Using Aerial Photography and GIS to Map the Forest-Tundra Ecotone in Rocky Mountain National Park, Colorado, for Global Change Research

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Abstract

Ecotones could be useful locations to monitor the potential effects of global change on the biosphere. The GRASS GIS and scanned, orthorectified aerial photography were used in combination with extensive ground-truthing to map and analyze the major zones (e.g., patch forest, krummholz) and zone limits within the forest-tundra ecotone of Rocky Mountain National Park in the Colorado Front Range. Only a small percentage of the 1,092-km length of zone limit-lines, and the 19,520 ha within the patch forest and krummholz zones, bears evidence of recent disturbance, in contrast to forest-tundra ecotones in arctic locations. The ecotone is patchy and the scale of patchiness is similar in the krummholz and patch forest zones, although krummholz patchiness is derived more from rock outcrops and meadow/wetland areas and less from natural disturbance than is the case for the patch forest zone. Scanned aerial photography may be useful for GIS analyses of ecotones and detection of global change, but spectral variation among photographs, the need for adequate ground control and DEM precision for accurate orthorectification, and the errors introduced through digitizing and interpretation are limitations.

Introduction

The response of natural ecosystems to global change may in the short term be complex and subtle (Ojima *et al.*, 1991), although in the long term major shifts in the distribution of biomes can be expected (Emanuel *et al.*, 1985; Smith *et al.*, 1992). The response may also be spatially heterogeneous, with some parts of the landscape responding more rapidly than others, because different environments may promote or discourage a response, and because the timing and spatial pattern of natural disturbances in part controls the rate of response (Payette and Gagnon, 1985; Overpeck *et al.*, 1990; Baker, 1993). Yet relatively little is known about how spatial variation in the environment and disturbances control the pattern of response in different landscapes.

Both remote sensing and geographic information systems (GIS) will have to play an essential role as tools for detecting, quantifying, and analyzing the spatial response of landscapes to global change. Substantial effort has already been expended to establish Long-Term Ecological Research (LTER) sites in the United States and elsewhere that will have sufficient remote sensing capabilities and GIS databases to be able to detect the effects of global change (Dyer *et al.*, 1988; Franklin *et al.*, 1990). However, some ecological phenomena will require special monitoring efforts using remote sensing and GIS techniques.

Ecotones (boundary zones between major ecosystems) are thought to be sensitive to global change and are important components of landscapes (Holland *et al.*, 1991; Hansen and di Castri, 1992), but may require special monitoring and analysis techniques (Johnston and Bonde, 1989; Johnston *et al.*, 1992). For example, the forest-tundra ecotone (FTE) may respond to global change by a lateral expansion of patches of trees, establishment of new trees in tundra, and/or by vertical growth of trees (Daly and Shankman, 1985; Vale, 1987; Slatyer and Noble, 1992). Although the major features of the FTE can be mapped using satellite imagery (e.g., Walsh *et al.*, 1989), changes in the FTE may be difficult to detect over short time periods with the spatial resolution of current satellite sensors. In this study it was determined that groups of trees and the difference between stunted trees and tundra can be detected and mapped using high altitude color infrared (CIR) aerial photography. These essential features of the FTE were identified and mapped using the CIR photographs (1:40,000 scale) available as part of the National Aerial Photography Program (NAPP) of the U.S. Geological Survey. However, there are limitations to the use of CIR photographs for mapping and analysis with GIS, including limited spectral resolution, geometric distortion, errors introduced through digitizing and interpreting the ecotone, and limited temporal coverage (Bolstad *et al.*, 1990; Bolstad, 1992).

In this paper, an application of the use of GIS and scanned aerial photography for mapping the FTE in Rocky Mountain National Park (RMNP), Colorado, is presented as a basis for further global change research. An analysis of the ecotone, and an assessment of the implications of this analysis for research on the effects of global change in the FTE, are also presented.

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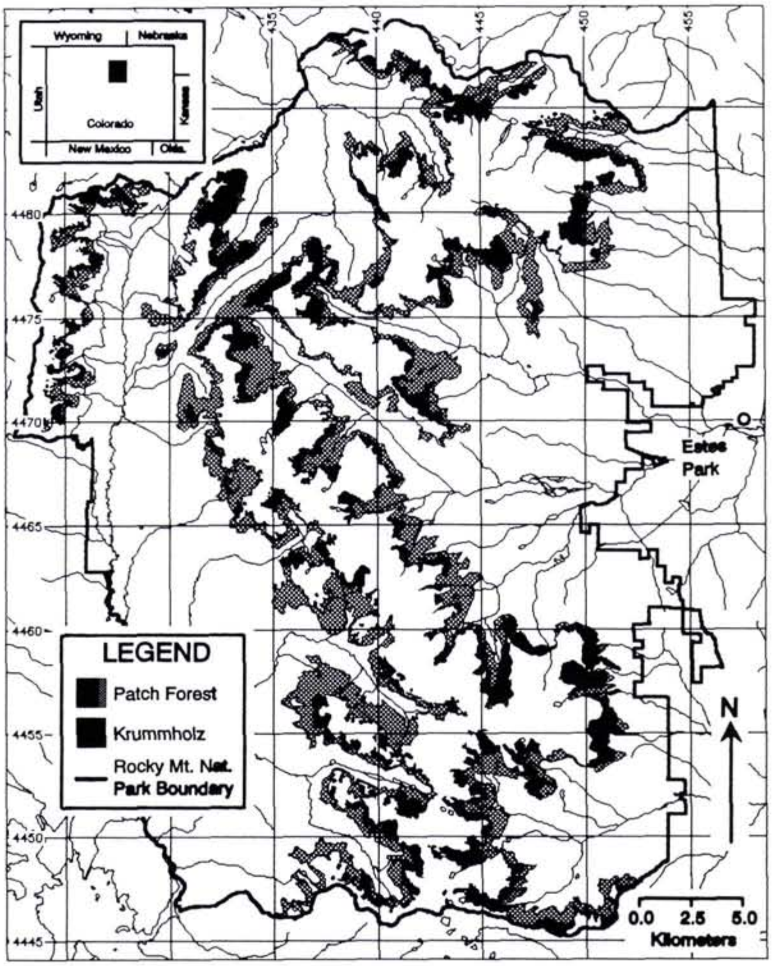

Figure 1. The study area is Rocky Mountain National Park. Grid lines are Universal Transverse Mercator lines at 5-km intervals. Only the two major zones of the forest-tundra ecotone are illustrated, as the boundaries for the other two zones (tundra zone and closed forest zone) are simply defined as buffers around these two main zones.

Methods

The study area consists of all the area within the FTE inside the borders of Rocky Mountain National Park (Figure 1). Stereo coverage of the FTE areas of RMNP was obtained with 1988 and 1990 CIR NAPP photographs (1:40,000 scale). A total of 65 photographs was acquired, but stereo coverage was not needed for the actual maps; a subset of 31 photographs provided minimum contiguous coverage of the FTE area. The 31 photographs were scanned at 200 dots per inch (approximately a 5-m resolution pixel) using a Howtek Scanmaster 3+ scanner (Howtek, Inc., Hudson, New Hampshire) in 3-band 24-bit color, and then input into the GRASS geographic information system (USA-CERL, 1991) on a Sun Sparcstation 1 workstation (Sun, Inc., Mountain View, California) where a color composite was created.

Each color composite was orthorectified using the GRASS i.ortho.rectify program. This program, which requires precise camera calibration data and a digital elevation model (DEM), effectively removes the radial, tilt, and relief distortion inherent in aerial photographs (Wolfe, 1983; Bolstad, 1992) and allows the photograph to be registered to a topographic map or other planimetric map. Standard U.S. Geological Survey topographic maps (1:24,000 scale) and 30-m resolution DEMs were used (U.S. Geological Survey, 1987).

There is error associated with orthorectification using standard U.S. Geological Survey maps and DEMs (1) due to imprecise location and digitization of control points on both the map and image, (2) because National Map Accuracy Standards also allow some errors in the topographic maps to which the image is registered, and (3) because the DEM has a coarser resolution than the scanned aerial photographs and also contains error. Average root-mean-square (RMS) error for the 31 orthorectified photographs was 14.27 m with a range of 8.96 to 18.54 m. This compares favorably with United States National Map Accuracy Standards (NMAS) which specify "...a 13-m error limit for 90 percent of the well-identified points on a 1:24,000-scale map" (Bolstad, 1992, p. 376). Chen and Lee (1993) were able to obtain RMS errors of 6.5 to

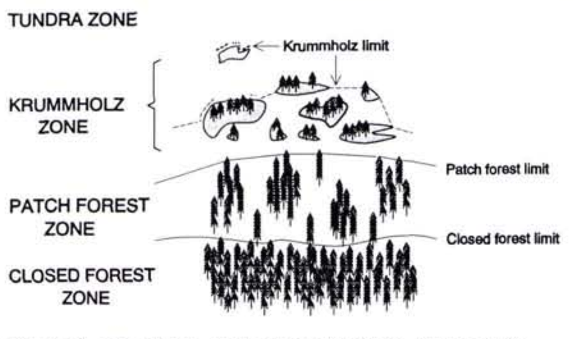

Figure 2. The lines and zones used to demarcate the major components of the forest-tundra ecotone.

6.6 m from orthorectification of a SPOT image. However, they had larger scale (1:5,000-scale) base maps from which to obtain ground control point locations, and they had DEMs with less positional error. Similar locational precision can be obtained using the Global Positioning System (GPS) (Clavet *et al.*, 1993). The U.S. Geological Survey is now producing black-and-white digital orthophotographs which will meet the NMAS for 1:12,000-scale maps (U.S. Geological Survey "Digital Orthophotos" factsheet). Locational errors of less than 1 m are attainable for these digital orthophotos if sufficiently precise ground control points and DEMs can be obtained (Light, 1993; Logan, 1993).

After the photographs had been orthorectified, they were trimmed to remove overlap and then patched together into a single mosaic for the whole FTE study area. This mosaic has a 5-m pixel resolution and overall dimensions of 50.35 km by 32.52 km (10,070 rows by 6,504 columns), requiring 65.5 megabytes of storage space in the GRASS GIS.

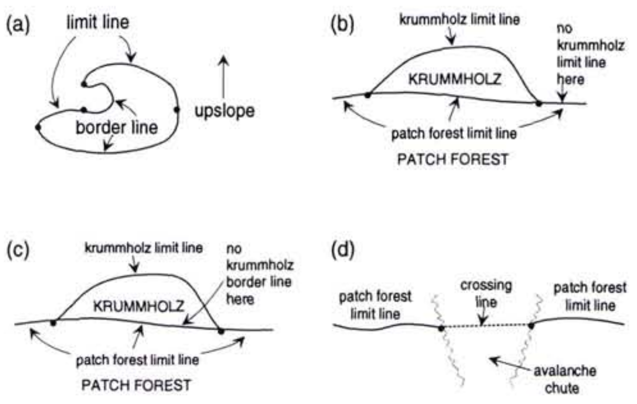

Figure 3. Mapping conventions used to interpret and digitize the components of the forest-tundra ecotone. (a) There is only one limit line for each location along a slope, but there may be more than one border line. (b) Limit lines are present only if the zone is present, so they may be discontinuous along a slope. (c) Border lines are not drawn if the limit line for the next lower zone is present where the border line would go. (d) Crossing lines are straight lines drawn across natural disturbance areas or where known environmental factors deflect or prevent tree growth.

The FTE was divided into "zones" by "limit lines" that could be identified on the aerial photographs (Figure 2). These limit lines and the resulting zones are based upon the growth form and patchiness of the trees (Arno and Hammerly, 1984). The closed forest limit is the upper elevational limit of closed forest, with erect, dense trees. The patch forest limit is the upper elevational limit of erect, patchy trees. The krummholz limit is the upper elevational limit of dwarfed, flagged, and cushion forms of tree species that become treelike on more favorable sites. The areas above, below, and between these limit lines comprise four zones (Figure 2).

About 95 percent of these limit lines were mapped in the field using binoculars from high elevation observation points. Lines were drawn in the field on mylar overlays on the stereo photographs with the aid of a mirror stereoscope. However, for about 5 percent of the lines, a location for direct observation could not be reached. All the lines mapped on the NAPP CIR photographs (1:40,000 scale) were subsequently checked using vertical color aerial photographs (1: 15,000 scale) taken specifically for RMNP in 1987. In only a few instances did these larger-scale photographs reveal a need for revising the field-mapped lines. The 5 percent of the lines not field-mapped were drawn under a mirror stereoscope using these larger-scale photographs. The lines were then digitized using the GRASS GIS, with the orthorectified 5-m resolution aerial photograph mosaic as a backdrop.

A number of mapping conventions were adopted for digitizing, so that future researchers could more precisely duplicate the methods and discern changes in these lines and zones. A snapping threshold of 5 m (points closer than this are merged into a single point) was used. *Limit lines* were defined as having the following properties. First, limit lines represent the single uppermost limit of each zone at each position along a slope; there is, therefore, no more than one closed forest limit line, patch forest limit line, or krummholz limit line for each location along a slope. As a result, limit lines do not fold under (Figure 3a). Second, the limit line is absent if the corresponding zone is absent; thus limit lines may be discontinuous along a slope (Figure 3b). The limit lines are of interest themselves, because of their utility in analyzing spatial variation in the components of the FTE. However, to obtain information about the zones, other lines had to be added to the limit lines to make closed polygons encompassing the zones. *Border lines* were defined as the other lines needed to make closed polygons (Figure 3a). Border lines must complete polygons, but, unlike limit lines, they can fold under or over if there is a limit line above (Figure 3a). Border lines are only present if there is not a limit line for the next lower zone where a border line would ordinarily be (Figure 3c). Limit lines and border lines were continuous on most uniform slopes, but sometimes were deflected or interrupted by natural disturbances (e.g., snow avalanche tracks) and certain obvious physical features (e.g., lakes). *Crossing lines* were defined as lines that cross known natural disturbances or permanent environmental features (Table 1). These lines were drawn as straight lines beginning at the first place a limit line or border line was affected by disturbance or a deflecting environment (Figure 3d). Occasionally, lines must follow ridgelines in order to remain continuous, but ridgelines seldom represent true elevational limits. Lines were mapped along ridgelines only as border lines. Finally, a 30-m minimum distance standard was adopted for drawing

TABLE 1. LENGTHS (KM) OF BORDER LINES AND LIMIT LINES IN ROCKY MOUNTAIN NATIONAL PARK BY FTE ZONE. THE PERCENTAGE OF THE TOTAL BORDER OR LIMIT LINE LENGTH IS GIVEN IN PARENTHESES BELOW THE LENGTH.

	Closed Forest Border	Closed Forest Limit	Patch Forest Border	Patch Forest Limit	Krummholz Border	Krummholz Limit	Total
Uninterrupted	48.30	357.35	77.18	409.91	96.11	269.08	1257.93
	(84.2)	(91.2)	(86.5)	(96.5)	(86.7)	(98.3)	(93.3)
Avalanche chute crossing	—	12.81	0.19	6.51	—	0.84	20.35
	—	(3.3)	(0.2)	(1.5)	—	(0.3)	(1.5)
Mass movement/talus crossing	—	7.04	0.37	4.45	—	1.84	13.70
	—	(1.8)	(0.4)	(1.0)	—	(0.7)	(1.0)
Burn crossing	—	6.90	—	1.77	—	—	8.67
	—	(1.8)	—	(0.4)	—	—	(0.6)
Meadow/wetland crossing	0.30	2.01	—	0.56	—	0.08	2.95
	(0.5)	(0.5)	—	(0.1)	—	(0.0)	(0.2)
Lake crossing	0.47	1.05	—	1.26	—	1.61	4.39
	(0.8)	(0.3)	—	(0.3)	—	(0.6)	(0.3)
Rock outcrop crossing	0.16	4.46	—	0.34	—	0.27	5.23
	(0.3)	(1.1)	—	(0.1)	—	(0.1)	(0.4)
Ridgeline	8.13	—	11.52	—	14.73	—	34.38
	(14.2)	—	(12.9)	—	(13.3)	—	(2.6)
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Total	57.36	391.62	89.26	424.80	110.84	273.72	1347.60

the lines. First, adjoining patches of the same zone were connected if they were less than 30 m apart at their closest points. Second, adjoining zones were connected if the component patches were less than 30 m apart at their closest points. Gaps greater than 30 m were not crossed when drawing lines.

In addition to the FTE line analysis, the areas within the FTE were also analyzed. To determine the fraction of the closed forest zone occupied by natural disturbances and permanent features, a 500-m buffer was placed downslope from the closed forest limit. Closed forest extends below this buffer, but the purpose of this analysis was to determine the features of the closed forest zone adjoining the patch forest or krummholz zone. Similarly, a 100-m buffer was added upslope of the upper limit of the FTE so that the characteristics of the alpine area adjacent to the FTE could be identified. A smaller buffer was used here because there often was not much alpine area above the FTE. The major kinds of natural disturbances and permanent features (Table 2) within the entire area from the lower limit of the closed forest buffer to the upper limit of the alpine buffer were mapped and digitized using the stereo photographs and the GRASS GIS. A minimum mapping unit of 1 ha was used.

Several GRASS programs were used to complete the analyses. The GRASS v.report command was used to determine the lengths of each type of line, while the r.report command was used to determine the areas of each part of the FTE. The r.le programs (Baker and Cai, 1992) were used to calculate the density, size, shape, and amounts of perimeter of the patches that comprise the FTE. A patch is simply one of the polygons comprising the map of the FTE areas, which includes the major zones, natural disturbances, and permanent features (Table 2).

TABLE 2. AREAS (KM^2) COVERED BY NATURAL DISTURBANCES AND PERMANENT FEATURES IN ROCKY MOUNTAIN NATIONAL PARK BY FTE ZONE. THE PERCENT COVER WITHIN EACH ZONE IS GIVEN IN PARENTHESES BELOW THE AREA.

	Closed Forest	Patch Forest	Krummholz	Total	Adjacent Alpine
Uninterrupted	150.32	92.14	47.78	290.24	—
	(87.2)	(74.1)	(67.4)	(79.0)	—
Avalanche chutes	2.54	3.33	1.05	6.92	0.35
	(1.5)	(2.7)	(1.5)	(1.9)	(0.6)
Mass movement/talus	2.08	4.83	3.75	10.66	13.00
	(1.2)	(3.9)	(5.3)	(2.9)	(23.5)
Burn	9.85	5.69	0.50	16.00	0.33
	(5.7)	(4.6)	(0.7)	(4.4)	(0.6)
Meadow/wetland	4.41	8.85	8.68	21.91	4.23
	(2.6)	(7.1)	(12.2)	(6.0)	(7.6)
Lake	0.72	1.13	0.65	2.50	0.42
	(0.4)	(0.9)	(0.9)	(0.5)	(0.8)
Rock outcrop	2.38	8.33	8.49	19.20	18.12
	(1.4)	(6.7)	(12.0)	(5.2)	(32.7)
Herbaceous veg.	—	—	—	—	14.19
	—	—	—	—	(25.6)
Patchy rock outcrop/	—	—	—	—	4.75
Herbaceous veg.	—	—	—	—	(8.6)
Total	172.30	124.30	70.90	367.43	55.39

Results

There is a total length of about 1,348 km of FTE border and limit lines in RMNP, with most of this total (81 percent) being limit lines (Table 1). A slightly larger percentage of the 1,092 km of limit line length is patch forest limit (39 percent) than is closed forest limit (36 percent) or krummholz limit (25 percent). In contrast, more of the border line length is krummholz border than is patch forest or closed forest border. The krummholz zone is less continuous than are the other zones, and, as a result, there are more of the discrete patches that have border lines.

Most of the border and limit line length (93 percent) is uninterrupted by permanent features or disturbed areas. Permanent features (i.e., meadow/wetland areas, lakes, and rock outcrops) interrupt the border and limit lines over only 0.9 percent of their length. Both rock outcrop and wetland/meadow interruptions decrease upwards, while lake interruptions increase upwards in elevation from forest to krummholz (Table 1).

Only 3.1 percent of the total length of border and limit lines is recently disturbed. Among the disturbances that interrupt the FTE, avalanche chutes account for the greatest percentage (1.5 percent) of the total border and limit line length, followed by mass movements and talus slopes (1.0 percent) and recent burns (0.6 percent). For all three disturbance types, and for the total of the three disturbance types, the length of disturbed lines decreases upwards in elevation from forest limit to patch forest limit to krummholz limit. There were 135 separate avalanche-chute crossings, 64 mass-movement and talus-slope crossings, and 14 burn crossings in the whole FTE. However, a single disturbance may be represented in these figures by more than one crossing, as there may be, for example, both a patch forest crossing line and a krummholz crossing line for the same disturbance.

The area analyses produced somewhat different results (Table 2). The area of patch forest within RMNP is 12,430 ha, while krummholz occupies 7,090 ha. The reported area of closed forest and adjacent alpine (Table 2) are not estimates of the amount of these ecosystems within RMNP as these figures represent only the area within the 500-m closed forest and 100-m alpine buffers. The 19,520 ha within the two main zones of the FTE makes up about 18 percent of RMNP's total area.

Most of the FTE area (79 percent) is uninterrupted by permanent features or natural disturbances, although the amount of uninterrupted area decreases from closed forest to krummholz (Table 2). Permanent features interrupt about 11.7 percent of the FTE area, with both meadow/wetland area and rock outcrop area several times more abundant in the patch forest and krummholz than in the closed forest. About 9.2 percent of the FTE area has been recently disturbed, with almost half of that area (4.4 percent) burned, and with lesser amounts of area disturbed by avalanches and mass movements. The highest percentage of burned area is in the closed forest (5.7 percent), with a slightly lower percentage of the patch forest recently burned (4.6 percent) and with very little of the krummholz burned (0.7 percent). The area occupied by mass movement/talus, in contrast, increases upwards from closed forest to alpine, while the amount of area disturbed by avalanches is highest in the patch forest zone. The alpine area adjacent to the upper limit of the FTE has a high percentage of rock outcrops (32.7 percent) and mass movement/talus areas (23.5 percent), and lesser amounts of meadow/wetland area and herbaceous vegetation.

The line and area analyses produced different estimates of the amount of the FTE interrupted by permanent features and natural disturbances, but these differences derive from two sources. First, in interpreting the aerial photographs, "interruptions" of FTE lines were in practice limited to rather small displacements of an otherwise uniform limit line. When an FTE line followed the lower limit of a rock outcrop or mass movement/talus area over an extensive length, this was not interpreted as an interruption. There is considerable ambiguity in determining what is or is not an interruption of a limit line. This problem is mostly confined to rock outcrops and mass movement/talus interruptions as these often follow horizontally along the upper limit of the FTE. It is less a problem for avalanche chutes, burns, meadow/wetland areas, and lakes as these usually are confined to short lengths and cut across limit lines. Thus, the line analysis probably underestimates the amount of line length affected by rock outcrops and mass movement/talus areas and to a lesser extent other interruptions. Second, there is undoubtedly a real difference between the amount of limit/border line length and total FTE area interrupted by permanent features and disturbances. Only 14 of the 25 discrete fire patches in the total FTE area, for example, happen to intersect an FTE limit or border line. Similarly, there is little meadow/wetland interruption of the limit lines (Table 1), even though meadow/wetland areas occupy 6 percent of the FTE area (Table 2). The line and area analyses are thus complementary and measure slightly different aspects of the forest-tundra ecotone.

There are 2819 patches in the patch forest and krummholz zones of the RMNP FTE. A patch is a polygon representing one of the major kinds of natural disturbances or permanent features in each zone (Table 2). The patch forest and krummholz zones are remarkably similar in terms of the density of patches and their average size and shape, which is slightly elongated (Table 3). There are more patches in the patch forest zone and there is more perimeter length (Table 3), but this is only because the patch forest zone occupies more total area (Table 2). However, the source of patchiness in the two zones is different; there is much more patchiness from permanent features, especially rock outcrops and meadow/wetland areas, in the krummholz zone than in the patch forest zone, and there is a little less patchiness from disturbance in the krummholz zone (Table 2). The closed forest zone tends to have larger patches, and thus lower density, and has patches with more compact shapes and less perimeter than is the case for the patch forest and krummholz zones (Table 3), primarily because there are fewer small, permanent features interrupting the closed forest zone (Table 2).

Discussion

Mapping Ecotones Using Scanned Aerial Photographs

Substantial research has been done on methods for detecting and quantifying ecotones using satellite imagery (e.g., Johnston *et al.*, 1992). However, in our experience these images do not currently have sufficient spatial resolution to enable detection of the kinds of short-term changes that might characterize the initial response of the FTE to global change. NAPP CIR photographs (1:40,000 scale) were found to be adequate for mapping the FTE zones, but photographs as fine as or finer than 1:15,000 scale will be necessary to detect significant changes in tree growth, tree mortality, and tree density that probably will occur in the early stages of ecotone response to global change.

There are problems in using scanned aerial photographs for analyses of large areas, such as RMNP, for global change research. First, orthorectification is essential to remove most of the distortion inherent in aerial photographs, so that the photographs will be nearly planimetric (Bolstad, 1992). In the case of some of the 31 photographs, it was difficult to locate sufficient control points, identifiable on both the aerial photographs and topographic maps, to complete the orthorectification, particularly in the mountainous and undeveloped parts of RMNP. Second, the amount of positional error (8.96 to 18.54 m RMS error) may be too large for adequate detection of short-term changes in FTE location. Current GPS technology could be used to decrease this error by one-half or more, but it would have been too time-consuming and expensive, for this project, to obtain an adequate number of GPS control points for orthorectifying the 31 photographs. Third, the process of scanning and orthorectifying aerial photographs is time consuming. It required about 5 hrs to scan each photograph into GRASS and complete the orthorectification. In the case of this study, the required time was manageable for the 31 NAPP CIR photographs required for minimum coverage of the RMNP FTE, but the time required precluded use of the more than 100 1:15,000-scale photographs for the same area. Finally, one of the most significant limitations in

Table 3. Landscape Structure Indices for the FTE in RMNP. Mean Patch Shape Uses the Corrected Perimeter/Area Index (Baker and Cai, 1992), in Which Values Vary from 0.0, for a Circle, to Infinity. A Square Has the Value 1.1. The Sum of the Perimeters Is The Sum of the Total Amount of Perimeter for Each Patch, Including Limit Lines and Border Lines.

	Closed Forest	Patch Forest	Krummholz
Number of patches	1201	1788	1031
Density of patches (No./1000 ha)	70	144	145
Mean patch size (ha)	81.5	61.6	66.2
Mean patch shape	1.53	1.73	1.79
Sum of perimeters (km)	1293	2444	1468
Mean perimeter length (km)	1.08	1.37	1.42

Number of patches by *size class (ha):*

	0.0–22.5	22.6–45.0	45.1–67.5	67.6–90.0	90.1–112.5	112.6–135.0	135.1–157.5	157.6+
Closed forest	977	79	48	15	12	11	10	49
Patch forest	1308	165	82	52	33	20	16	112
Krummholz	591	148	81	41	29	15	15	111

Number of patches by shape index class:

	0.5–1.0	1.1–1.5	1.6–2.0	2.1–2.5	2.6–3.0	3.1–3.5	3.6–4.0	4.1+
Closed forest	9	798	196	84	54	36	8	16
Patch forest	2	930	456	187	96	41	23	53
Krummholz	0	423	327	163	64	20	12	22

using scanned aerial photographs for global change research is that each photograph has a different spectral representation of the same features, as the light conditions and the position of the camera change from photograph to photograph. Although there are methods for correcting a set of adjoining photographs to a common spectral representation, they are not simple and GRASS does not have this capability. As a result, it is more difficult to use objective ecotone detection methods to identify and map ecotone locations across several photographs of a large area, as is possible within a single satellite image of a large area (Johnston *et al.*, 1992). It was possible to digitize the FTE lines across orthophotograph boundaries on screen in spite of spectral differences. The digitized lines, however, do contain more human subjectivity than is the case with more objective ecotone identification algorithms.

Natural Disturbance in the RMNP FTE

Although disturbance may be a salient feature of the forest-tundra ecotone environment in some areas (e.g., Veblen, 1979) and control its location, only a small percentage of the FTE lines and areas in RMNP have been affected by recent disturbances, such as snow avalanches, mass movements, and fires. Snow avalanche paths are numerous, but are usually relatively narrow. Mass movement tracks are generally wider than are avalanche paths, but are fewer. There are only about 25 recent burns in the FTE, although some of the burns affect a wide swath of the FTE. The krummholz zone, in general, and the krummholz limit, in particular, are not greatly affected by natural disturbances other than mass movement/talus areas (Tables 1 and 2). The prevalence of rock outcrops and mass movement/talus areas in the alpine area adjacent to the upper limit of the FTE (Table 2) suggests that rockiness strongly influences the location of the upper FTE limit. It is not easy to determine from the aerial photographs whether individual talus areas are or are not producing active disturbances that discourage tree growth; thus, it remains unclear as to whether it is the rockiness itself or mass movement of the rocks that characterizes the adjacent alpine area in the mass movement/talus areas.

These data suggest that the FTE in RMNP is not a very disturbance prone environment, although there are limits to these data. Perhaps larger percentages of the FTE lines and areas were disturbed in exceptional episodes in the past and have recovered sufficiently so that evidence of disturbance is not visible now in aerial photographs. For example, episodes of exceptional mass movement have been associated with earthquakes elsewhere (Veblen and Ashton, 1978). There was also a period of exceptionally high fire frequency associated with European settlement of the Front Range in the latter part of the nineteenth century (Veblen and Lorenz, 1991). However, trees re-establish slowly in the FTE due to the adverse climate, and evidence of canopy-destructive natural disturbance in the FTE is generally apparent for decades or even more than 100 years. For example, the fire that in the 1850s burned the upper reaches of Sundance Creek in RMNP (Willard and Foster, 1990) is still very visible on our 1990 aerial photographs. Another kind of disturbance, by the spruce beetle, could also have affected the FTE in the past. A spruce beetle outbreak is known to have killed *Picea engelmannii* (Engelmann spruce) over a large part of the southern Rocky Mountains in the last half of the nineteenth century (Baker and Veblen, 1990). Evidence of this outbreak is not visually apparent today. Nonetheless, with the exception of disturbance by spruce beetle, the data presented here do not seriously underestimate the percentage of the FTE lines affected by canopy-destructive natural disturbances over the last century. However, detailed field research is really necessary to identify disturbances of lesser severity that may not have destroyed the forest canopy (Lorimer, 1985).

The alpine FTE in RMNP may be less disturbance prone than are other FTEs. Fire frequency in Rocky Mountain subalpine forests is relatively low (Romme, 1982) compared to fire frequency in the arctic FTE in Canada (Payette *et al.*, 1989). The area affected by snow avalanches in the RMNP FTE is probably low because of a low average snowfall compared to that in other parts of the western United States. The probability of mass movements is also low, as RMNP contains relatively stable Precambrian igneous and metamorphic rocks, and is not in a tectonically active area (Braddock and Cole, 1990).

Landscape Structure in the FTE

The FTE is comprised of patches of krummholz and patch forest (Table 3). The FTE is patchy in part because continuous reaches of forest are interrupted by drainage divides, rock outcrops, and other permanent features, as well as natural disturbances. Given the relatively small percentage of FTE line lengths (Table 1) and area (Table 2) that is recently disturbed, a substantial part of the patchiness in the FTE is the result of the dissected terrain, containing rock outcrops, lakes, and wetlands resulting from past orogeny and Pleistocene glaciation. Patchiness appears to increase with elevation, even on smooth topographic surfaces, suggesting that adverse climate also tends to be associated with increased patchiness.

The patchiness of the ecotone may influence the response of the ecotone to global change. It can be hypothesized that, if the ecotone responds to climatic change by increased height growth and lateral expansion of krummholz patches (e.g., Vale, 1987), then the density of patches, and their size, shape, and amount of perimeter, will influence how rapidly and in what manner the ecotone responds. Similar levels of patchiness characterize both patch forest and krummholz zones (Table 3), suggesting that from the standpoint of patchiness there is comparable potential for a response to change in these two zones.

Sensitivity of the FTE to Global Change

It is unclear whether FTEs less prone to disturbance, such as the RMNP FTE, will be sensitive locations that will respond rapidly to global change. One perspective is that natural disturbance may hasten the response of FTE position and structure to climatic change (Sirois and Payette, 1991). Low-disturbance environments, such as the RMNP FTE, may then respond less rapidly to climatic change, as trees may persist, due to long lifespans and asexual regeneration, in locations that become climatically unfavorable for successful regeneration by seedlings (Elliott-Fisk, 1983; Hansen-Bristow and Ives, 1984). Another perspective is that patterns of tree regeneration and growth in the RMNP FTE may be more climatically controlled than in FTEs and other ecotones subject to greater disturbance. As a result, short-term growth and demographic processes may be more directly influenced by climatic fluctuations in the RMNP FTE than in FTEs recovering from recent disturbances. However, the prevalence of rocky areas adjacent to the current upper FTE limit suggests that physical barriers to tree establishment may also be important in controlling FTE limits in RMNP. Additional research will be required to determine which kinds of ecotone and which locations within ecotones may be most sensitive to global change.

Conclusions

Scanned aerial photography, extensively ground-truthed, was used to map and analyze the FTE in RMNP. The major limitations of this map are the remaining positional error that could not be removed from the photographs without more expensive and time-consuming methods of obtaining ground control, the errors introduced through digitizing, and the human subjectivity that influenced the placement of the FTE lines. Nonetheless, the FTE lines and zones are probably more precisely identified and mapped than would have been the case had currently available satellite imagery been utilized, assuming the same method of orthorectification, due to the greater spatial resolution (< 1 m) available in the aerial photographs (Light, 1993) for the field mapping phase of the project.

Research directed at understanding how vegetation will respond to global change may require several scales of study, including detailed field studies and broader-scale remote sensing and GIS analyses. It will require detailed field studies, for example, to determine whether the RMNP FTE is likely to be sensitive to climatic fluctuations, how it may respond, and whether some settings are more sensitive than others. The FTE map will be used to select a spatially stratified sample for the field research phase of our analysis of the potential effects of global change on the RMNP FTE. The GIS will also be used to analyze the relationship of the FTE lines, zones, and patches with environmental factors.

This study suggests that scanned aerial photography, together with GIS and remote sensing tools, may enable timely detection and analysis of the kinds of changes in ecotones that may precede their actual movement in response to global change, but there remain limitations in obtaining sufficient locational precision, and there will be difficulties in using this approach over large areas until a national program for the uniform production of color digital orthophotographs is fully implemented.

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References

Arno, S.F., and R.P. Hammerly, 1984. *Timberline: Mountain and Arctic Frontiers*, The Mountaineers, Seattle, 304 p.

Baker, W.L., 1993. Spatially heterogeneous multi-scale response of landscapes to fire suppression, *Oikos*, 66:66–71.

Baker, W.L., and Y. Cai, 1992. The r.le programs for multiscale analysis of landscape structure using the GRASS geographical information system, *Landscape Ecology*, 7:291–302.

Baker, W.L., and T.T. Veblen, 1990. Spruce beetles and fires in the nineteenth-century subalpine forests of western Colorado, U.S.A., *Arctic and Alpine Research*, 22:65–80.

Bolstad, P.V., 1992. Geometric errors in natural resource GIS data: tilt and terrain effects in aerial photographs, *Forest Science*, 38: 367–380.

Bolstad, P.V., P. Gessler, and T.M. Lillesand, 1990. Positional uncertainty in manually digitized map data, *International Journal of Geographical Information Systems*, 4:399–412.

Braddock, W.A., and J.C. Cole, 1990. *Geologic map of Rocky Mountain National Park and Vicinity, Colorado*, U.S. Department of Interior, U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1973.

Chen, L.-C., and L.-H. Lee, 1993. Rigorous generation of digital orthophotos from SPOT images, *Photogrammetric Engineering & Remote Sensing*, 59:655–661.

Clavet, D., M. Lasserre, and J. Pouliot, 1993. GPS control for 1: 50,000-scale topographic mapping from satellite images, *Photogrammetric Engineering & Remote Sensing*, 59:107–111.

Daly, C., and D. Shankman, 1985. Seedling establishment by conifers above tree limit on Niwot Ridge, Front Range, Colorado, U.S.A., *Arctic and Alpine Research*, 17:389–400.

Dyer, M.I., F. di Castri, and A.J. Hansen, 1988. Geosphere- biosphere observatories: their definition and design for studying global change, *Biology International*, Special Issue 16.

Elliott-Fisk, D.L., 1983. The stability of the northern Canadian tree limit, *Annals of the Association of American Geographers*, 73: 560–576.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson, 1985. Climatic change and the broad-scale distribution of terrestrial ecosystem complexes, *Climatic Change*, 7:29–43.

Franklin, J.F., C.S. Bledsoe, and J.T. Callahan, 1990. Contributions of the long-term ecological research program, *BioScience*, 40:509–523.

Hansen, A.J., and F. di Castri (editors), 1992. *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows*, Springer-Verlag, New York, 452 p.

Hansen-Bristow, K.J., and J.D. Ives, 1984. Changes in the forest-alpine tundra ecotone: Colorado Front Range, *Physical Geography*, 5:186–197.

Holland, M.M, P.G. Risser, and R.J. Naiman, 1991. *Ecotones: The Role of Landscape Boundaries in the Management and Restoration of Changing Environments*, Chapman and Hall, New York, 142 p.

Johnston, C.A., and J. Bonde, 1989. Quantitative analysis of ecotones using a geographical information system, *Photogrammetric Engineering & Remote Sensing*, 55:1643–1647.

Johnston, C.A., J. Pastor, and G. Pinay, 1992. Quantitative methods for studying landscape boundaries, *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows* (Andrew J. Hansen and Francesco di Castri, editors), Springer-Verlag, New York, pp. 107–125.

Light, D.L., 1993. The National Aerial Photography Program as a geographic information system resource, *Photogrammetric Engineering & Remote Sensing*, 59:61–65.

Logan, B.J., 1993. Digital orthophotography bolsters GIS base for wetlands project, *GIS World*, June: 58–60.

Lorimer, C.G., 1985. Methodological considerations in the analysis of forest disturbance history, *Canadian Journal of Forest Research*, 15:200–213.

Ojima, D.S., T.G.F. Kittel, T. Rosswall, and B.H. Walker, 1991. Critical issues for understanding global change effects on terrestrial ecosystems, *Ecological Applications*, 1:316–325.

Overpeck, J.T., D. Rind, and R. Goldberg, 1990. Climate-induced changes in forest disturbance and vegetation, *Nature*, 343:51–53.

Payette, S., and R. Gagnon, 1985. Late Holocene deforestation and tree regeneration in the forest-tundra of Québec, *Nature*, 313: 570–572.

Payette, S., C. Morneau, L. Sirois, and M. Desponts, 1989. Recent fire history of the northern Québec biomes, *Ecology*, 70:656–673.

Romme, W.H., 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park, *Ecological Monographs*, 52: 199–221.

Sirois, L., and S. Payette, 1991. Reduced postfire tree regeneration along a boreal forest-forest-tundra transect in northern Québec, *Ecology*, 72:619–627.

Slatyer, R.O., and I.R. Noble, 1992. Dynamics of montane treelines, *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows* (Andrew J. Hansen and Francesco di Castri, editors), Springer-Verlag, New York, pp. 346–359.

Smith, T.M., H.H. Shugart, G.B. Bonan, and J.B. Smith, 1992. Modeling the potential response of vegetation to global climate change, *Advances in Ecological Research*, 22:93–116.

USA-CERL, 1991. *GRASS Version 4.0 (Geographic Resources Analysis Support System) User's Reference Manual*, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois, 513 p.

U.S. Geological Survey, 1987. *Digital Elevation Models*, National Mapping Program, Technical Instructions, Data Users Guide 5, Reston, Virginia.

Vale, T.R., 1987. Vegetation change and park purposes in the high elevations of Yosemite National Park, California, *Annals of the Association of American Geographers*, 77:1–18.

Veblen, T.T., 1979. Structure and dynamics of *Nothofagus* forests near timberline in south-central Chile, *Ecology*, 60:937–945.

Veblen, T.T., and D.H. Ashton, 1978. Catastrophic influences on the vegetation of the Valdivian Andes, Chile, *Vegetatio*, 36:149–167.

Veblen, T.T., and D.C. Lorenz, 1991. *The Colorado Front Range: A Century of Ecological Change*, University of Utah Press, Salt Lake City, 186 p.

Walsh, S.J., L. Bian, D.G. Brown, D.R. Butler, and G.P. Malanson. 1989. Image enhancement of Landsat Thematic Mapper digital data for terrain evaluation, Glacier National Park, Montana, *Geocarto International*, 3:55–58.

Willard, B.E., and S.Q. Foster, 1990. *A Roadside Guide to Rocky Mountain National Park*, Johnson Books, Boulder, Colorado, 318 p.

Wolfe, Paul R., 1983. *Elements of Photogrammetry, Second Edition*, McGraw-Hill, New York, 628 p.

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