purpose of this project is to evaluate the usefulness of AVIRIS data for detecting and mapping infestations of the invasive weed, Leafy Spurge. The project is a collaborative effort between NASA and Department of Interior National Park Service and U.S. Geological Survey, to demonstrate the use of imaging spectrometry to map invasive weeds as part of a technology transfer program at the Theodore Roosevelt National Park (TRNP) in North Dakota (Figure 1). One goal of the program was to demonstrate methods for mapping invasive weeds using commonly available image processing software tools that could be adopted by resource managers at National Park Units and other resource managers in the Department of Interior.

Theodore Roosevelt National Park (TRNP) has 574 species of vascular plants, most typical of the rolling plains of the Missouri Plateau badlands, although Great Basin, desert, and boreal forest species are represented. Of these, 59 species are not native to the park (about 10% total flora). The most invasive exotic with the greatest potential for damage to native plant communities is Leafy Spurge (Trammell, 1994). It was introduced into North Dakota during the Homestead Period (Redente, 1993) and has spread throughout the state. Leafy Spurge causes severe ecosystem impacts due to its aggressive growth relative to that of native flora, the ability to invade noninfested habitats, persistence once established, forming nearly monotypic stands (Trammell and Butler, 1995) and capability to alter ecological processes and visitor perceptions of the park.

Leafy Spurge is found throughout the park in all habitat types, although it prefers stream beds, drainages, and wooded draws (Anderson et al., 1996). The greatest concentration is found west of the Little Missouri River and along its major drainages in the South Unit of the park. In 1970 an estimated 13 ha. in 103 patches ranging in size from $<1m^2$ to 1.2 ha. were infested. Infestation now covers 725 to 1,700 ha out of 19,021 ha., or 5 - 10% of the total area of the Southern TRNP Unit. In 1993 the National Park Service (NPS) produced a Geographic Information System (GIS) map of Leafy Spurge in the TRNP based on extensive field observations combined with detailed photogrammetry. The existing map is of questionable accuracy given how rapidly the weed is spreading. Park management hopes that new sensors such as AVIRIS will allow them to develop accurate maps of weed infestations to more effective aid mitigation and control measures.

2. METHODS

All field data and AVIRIS data were collected during the week of July 5th, 1999 when Leafy Spurge was flowering. Ground-level photographs (both digital and film), and plant spectra data where collected, and locations were identified using real-time DGPS (PRO-XRS, Trimble Navigation, Sunnyvale, CA). The AVIRIS flight occurred on July 6, 1999, under clear sky conditions. Four flight lines, of four scenes each, were flown over TRNP and the surrounding area. This study focused on the scene that encompasses the Southern Unit along the Little Missouri River, which included the majority of our field data.

Polygons representing the most homogeneous plant stands we could locate were mapped with GPS to provide training sets for the image analysis. With the exception of Snowberry, no stands were entirely monocultures, so the polygons represent the densest stands of each species within the park. The mapping criteria were based upon accessibility, spatial extent, and species-specific relative density. Plant canopy spectra (325 - 2500nm) were obtained using the GER 2600 spectrometer (GER Corp., Millbrook, NY) with a 23° field-of-view (FOV). Target plants were randomly selected within the purest, densest stands and estimates of percent cover were recorded. Snowberry samples were estimated to be 100% cover pure while “dense” Leafy Spurge samples ranged from 75-95% cover. Species with architectures like Silver Sage only covered 50% of the FOV in most cases. Generally, the nontarget background plants were grasses and dry plant litter. Spectral measurements were made at approximately 1 m above the canopy, giving an approximately 0.40 m diameter ground spatial resolution.

For every ground target, five separate replicate spectra were measured (each with 5 spectra internal average), and averaged for each ground target. In total 2514 individual spectra were measured in 1999, representing 475 ground targets. Twelve of the most common associates of Leafy Spurge were measured, including Silver Sage, Snowberry, Sweet Clover, Juniper, and various native and introduced grasses and mixtures of these species. In addition to the plant spectra, two transects were obtained over an asphalt parking lot that was used as an image calibration site. The calibration data was obtained within an hour of acquiring the AVIRIS imagery.

Field spectra were analyzed using both the UC Davis developed Spectra Analysis and Management System (SAMS) and Environment for Visualizing Images (ENVI) software (Research Systems, Inc., Boulder, CO) packages. SAMS was used to organize, manage, examine, and mine the field spectra and their metadata. In general, SAMS facilitated a quick and easy qualitative understanding of the spectral characteristics that were used in AVIRIS image analysis. In addition to the qualitative analysis, SAMS facilitated more quantitative techniques by porting the spectra as a pseudo-data cube to the ENVI software program. ENVI allowed us to process field spectra using common image processing algorithms for more robust evaluation of results. We applied linear unmixing, Principle Components Analysis (PCA), and Spectral Angle Mapper (SAM) algorithms to the field spectra. We also took advantage of the n-Dimensional Visualizer, which is unique to ENVI. Where library endmembers were required, we used the mean spectrum for all samples of a given plant species as the endmember.

AVIRIS image processing was conducted in ENVI except for calibration to reflectance, which was done using a modified version of MODTRAN, calibration site field spectra, and perl scripts. Numerous image analysis techniques were explored for this study. The common multispectral transformations, NDVI, simple vegetation index (VI), and chlorophyll region slope, were tried. Besides these three simple transformations, the SAM algorithm was applied to the original reflectance data as well as Principle Components (PCA) and Minimum Noise Fraction (MNF) transformations of the data. When applying SAM to the raw reflectance data, we used both the full set of bands (minus bad bands) and a subset of eleven bands that captured the general behavior of the spectra. The eleven bands were for the following wavelengths: 478, 557, 606, 636, 683, 779, 1020, 1200, 1510, 1660, 2210 nm. Despite success in using linear unmixing on the field spectra, we did not use it on the AVIRIS data because it required endmembers for several species that we could not locate in the imagery.

The SAM algorithm is a supervised classification method that requires careful endmember or training set selection. Four criteria were employed for selecting eight Leafy Spurge training sets: 1) Personal knowledge of some locations of Leafy Spurge; 2) The NPS 1993 Map of Leafy Spurge; 3) NDVI values above 0.65; and 4) A qualitative understanding of Leafy Spurge spectra, gained from the field spectral analysis and SAMS software. Using these criteria, we selected eight Regions Of Interest (ROI), > 150 pixels, as Leafy Spurge training sets. A mean spectrum for each of the eight ROIs was calculated and used as endmembers for the SAM algorithm, which produced one rule image for each endmember. SAM was applied on the original reflectance data and on PCA and MNF transformations. Low pixel values in a rule image indicate similarity to the endmember. Because endmembers varied, each rule image produced a slightly different similarity map. Comparison against the 1993 Leafy Spurge map indicated that six of the rule images derived from the MNF transformed data best represented the Leafy Spurge distribution. We used only MNF bands 3 through 17 of the combined rule images as input to the SAM algorithm and we established a threshold that captured a significant portion of the Leafy Spurge distribution. The threshold (500 DN) was placed as high as possible while closely matching the existing map and our knowledge of some sites of infestation. We identify this first classification stage “Tier 1” which we consider a conservative estimate of the distribution of Leafy Spurge in TRNP.

The “Tier 2” classification attempts to capture more of the Leafy Spurge distribution and has a lower confidence because it accepts a larger number of matching pixels. We established an upper bound on the rule image digital numbers (DN) that captured, as much as possible, the locations where field-measured ground truth polygons were included and where speckling occurred only at random pixels throughout the image. This occurred at about 700 DN. We then masked all pixels with values >700 to equal 700. After running a low pass (3x3) filter over the modified rule image to reduce speckle, we used multiple thresholds to establish the best fit the data.

During the threshold exploration process, the upper and lower threshold bounds were performed on non-georeferenced data. Once threshold values had been identified, we masked and re-thresholded the georeferenced rule image. Georeferenceing was performed in ENVI using the UTM projection, NAD83 datum, 17.5 m pixels, nearest neighbor interpolation, and triangulation warping parameters. Classification validation was performed in the Arc/Info GIS software package (ESRI, Redlands, CA). The 1993 vector map of Leafy Spurge was converted to raster with 17.5 m cells. The Tier 1 and Tier 2 classifications were ported from ENVI into Arc/Info. Twelve validation zones were identified. For each validation zone cell counts were obtained for Tier 1, Tier 2, and ground truth coverages. Ratios of classification to ground truth cell counts were calculated for each validation zone.

3. RESULTS

3.1 Field Spectra

Numerous algorithms and tools applied to the combinations of field spectral data showing that various methods were successful in separating the Leafy Spurge spectra from other species in the community (Figure 2). Linearly unmixed products of Leafy Spurge, Sweet Clover, and Snowberry in the n-Dimensional Visualizer, could manually classify 96% samples (n=96) correctly. SAM applied to the same linear unmixed products classified 99% correctly. Leafy Spurge, Silver Sage, Snowberry, and a mixture of native grasses and sedges, could be manually classified with 99.5% accuracy (n=182) using the PCA products in the n-Dimensional Visualizer. A more complicated data set comprising nine species, including Leafy Spurge, Silver Sage, Snowberry, Sweet Clover, Juniper, Western Wheat grass, Green Needle grass, Smooth Brome, and miscellaneous sedges (n=269) also yielded positive classification results (93% correct). Using PCA transformed data as input to SAM (omitting band 1; bands 2-5 used), 61 Leafy Spurge spectra were classified, with 77% correct, 23% unclassified, and 6.6% mis-classified. When considering all 269 spectra in the data set, 93% were correctly classified. PCA Band 1 was primarily related to albedo and was not sensitive to spectral variability.

Figure 2 shows the primary spectral differences between the dominant species in the habitat invaded by Leafy Spurge. Distinctive differences were apparent in reflectance in the visible spectrum and in the slope between green and red wavelengths. In the near-infrared, differences in magnitude of reflectance and in the slope of the reflectance between 700-1300 nm and differences in the depth of water absorption bands. These spectral differences allow separation of most species as shown in Figure 3 for Leafy Spurge (blue), Sweet Clover (red) and Silver Sage (green). The other species (Snowberry, Juniper, and non-native grasses) are not separable in this spectral projection (shown in brown) are separable in other orientations.

3.2 AVIRIS Data

Multiple methods of geo-registration were tried, including rotation, scaling, and translation (RST), polynomial modeling, and triangulation. A USGS Digital OrthoQuad with an estimated accuracy of 5 m was used as the base map. A second degree polynomial gave satisfactory results but triangulation proved best yielding about 2.5 pixels (42.5-m) error. A polynomial fit may have yielded better results if better ground control points were available.

Figure 4 shows a false color image of bands at 990, 683 and 557 nm as red, green and blue colors respectively. The Little Missouri River is highlighted in dark blue. The color balance was stretched to emphasize the dendritic drainages in this badlands topography. Most of the park is vegetated except steep canyon slopes, therefore a VI or NDVI presentation provides little discrimination in the location of vegetation within the park. Of the techniques applied to the image (e.g., VI, NDVI), only the combination of MNF and SAM algorithms yielded good results. All other techniques produced maps that depicted Leafy Spurge throughout all drainages in the TRNP, which basically identified riparian zones as Leafy Spurge, a distribution known to be incorrect.

Selection of a subset of MNF bands was critical to the map product. MNF bands >17 were omitted due to noise and bands 1 and 2 were omitted because they were dominated by atmospheric effects and did not exhibit landscape patterns. When the analysis process used bands 1-17, the results were poor but limiting the analysis to bands 3-17 was successful. None of the PCA bands showed atmospheric effects and we had no criteria to remove PCA bands 1 or 2, which possibly caused the classification to be less successful than the MNF transform. Statistics for Tier 1 and Tier 2 (multiple thresholds) are shown in Table 1, indicating mapping accuracy relative to 1993 map of Leafy Spurge for twelve polygon zones within the park (locations shown in Figure 5). The conservative Tier 1 underestimates the 1993 mapped pixels. The threshold most closely matching the 1993 Leafy Spurge distribution is at a DN of 620 with a mean pixel match of 93.3% of the 1993 map.

Table 1. Percent match between AVIRIS predicted Leafy Spurge pixels and 1993 NPS map for 12 polygons (identified on Figure 5). Tier 1 indicates minimum weed distribution and Tier 2's indicate alternate thresholds for increased distribution of Leafy Spurge. Tier 2 at 620 was threshold used in Figures 5 and 6.

Polygon#	Tier 1	Tier 2 (590)	Tier 2 (605)	Tier 2 (620)	Tier 2 (635)	Tier 2 (650)
1	84.3	122.4	132.5	144.2	158.2	176.2
2	42.3	63.4	70.7	79.5	90.1	104.8
3	28.2	43.1	49.1	57.6	66.6	74.9
4	28.0	39.3	46.4	56.1	65.6	77.7
5	35.4	53.1	62.7	72.3	85.2	99.3
6	23.4	31.6	40.9	51.2	64.9	81.0
7	67.0	102.4	118.1	138.4	163.9	195.1
8	65.9	87.1	91.7	97.2	102.8	109.7
9	84.5	108.4	117.1	123.8	131.5	140.3
10	72.9	97.3	102.3	106.9	111.5	118.3
11	49.0	75.3	84.2	94.3	104.3	116.6
12	53.2	77.2	87.8	97.9	108.7	125.1
Average	**52.8%**	**75.1%**	**83.6%**	**93.3%**	**104.4%**	**118.3%**

Figure 5 shows the 1993 TRNP map of Leafy Spurge in the park on the left and the AVIRIS derived map of Leafy Spurge on the right. The locations of the 12 polygons used for statistical comparison are shown on the figure. The difference in distribution between Tier 1 (green) and Tier 2 (blue) are shown. Clearly, the overall distribution and patchiness is captured in the AVIRIS analysis. However, if the entire park is compared on a pixel-by-pixel basis to the 1993 map, the accuracy statistics are low, due to misregistration issues cited above. To evaluate the map in greater detail, we examined each of the 12 polygons for distribution and accuracy. Figure 6 shows two examples, of a "good" fit and a poor fit to the 1993 map. In Zone 9, the AVIRIS results are 123.8% of the 1993 Leafy Spurge map. While the general location of the Leafy Spurge prediction is correct, some misregistration is apparent. In Zone 4, the 1993 data indicates a more continuous distribution. Despite the fact that AVIRIS mapped pixels fall within the polygons, most of the area is not mapped as Leafy Spurge. Additional ground validation at the site could resolve whether the current distribution is closer to the AVIRIS map or the 1993 map.

4. DISCUSSION

Except for calibrating AVIRIS data to reflectance, the GER field spectra were not directly used for image analysis. However, analysis of the field spectra did establish which plant species were most similar to Leafy Spurge and that commercial remote sensing tools were able to identify Leafy Spurge spectra under conditions where pixel identity, pure endmembers, and no mixed pixels (except for the ubiquitous grass and litter background) were known. The SAMS software was an integral part of analysis of field spectra and was used to establish the general relationships among species in the large spectral data set and for quality control of the data. SAMS facilitated porting the data to the ENVI software for further statistical analysis.

First we tested several multispectral transformations, which include the NDVI, the normalized vegetation index, and the slope across the chlorophyll region. None of these methods yielded images that matched the locations of ground truth polygons or the 1993 Leafy Spurge map; accuracy results were so poor as to not warrant inclusion in the paper. Primarily, the methods overestimated Leafy Spurge and identified it in all riparian zones in the TRNP. Principle Components, Minimum Noise Fraction, and Spectral Angle Mapper were more successful in mapping

Leafy Spurge but only the MNF transformed imagery yielded realistic results. Linear unmixing, though successful on the field spectra, was not used.

The most subjective part of the AVIRIS analysis process was deciding the threshold for the rule image. The rule image contains a continuum of values and does not explicitly provide a basis to determine which are Leafy Spurge and which are not. Because we assume this method is going to be applied by on-site users for the NPS, this is not as much of a limitation as it would be for a global algorithm. If the rule image is exact and the wrong threshold is chosen, it will result in under or over estimating the locations of Leafy Spurge. We considered approaching the threshold problem within a rule-based GIS, however, the best indicators that we could have added were stream proximity, topographic slope, and soil type. After careful consideration of the errors in those data layers and the nature of the threshold problem, we concluded that the overall accuracy would not be improved. In the end, we selected two thresholds to bracket the distribution: a conservative lower bound (Tier 1) and a looser upper bound (Tier 2). Tier 1 used non-smoothed data while Tier 2 was smoothed using a 3 x 3 low pass filter.

Validation of the AVIRIS derived Leafy Spurge map was done both qualitatively and statistically. A qualitative assessment was performed overlaying the 1993 Leafy Spurge (vector) map on the rule image Tier 1 and 2 classifications and visually comparing their patterns. Patterns were markedly similar. Most field-measured polygons had similarly shaped patches as AVIRIS classified pixels and boundaries were inside or near the polygons. Practically no classified Leafy Spurge pixels occurred in regions of the park that did not have Leafy Spurge in the 1993 map. Some contiguous pixels were classified as Leafy Spurge that were not mapped in 1993, but these are almost always located between mapped 1993 patches or are extensions of mapped patches. The spatial registration errors in both the AVIRIS data and the vector map could not support a more detailed accuracy assessment. The image is estimated to be spatially accurate to within 2.5 pixels (42.5m) while the 1993 map has a larger minimum mapping unit and has a spatial error of at least this magnitude. Statistical validation compared the classification with the ground truth map by area. Twelve mapped zones were compared that had different levels of weed infestation and spatial patterns.

With regard to the validation assessments, reasons for discrepancies between the classification and ground truth include: (1) Standard errors in photo interpretation and map location. (2) The aerial photos used to create the 1993 map had very high spatial resolution, enabling the photo interpreter to identify polygons of low density Leafy Spurge and small patches. (3) Areas of low or no Leafy Spurge may have been included in dispersed dense patches. (4) Leafy Spurge located under tree canopies were mapped which were not detectable in our AVIRIS methods. (5) The Leafy Spurge distribution may have changed between 1993 and 1999, given the rate of invasion. (6) The GPS equipment used in 1993 may have introduced a significant spatial location error. (7) AVIRIS pixels probably did not resolve subpixel patches of low density Leafy Spurge. (8) Leafy Spurge AVIRIS pixels may have been confused with other species in the TRNP and mis-classified.

5. REFERENCES

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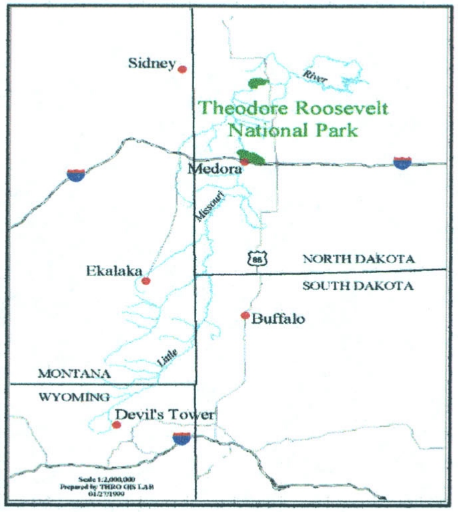

Figure 1. Location of Theodore Roosevelt National Park, North Dakota.

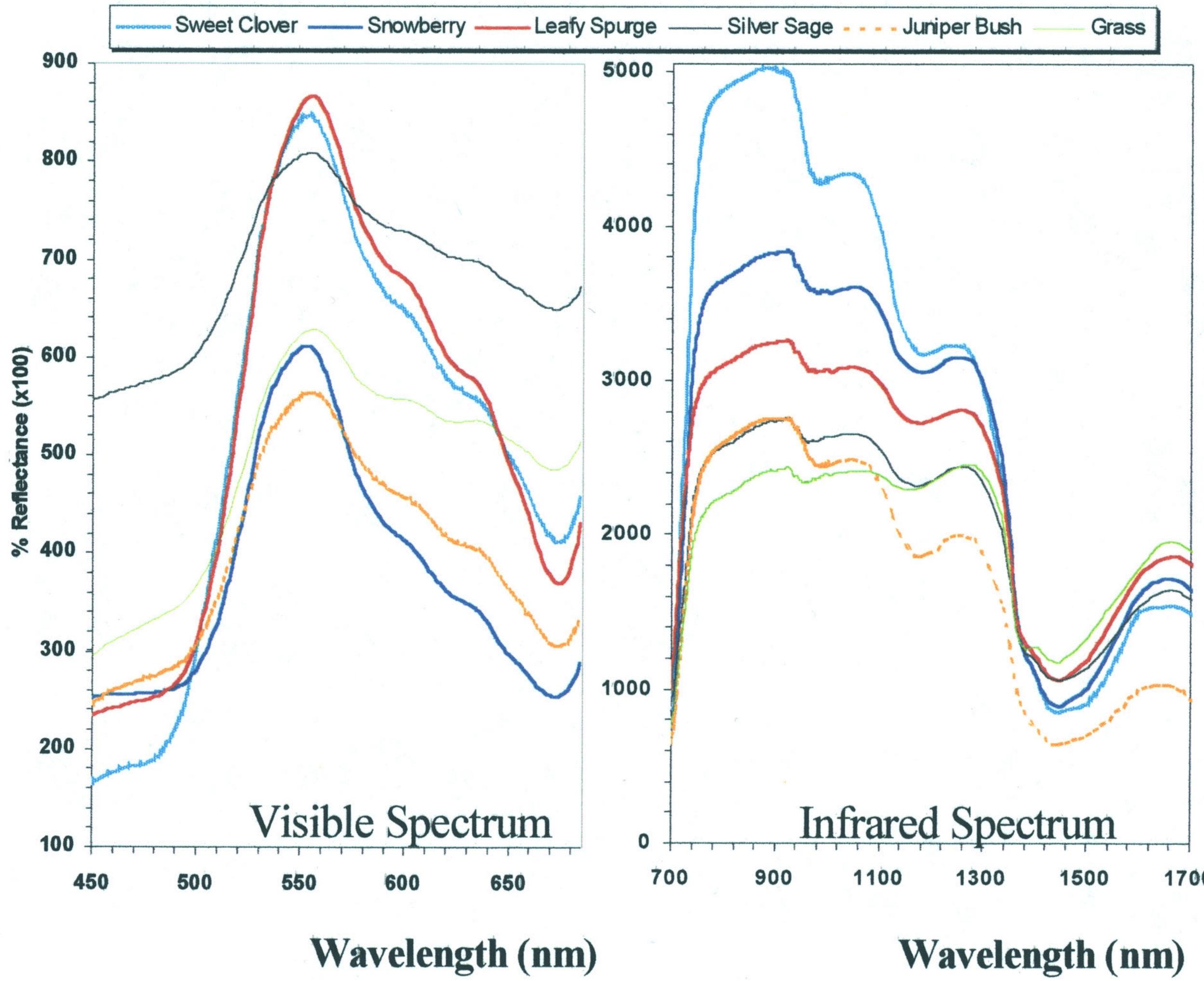

Figure 2. Spectral Differences among different species in areas infested with Leafy Spurge at TRNP.

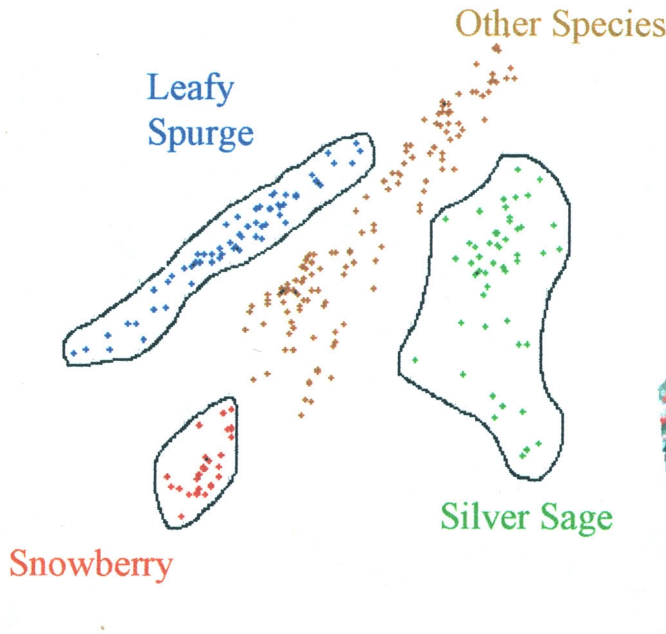

Figure 3. n-Dimensional Visualizer projection showing spectral separation of common species at TRNP using field canopy spectra.

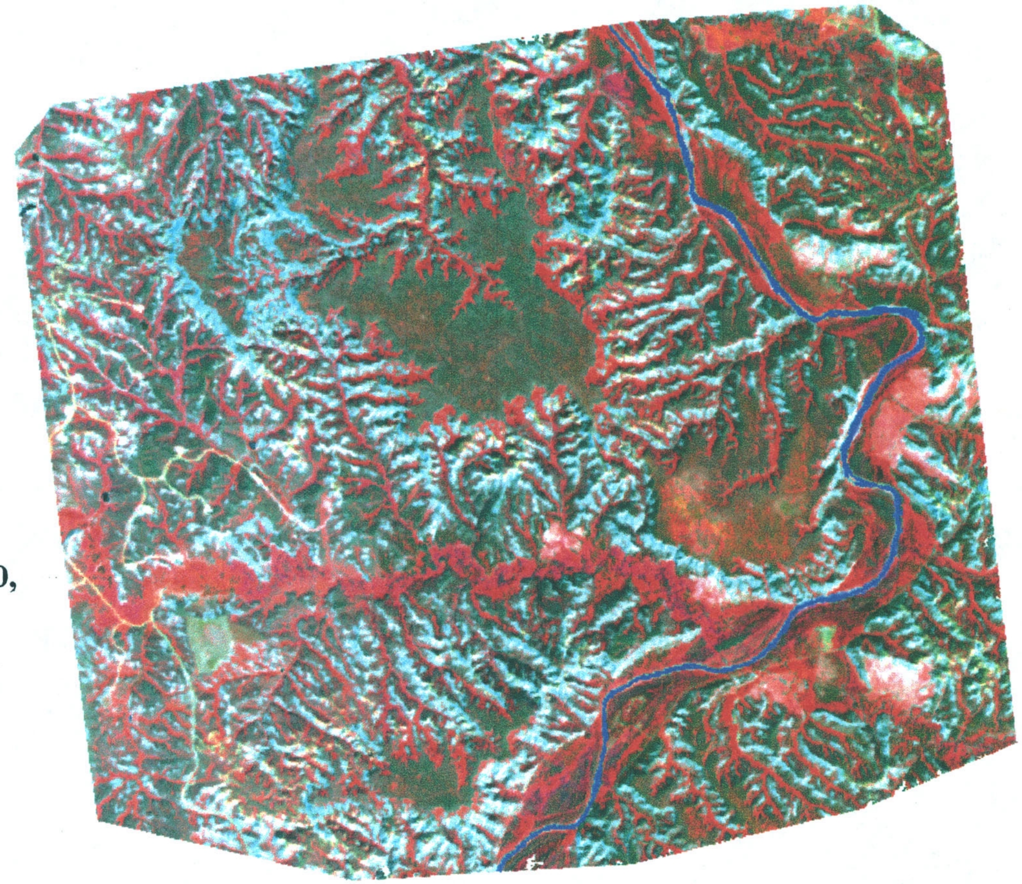

Figure 4. False Color AVIRIS Image showing 990, 683, 557 nm as red, blue and green. The Little Missouri River is in blue. Linear contrast stretch highlights drainages, with vegetated areas in red.

Most of the park is vegetated.

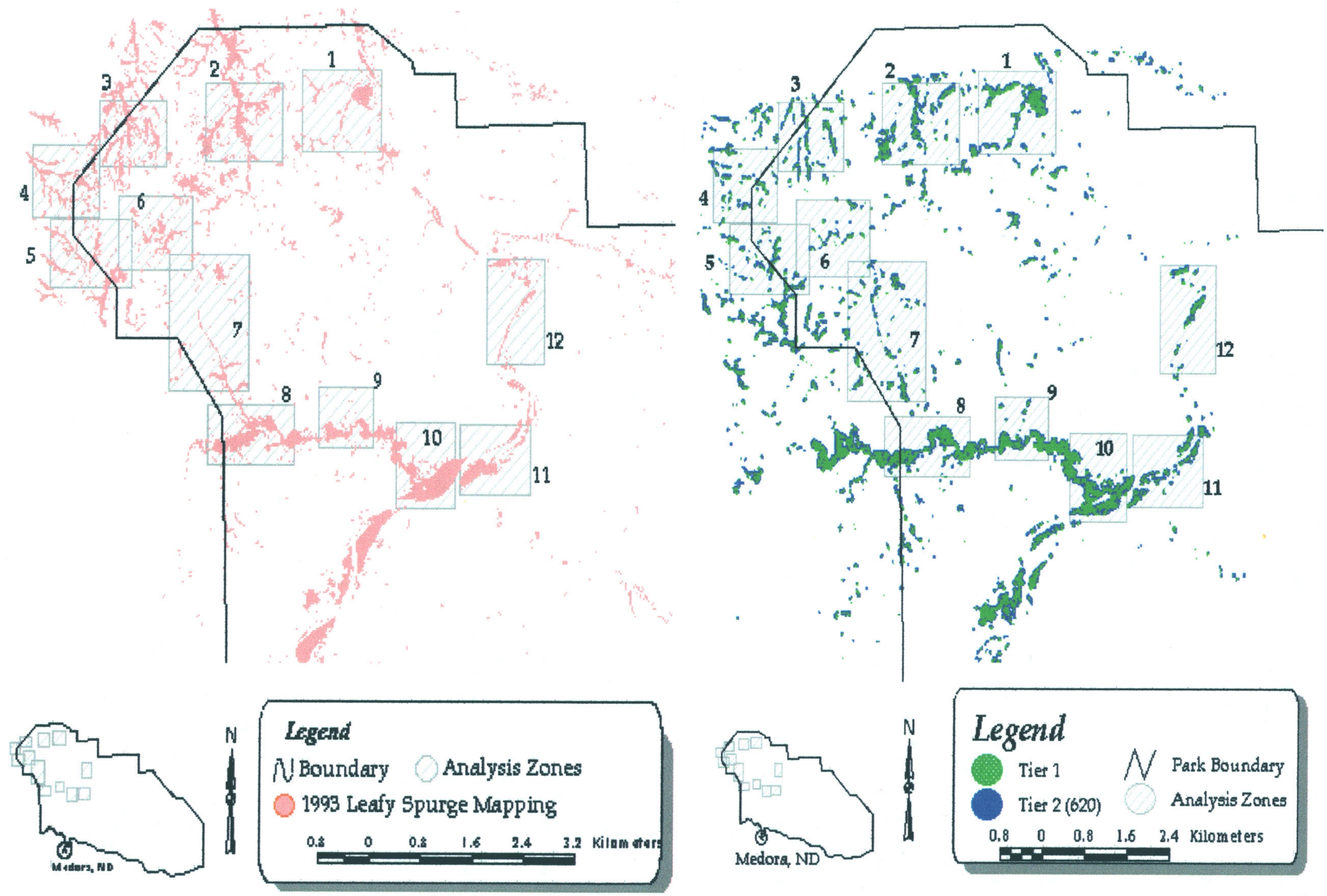

Figure 5. Left panel shows the 1993 map of Leafy Surge in the TRNP. Right panel shows the AVIRIS mapped Leafy Spurge based on spectral identification. Location of polygons are indicated.

Good fit
(zone 9)

Poor fit
(zone 4)

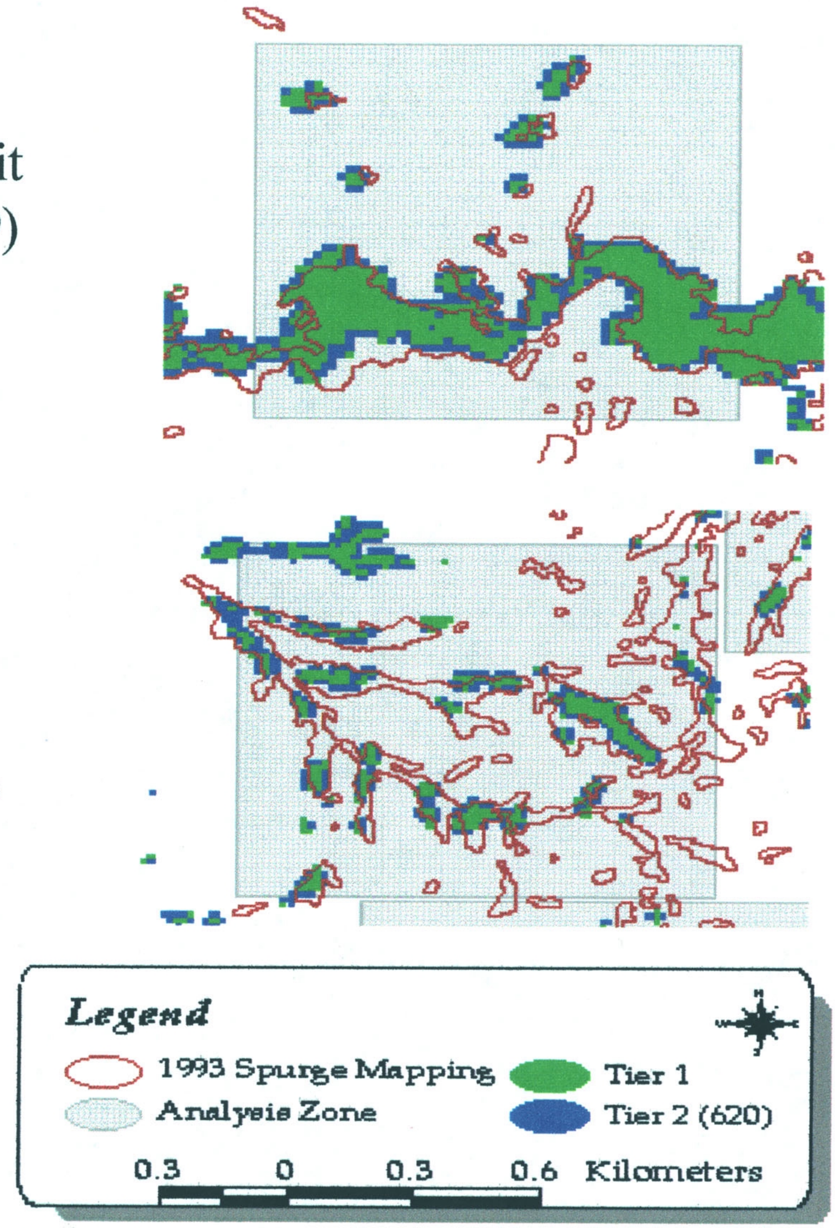

Figure 6. Map of Zones 9 and 4 showing a good fit of predicted weed distribution and example of a poor fit.