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Tree invasion within a pine/grassland ecotone: an approach with historic aerial photography and GIS modeling

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Abstract

In previous studies, evidence of tree invasion into grasslands has mainly been through comparison of historical terrestrial photographs and/or tree age data. The goal of this paper is to provide a quantitative description of the tree invasion process at a landscape scale using historical aerial photography, image processing and geographic information systems (GIS) approaches. Various map interpretive techniques provided evidence of shifts in the ponderosa pine-grassland ecotone along the Colorado Front Range since the late 1930s. Historical aerial photos were digitally scanned and the outlines of tree invasions into the grassland were determined based on gray tone density slicing. Image processing of digitized aerial photography identified areas of change in tree cover and quantified locations and total hectares of tree invasions into grassland areas. Overall, the results clearly show an increase in woodland areas where there formerly existed grasslands. GIS modeling was used to relate tree invasion patterns to topographic orientation and changes in settlement patterns. The importance of terrain aspect on rate of tree invasion is clearly shown by the greater rate of tree invasion on north-facing slopes (generally moister with less heat stress) versus south-facing slopes. The most dramatic change in the controls of vegetation patterns over the past one or two centuries has been the decline in fire frequency due to fire suppressing policy since ca. 1920. However, changes in grazing regimes may also have played an important role. When comparing these results to the instrumental climate record of the area, periods of favorable climatic conditions for seedling establishment generally correspond to periods of increased rate of tree invasion into grassland areas. © 1997 Published by Elsevier Science B.V.

Keywords: Image processing; Ponderosa pine; Colorado Front Range

1. Introduction

1.1. Ecological controls of lower timberline in the Western United States

Researchers and managers have long been interested in the phenomena of shifts in lower timberline ecotones, including tree invasions into grasslands at lower timberlines (Vale, 1975; Rogers, 1982; Veblen and Lorenz, 1988). Occurring at the extreme limits

Abbreviations: DEM, Digital Elevation Model; GIS, Geographic Information Systems; USGS, United States Geological Survey; UTM, Universal Transverse Mercator

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of tolerance for particular plant species, ecotones are regions that show more rapid ecological change (Neilson, 1993). Lower timberline ecotone refers to the lower elevational limit of forest cover, usually controlled by water availability and other climatic factors. Evidence of tree invasion usually includes a comparison of historical terrestrial photographs and/or tree age data.

During the last 10000 years in the Rocky Mountains, climatic variations affected the ecotone from the plains grasslands to the coniferous forest (Daubenmire, 1943; MacDonald, 1989). On a shorter temporal scale, many forest-grassland ecotones in the western United States appear unstable, experiencing tree invasion since the mid-1800s. For example, ponderosa pines (*Pinus ponderosa*) have invaded the prairies while junipers (*Juniperus monosperma*) have spread in both the Southwest and the Great Basin (Foster, 1917; Johnsen, 1962; Burkhardt and Tisdale, 1976; White, 1985). Along the Colorado Front Range, nineteenth century photographs of the lower ecotone show grass cover in areas currently dominated by ponderosa pines. In addition to historical photographic evidence of tree invasion, the absence of dead-standing trees, stumps, or logs along lower ecotone boundaries suggests a lack of tree cover for at least a century before Euro-American settlement (Mast, 1993).

At some sites, position of treeline, both altitudinal and latitudinal, is closely related to warm-season temperatures and amount of precipitation (Franklin et al., 1971; Agee and Smith, 1984). Along the lower ecotone of the Colorado Front Range, although ponderosa pine dominates with a wide ecological tolerance as a mature tree, low temperatures can limit ponderosa pine seedling establishment due to direct damage to tissue, freezing of soil, and through frost heaving (Schubert, 1974). In addition, frequent droughts in spring and/or competition for water with bunch grasses may limit ponderosa pine establishment at the lower timberline ecotone (White, 1985). On the other hand, periods of greatly improved water balance may favor forest expansion into grasslands (Buell and Cantlon, 1951). To test the importance of moister conditions, this study analyzes the rate of tree invasions into grasslands on moister north-facing slopes versus drier south-facing slopes.

In addition to climatic factors, disturbances such as fire and grazing also play critical roles in the development of structure, composition and function in the forest-grassland ecotone. Some researchers believe that frequent fires previously maintained grasslands in areas where forests are potentially favored by climate (Sauer, 1950; Buell and Cantlon, 1951; Vale, 1982). In many parts of North America, frequent natural or human-initiated fires maintain grass cover and limit tree invasion by killing tree seedlings (Buell and Buell, 1959; Johannessen et al., 1971; Bragg and Hulbert, 1976). With regards to the impacts of herbivores on tree seedling establishment, moderate livestock grazing may facilitate tree invasion since few seedlings are trampled, bare mineral soil is exposed, and competition from grasses is reduced. On the other hand, intense livestock grazing may prevent widespread tree invasion due to trampling and direct herbivory on seedlings and saplings (Dunwiddle, 1977). Similarly, wild mammalian herbivores may directly weaken or kill ponderosa pines by over browsing, twig cutting, partial bark stripping, or girdling of trees. For example, mule deer (*Odocoiles hemionus* crooki) and elk (*Cervus canadensis* merriami Nelson) often cause severe damage or even kill ponderosa pines by browsing on terminal shoots of small trees and by rubbing their antlers against the bark (Heidmann, 1972; Heidmann et al., 1982).

1.2. Using image processing and GIS to detect ecotone changes

With digital image processing and geographic information systems (GIS) techniques, it is possible to detect and quantitatively analyze vegetation changes along ecosystem boundaries over time. In this study, analyses of historic aerial photography with image processing and GIS methods assisted in detecting ecotonal spatial patterns at a landscape scale in the northern Colorado Front Range. These digital change detection techniques showed changes in vegetation cover and settlement patterns (cf. Johnston and Bonde, 1989) over different environmental gradients from 1938 to 1990. During this period, human activities increasingly altered lower timberline vegetation and boundary locations at the interface between urban areas and wildlands. Changes in lower ecotone habitats may in turn reflect human alterations of fire and grazing regimes, as well as periods of contrasting rainfall and temperature. Since the resulting rates of vegetation change along these ecotones depend in part on habitat type such as slope aspects, shifts in spatial distribution of trees during the past 50 + years should vary according to different environmental gradients.

Image processing and GIS techniques in this study may provide improved management programs for the Colorado Front Range. First, these techniques can visually and analytically show changes in vegetation over time, including forest invasion into grasslands (Krummel, 1987). Second, analyses of changes in urban areas and settlements in the Front Range may indicate areas of increased urban-wildland interface. Third, spatial analyses comparing wooded areas to settlement areas may assist in determining if any correlation exists between settlement patches and deforested areas. Finally, image processing and GIS techniques may show areas where management techniques, such as prescribed burning, might be used by identifying settlement densities, slope conditions, aspect, current vegetation type, and various other factors that effect burning conditions.

2. Study area

The Colorado Front Range is a north-south oriented massif, extending approximately 150 km south from the Wyoming border (Fig. 1). The bedrock consists of a core of acidic Precambrian intrusives, which in turn are intruded by acidic Tertiary plutons (Thornbury, 1965; Ives, 1980). In the lower montane forest, the most common soil types are cryoboralfs, but ustolls are also found on south-facing slopes (Johnson and Cline, 1965; Peet, 1981). Typically, the soils in the lower montane zone of the Colorado Front Range are rocky, thin, immature, and slightly acidic. According to climatological data from Boulder, Colorado, that correspond to the study sites sampled, mean annual precipitation is 395 mm, with January being the driest month and May the wettest month. July mean daily temperature maximum is 31°C, while the mean daily temperature minimum is −8°C in January.

The lower montane zone in the Colorado Front Range (from ca. 1800 and 2600 m) is characterized by ponderosa pines on south-facing slopes and Douglas-firs (*Pseudotsuga menziesii*) and ponderosa pines on north-facing slopes. Drier and warmer south-facing slopes contain a lower tree density and higher herbaceous density than adjacent north-facing slopes (Marr, 1965). Rocky mountain junipers (*Juniperus scopulorum*) exist in the drier open sites on the south-facing slopes or along recently disturbed areas. Common understory species include common juniper (*Juniperus communis*), wax currant (*Ribes cereum*), yucca (*Yucca glauca*), prickly pear cacti (*Opuntia rafinesquei*), kinnikinnik (*Arctostaphylos uva-ursi*), and waxflower (*Jamesia americana*) (Marr, 1965). Along the plains grassland region up to ca. 1750 m, common grasses include grama grasses (*Bouteloua* species), little bluestem (*Andropogon scoparius*), needle grasses (*Stipa* species), cheatgrass (*Bromus tectorum*) and wheatgrasses (*Agropyron* spp.), with blue grama grass (*Bouteloua gracilis*), spike fescue (*Leucopoa kingii*) and buffalo grass (*Buchloe dactyloides*) more dominant in the lower montane zone (Weber, 1976).

The nearly ubiquitous charcoal found in the soils of the Colorado Front Range forests suggests widespread importance of fire as an ecological disturbance (Peet, 1981; Veblen, 1986). Shade-intolerant ponderosa pines in lower montane forests are adapted to and directly benefit from repeated, low-intensity burns. With ample flammable grasses and forbs, ponderosa pine woodlands burned frequently in the Rocky Mountains in the past due to a combination of lightning fires and aboriginal burnings (Weaver, 1951; Dieterich, 1980; Arno, 1980; Gruell, 1985; Goldblum and Veblen, 1992).

Human-caused fires occurred in the Colorado Front Range since the arrival of aboriginal people at least 8000 years ago (Husted, 1965; Benedict, 1974). Before Euro-American settlement, the lower montane region consisted of open forests with low tree density (Marr, 1965). In 1858, when the Euro-American settlers and prospectors arrived in Boulder County, the frequency of wildfires dramatically increased (Veblen and Lorenz, 1986; Goldblum and Veblen, 1992). Since the 1920s, fire suppression policies in the Colorado Front Range have reduced the frequency and extent of wildfires. Fire exclusion results in increased tree density inside forests and promotes invasion of trees into grasslands and shrublands (Gruell, 1980; Veblen and Lorenz, 1986; Peet, 1988).

In regard to herbivore impacts in the Boulder County urban-wildland interface, large increases in numbers of mule deer developed in part due to protection from hunting during most of the twentieth century. In addition, active cattle grazing occurs in many areas managed by Boulder City Open Space (Mast, 1993).

Study areas for this project were selected based on general ecotonal boundaries, gradient of topographic orientation, and availability of historic photography and digital elevation models (DEMs). Specific areas analyzed from historic aerial photography, dating from 1937 through 1990, included the lower

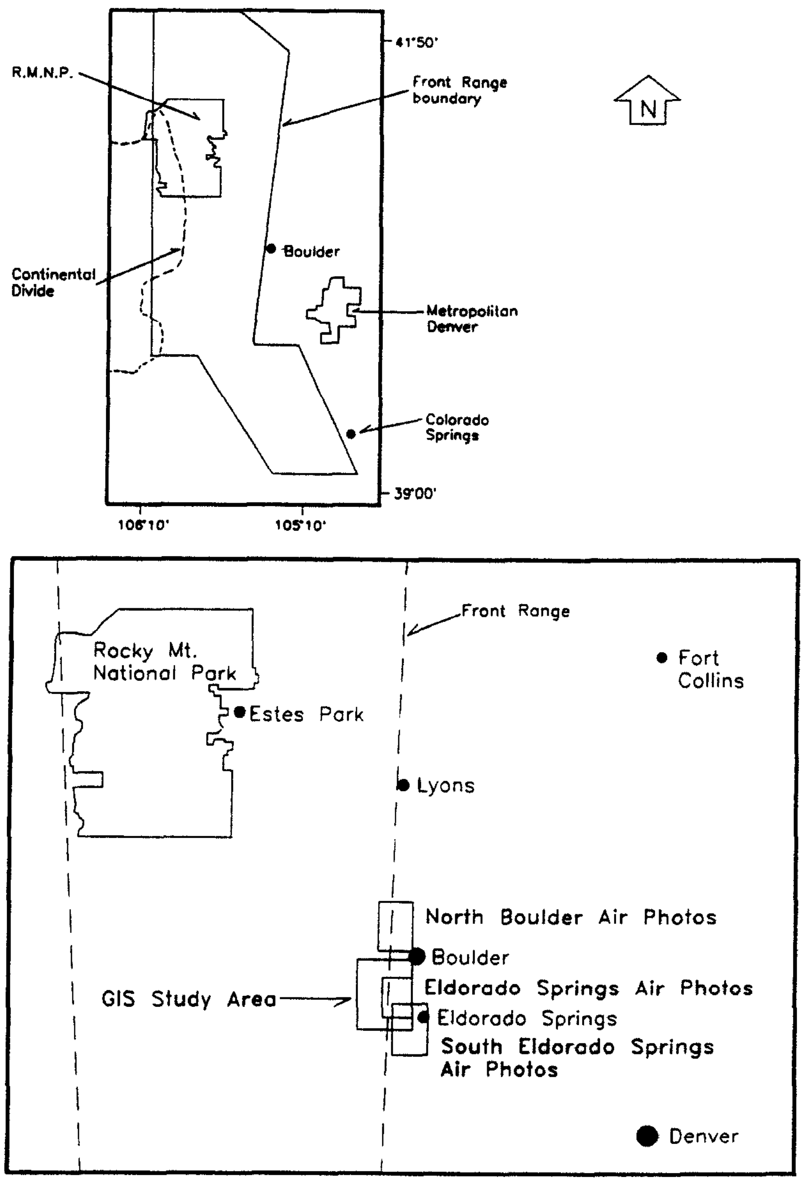

Fig. 1. Study areas along the Colorado Front Range.

Table 1
Aerial photography information (all panchromatic film)

Location	Date	Scale
North Boulder	1941	1:20000
	1953	1:37400
	1990	1:40000
South Eldorado Springs	1937	1:20000
	1971	1:26750
	1988	1:40000
North Eldorado Springs	1937	1:20000
	1971	1:26750
	1988	1:40000

ecotonal region of the Colorado Front Range from south of the Jefferson County line to north of Colorado Highway 94 (approximately 50 km) (Fig. 1). Since this research focused on changes within or near ecotonal boundaries, the section of historic change only included lower timberline habitat. Three separate study sites were used to quantify vegetation cover changes and characterize the relationship between tree invasion and topographic orientation (Fig. 1). Aerial photo dates, scales, and locations (chosen based on availability and overlap with study areas in a corresponding stand-scale research project) are listed in Table 1. The study area for the GIS analyses of habitat and settlement changes along lower timberline focused on the Eldorado Springs topographic quadrangle (1:24000 scale) that includes the southern end of the city of Boulder (Fig. 1). Historic topographic maps obtained from the United States Geological Survey (USGS) consisted of 1942, 1965, and 1971 data. Since the 1971 map is the most recent map available for the area, the impacts of settlement in the lower Front Range since 1971 are not included in the GIS portion of the analysis.

3. Methods

3.1. Introduction

The primary sources of data for accurately mapping historic changes in land cover characteristics over broad areas are limited to historic vertical aerial photography and historic topographic and planimetric maps. Several previous studies make use of historic aerial photography for delineating changes in vegetation cover (Jensen et al., 1986; Ferguson et al., 1993) or land cover changes (Baker et al., 1979; Adeniyi, 1980). However, the analysis of historic black/white photography for a variety of land use cover types is limited to visual interpretation. Before the 1950s, historic aerial photography collected generally used a non-metric camera with only black/white panchromatic film. Thus, this early photography has limited applications to photogrammetric or digital image processing methods.

Because of their relative obscurity and the unfamiliarity in quality and underlying mapping methods, few studies have taken advantage of historic topographic maps from the USGS for detecting changes in land cover (Hodgson and Alexander, 1990; Smith, 1994) or terrain (Mahoney et al., 1991; Butler and Schipke, 1992). In many geographic areas, very detailed topographic maps date as far back as the late 1800s.

Historic photography and topographic maps are ideally suited for the constrained domain of mapping tree invasion and settlement change along the Colorado Front Range. Tonal differences between ponderosa pine/Douglas-fir (the predominant vegetation) and grassland on the black/white historic photography permitted digital detection of tree cover change. Similar methods were used for tree invasion studies along environmental gradients (Archer et al., 1988; Scanlan and Archer, 1991). In addition, GIS analyses helped to determine forest and grassland conditions and settlement patterns over time for the quadrangle that corresponded with the historic aerial photographs. Of special interest is the relationship between changes in tree cover and urban-wildland interface growth over a 30 year period.

3.2. GIS database

A historic digital change database of aerial photography, land cover, and elevation was created from historical and recent aerial photography provided by the University of Colorado-Boulder Geography Department, USGS Denver and USGS Sioux Falls offices. Historic topographic maps were also obtained through the University of Colorado-Boulder's Geography Department. The Digital Elevation Models (DEMs) were obtained from the USGS offices.

After determining the scale of each photo, the photo was digitally scanned at a 2.5 m by 2.5 m nominal ground resolution. Ground control points (at least 10 per photo), digitized from topographic map sheets, helped to rectify each photo to the Universal Transverse Mercator (UTM) map projection. The UTM map projection permitted metric distance and areal changes to be assessed in ground units. The 2.5 m sampling resolution, deemed adequate for detecting changes in tree cover, was commensurate with the information content and rectification accuracy of the aerial photography.The geometric fidelity problem of the historic photography was minimized by limiting the area of interest on each photographic frame. By focussing on the central portion of the photograph (i.e. the portion with minimum relief displacement), a polynomial rectification was adequate for maintaining a rectification of less than one pixel in root mean square error.

Using bilinear interpolation, USGS DEMs with an inherent sampling resolution of 30 m were resampled to the 2.5 m × 2.5 m spatial resolution of the historic aerial photography. Although it is acknowledged that the topographic detail of the new 2.5 m DEM is still near the 30 m sampling resolution of the original DEM, the landscape effects of topography on tree cover are assumed to take place at this coarser scale. The resampling to a higher spatial resolution was only performed for consistency with the digital photography.

For the GIS analysis, topographic maps of the ecotonal area helped to identify urban areas and wooded cover, defined by USGS as an area of normally dry land containing tree cover with a heights of at least 2 m and dense enough to afford cover for troops (plus contain a tree density of at least 20%) (Thompson, 1979). Digitized features using AutoCad and the GIS program IDRISI included all urban areas, lakes, non-wooded areas, and wooded areas within non-wooded areas. The known minimum horizontal accuracy for these maps is 12.19 m based on the circular map accuracy standard. The digitizing relative accuracy in ground units varied between 1.8 m (root mean square error) and 6.1 m (circular map accuracy standard).

3.3. Change detection and environmental gradient analyses

A unique brightness value to tree cover relation was required, due to possible different solar illumination for each photo collection date. Field work helped to determine present vegetation cover, the tonal signature of vegetation on recent photography, and to extrapolate to photographs. After determining the range of brightness values representing tree cover in the image processing software Erdas Imagine, density slicing (dividing into categories based on photographic tone) was used to transform each digital photograph into a binary 'tree cover' versus 'no tree cover' mask. Boolean logic formed the basis of the binary map model, with conditional 'if/then' statements separating tree pixels from pixels with no trees.

The change detection model included three different periods (e.g. 1937, 1971, 1988) to determine the amount and rate of tree invasion (or, conversely grassland spread). By subsetting the images, analyses included only the areas of common overlap between images of different periods. The sample criteria table (Table 2) illustrates the change detection logic. The resulting output pixel value represents the change and nature of change in the cover type of that individual pixel for the three image dates compared. Output maps display vegetation change based on 'tree cover' versus 'no tree cover'. Hard copy images show specific areas of change from grassland to tree cover in the three-date models, providing visual interpretation of vegetation change over time. Besides mapped images, histogram summaries indicated the frequency and area of each change cate-

Table 2
Criteria table for the three-date image processing models showing changes in tree cover between three periods

Code	Oldest air photo	Middle air photo	Latest air photo
1	Tree cover	Tree cover	Tree cover
2	Tree cover	Tree cover	No tree cover
3	Tree cover	No tree cover	Tree cover
4	No tree cover	Tree cover	Tree cover
5	Tree cover	No tree cover	No tree cover
6	No tree cover	No tree cover	Tree cover
7	No tree cover	Tree cover	No tree cover
8	No tree cover	No tree cover	No tree cover

Table 3
Criteria table for vegetation change by aspect for three-date image processing models, listing 32 possible classes based on 8 vegetation change classes and four aspect types

Vegetation change class	Aspect			
	North	East	South	West
T-T-T	1	2	3	4
T-T-NT	5	6	7	8
T-NT-T	9	10	11	12
NT-T-T	13	14	15	16
T-NT-NT	17	18	19	20
NT-NT-T	21	22	23	24
NT-T-NT	25	26	27	28
NT-NT-NT	29	30	31	32

gory for each study area.

After the creation of the change detection maps, a five by five moving filter (based on the root mean square error of the rectified images) was added to minimize the spatial variation due to micro-topography and small rectification errors on each change detection output image file. Comparisons of the results of the model filters to field data for areas of known cover change ensured that filter size did not mask areas of actual change.

DEMs with 30 m × 30 m sampling resolution quantified the importance of environmental gradients, especially aspect, on the change detection maps. After resampling the DEMs to the same area and pixel size as the change detection images, a map of topographic aspect was derived. Next, the aspect map was reclassified into a four category (north, south, east, west) direction map. Finally, aspect maps and the change detection maps (three date model maps) were digitally overlaid by using a criteria table (Table 3). Hence, the thirty-two possible output classes in the change detection aspect maps included the four cardinal directions and the eight change categories defined from the vegetation change map. Interpreting the importance of aspect for tree invasion, especially for the north- versus south-facing slopes, included the percentage areal cover of each aspect that changed over the three periods.

3.4. Tree invasion and settlement pattern analyses

After the digitizing process, the vector data model representations (based on x and y values) were transformed into a raster data model (based on grids with a 60 m by 60 m cell size). Next, calculation of the total hectares found in each land cover category helped to detect quantitative change over time. Final GIS maps included urban areas, wooded areas, nonwooded areas, and lakes for each of the three topographic maps. A summary map shows changes over time from 1942 to 1965 in the nonwooded to wooded category.

Similarly, analyses of the 1942, 1965 and 1971 urban data assisted in determining changes in urban-wildland settlement.

4. Results and interpretations

4.1. Change detection analyses

Image processing of digitized aerial photography identified areas of change in tree cover and quantified locations and total hectares of tree invasions into

Table 4
Results from the three-date image processing models, shown as percentage per category type

Code number #: Cover	N Eld Springs 1937-71-88	N Eld Spr 5 × 5 1937-71-88	S Eld Springs 1937-71-88	N Boulder 1941-53-90
1: T-T-T	4.92%	4.63%	8.60%	16.41%
2: T-T-NT	0.82%	0.56%	1.87%	12.56%
3: T-NT-T	3.87%	3.17%	4.69%	9.44%
4: NT-T-T	15.39%	15.77%	20.24%	5.71%
5: T-NT-NT	3.83%	3.05%	4.16%	15.75%
6: NT-NT-T	25.01%	25.47%	21.20%	12.33%
7: NT-T-NT	6.10%	4.92%	9.16%	4.01%
8: NT-NT-NT	40.07%	42.44%	30.08%	23.79%

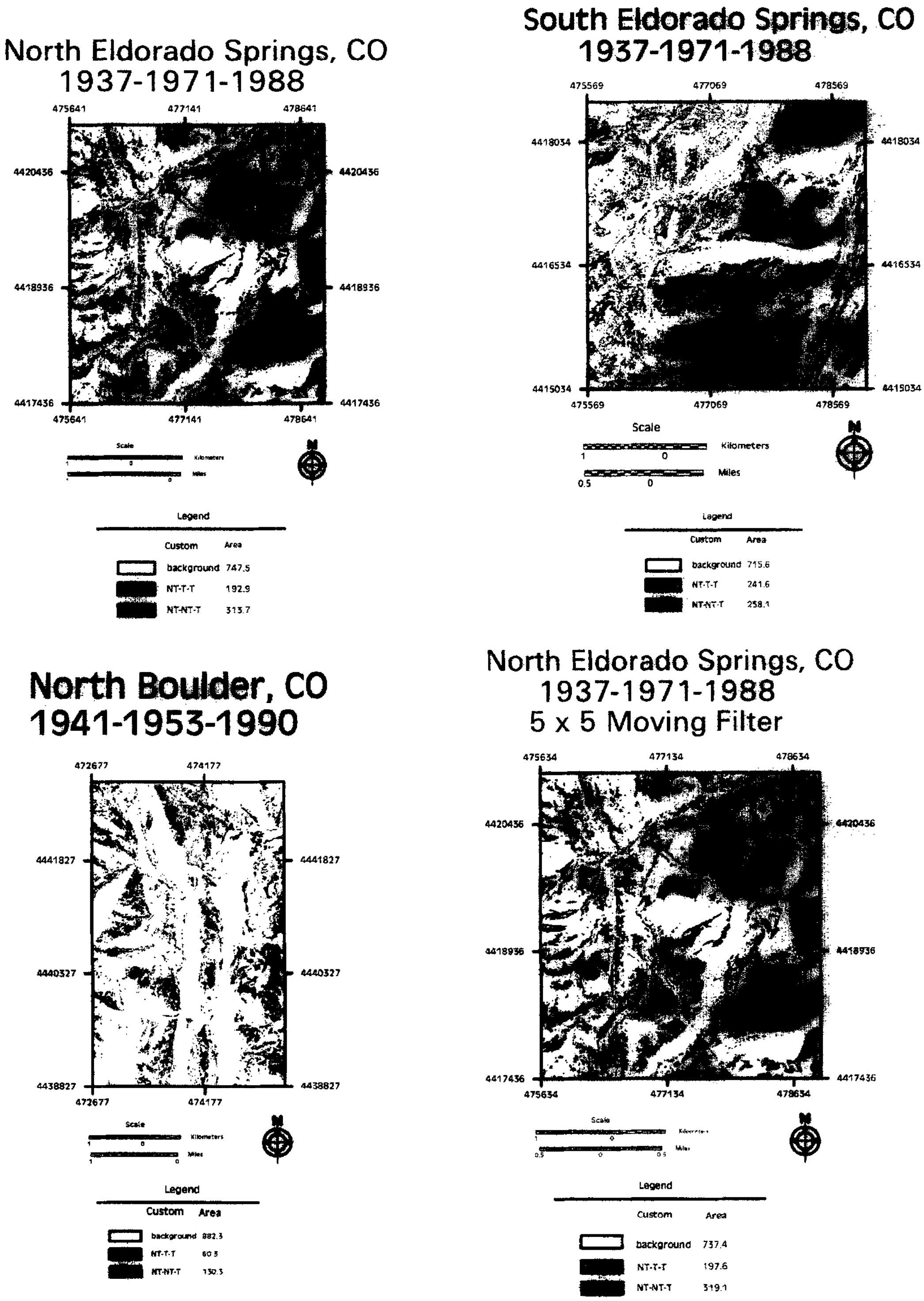

Fig. 2. Three-date change detection maps for the study areas, listing two periods of change to tree cover. Margin numbers are UTM coordinates and area is in hectares. Legend codes list NT-T-T (meaning no tree cover in first date with tree cover in the following two dates) and NT-NT-T (representing no tree cover in the first and second dates, with tree cover in the third date).

grassland areas. Vegetation change detection results from three-date air photo analyses are summarized in map form in Fig. 2 (includes a list of the hectares per category type) and in table form for percentage per category in Table 4. The importance of aspect in rate of tree invasion is summarized in Tables 5–7.

Overall, the lower timberline ecotone in the Eldorado Springs study site (Table 4, Fig. 2) shows the greatest increases occurring from 1971 to 1988. In the North Eldorado Springs area, 25% (314 ha) of the total area changed from grassland habitat in 1971 to tree cover (i.e. > 50% of the pixel was tree cover) in 1988, while only 15% (193 ha) of the area became tree cover from 1937 to 1971 (Table 4, Fig. 2). In the South Eldorado Springs area, 21% (258 ha) of the total area changed from grassland habitat in 1971 to tree cover in 1988, with a similar amount, 20% (242 ha), changing from grassland in 1937 to tree cover in 1971 (Table 4, Fig. 2). For comparison, only 0.8% (10 ha) in North Eldorado Springs area and 1.9% (23 ha) of the South Eldorado Springs area with trees in the 1937–1971 period shifted to grassland from 1971 to 1988 (Table 4). These small reversals from trees back to grasslands likely reflect the variety of negligible spatial errors in the database construction.

Table 5
Results from the combined three-date image processing models with the digital elevation model

Change class	Aspect	N. Eld. Spr. 1937-71-88		N Eld S 5 × 5 1937-71-88		S. Eld. Spr. 1937-71-88		N. Boulder 1941-53-90	
		ha	%	ha	%	ha	%	ha	%
T-T-T	N	30.4	2.852	30.2	2.86	33.9	3.25	64.8	8.91
	E	22.6	2.119	20.6	1.95	52.6	5.05	45.6	6.26
	S	3.58	0.335	2.83	0.27	8.18	0.78	8.41	1.16
	W	4.05	0.38	3.87	0.37	2.08	0.2	9.68	1.33
T-T-NT	N	3.47	0.325	2.61	0.25	4.89	0.47	52.6	7.23
	E	4.27	0.4	2.81	0.27	9.48	0.91	13.8	1.9
	S	0.95	0.089	0.42	0.04	4.92	0.47	6.64	0.91
	W	1.19	0.111	0.98	0.09	0.81	0.08	21.2	2.92
T-NT-T	N	22.9	2.146	20.3	1.92	14.6	1.4	19.8	2.72
	E	17.3	1.62	13	1.23	27	2.59	32.5	4.47
	S	3.43	0.321	2.45	0.23	5.58	0.54	8.89	1.22
	W	3.54	0.332	3.18	0.3	1.08	0.1	3.28	0.45
NT-T-T	N	72.4	6.778	73.1	6.91	68.4	6.56	5.49	0.75
	E	62.4	5.843	66.4	6.28	106	10.1	22.3	3.07
	S	17.3	1.616	18.8	1.78	21.5	2.07	9.2	1.26
	W	7.31	0.685	7.85	0.74	1.93	0.19	0.95	0.13
T-NT-T	N	14.4	1.351	12.5	1.18	8.69	0.83	30.5	4.2
	E	23.1	2.167	18	1.71	20	1.91	35.7	4.9
	S	6.9	0.646	4.93	0.47	11.6	1.11	24.4	3.35
	W	2.2	0.206	1.87	0.18	1.69	0.16	22.2	3.05
NT-NT-T	N	104	9.761	102	9.69	71.3	6.84	10.4	1.43
	E	94	8.802	95.4	9.03	118	11.3	56	7.7
	S	24.8	2.321	24.1	2.28	27.1	2.6	20.4	2.8
	W	8.85	0.829	8.98	0.85	2.64	0.25	1.81	0.25
NT-T-NT	N	23.4	2.192	19	1.8	19.2	1.84	2.79	0.38
	E	22.9	2.141	17	1.61	44	4.22	11.7	1.61
	S	14.5	1.357	11.5	1.08	23.8	2.28	9.5	1.31
	W	3.65	0.342	3.06	0.29	1.99	0.19	2.38	0.33
NT-NT-NT	N	118	11.03	115	10.9	65	6.24	15.8	2.18
	E	196	18.37	210	19.9	146	14	79.4	10.9
	S	118	11.03	126	12	105	10.1	66.7	9.17
	W	16.1	1.505	17.3	1.63	13.6	1.31	12.7	1.74

Results are classified into four aspect types, and listed by percentage and number of hectares per category type.

Table 6
Results form the combined three-date image processing models for north-facing slopes

Change class	Aspect	N. Eld. Spr. 1937-71-88		N Eld S 5 × 5 1937-71-88		S. Eld. Spr. 1937-71-88		N. Boulder 1941-53-90	
		ha	%	ha	%	ha	%	ha	%
T-T-T	N	30.4	7.827	30.2	8.04	33.9	11.8	64.8	32.1
T-T-NT	N	3.47	0.892	2.61	0.69	4.89	1.71	52.6	26
T-NT-T	N	22.9	5.891	20.3	5.39	14.6	5.09	19.8	9.8
NT-T-T	N	72.4	18.6	73.1	19.4	68.4	23.9	5.49	2.72
T-NT-T	N	14.4	3.709	12.5	3.33	8.69	3.04	30.5	15.1
NT-NT-T	N	104	26.79	102	27.2	71.3	24.9	10.4	5.16
NT-T-NT	N	23.4	6.016	19	5.05	19.2	6.7	2.79	1.38
NT-NT-NT	N	118	30.27	115	30.7	65	22.7	15.8	7.84
Total		389		376		286		202	

Results are shown as percentages and number of hectares per category type.

On the other hand, the region north of Boulder shows more variety of habitat change along the lower timberline ecotone, probably illustrating effects of recent fires and increased human settlement in this area (Table 4, Fig. 2). In the North Boulder study area, 12.3% (130 ha) of the total area changed from grassland habitat in 1971 to tree cover in 1988, while only 5.7% (60 ha) shifted from grassland in 1937 to tree cover in 1971. Yet in this region, 15.8% (169 ha) of the total area converted from tree cover in 1937 to non-tree cover in 1971 and 1988. Similarly, 12.6% (135 ha) of the total area shifted from tree cover in the 1937–1971 period to non-tree cover in 1988. Therefore, in the North Boulder study area a net decrease in tree cover occurred from 1937 to 1988.

When comparing the results of the binary combination model maps created without a filter to the results from the maps created with a moving filter, the general pattern of more grassland pixels occurs in all the moving filter maps. By using a five by five pixel moving filter, generalization in the vegetation cover change minimized spatial registration problems in the procedures. Consequently, the smoothed map eliminated pixels different from the neighboring pixels' values. In the North Eldorado Springs site, the results of these smoothed filtered images show slightly less area shifted from grassland to tree cover,

Table 7
Results from the combined three-date image processing models for south-facing slopes

Change class	Aspect	N. Eld. Spr. 1937-71-88		N Eld S 5 × 5 1937-71-88		S. Eld. Spr. 1937-71-88		N. Boulder 1941-53-90	
		ha	%	ha	%	ha	%	ha	%
T-T-T	S	3.58	1.893	2.83	1.48	8.18	3.93	8.41	5.46
T-T-NT	S	0.95	0.505	0.42	0.22	4.92	2.36	6.64	4.31
T-NT-T	S	3.43	1.815	2.45	1.28	5.58	2.68	8.89	5.77
NT-T-T	S	17.3	9.127	18.8	9.84	21.5	10.4	9.2	5.97
T-NT-NT	S	6.9	3.65	4.93	2.58	11.6	5.56	24.4	15.8
NT-NT-T	S	24.8	13.11	24.1	12.6	27.1	13	20.4	13.2
NT-T-NT	S	14.5	7.665	11.5	6	23.8	11.4	9.5	6.17
NT-NT-NT	S	118	62.3	126	66.2	105	50.6	66.7	43.3
Total		189		191		208		154	

Results are shown as percentages and number of hectares per category type.

Table 8
Results from the GIS analyses of the Eldorado Springs Quadrat Topographic Maps for 1942, 1965, and 1971, shown in number of hectares per coverage type

1942	Cover type	Hectares
	Buildings	195.84
	Tree cover	9326.16
	Urban	25.56
	Non-wooded	5058.36
	Lakes	4.32
1965	Cover type	Hectares
	Buildings	222.48
	Tree cover	10548.36
	Non-wooded	3598.92
	Lakes	143.28
	Urban	97.20
1971	Cover type	Hectares
	Buildings	264.24
	Tree cover	10524.96
	Non-wooded	3560.28
	Lakes	143.28
	Urban	117.00

but overall agree with the general trend of increase tree cover (Table 4, and comparison on Fig. 2).

4.2. Environmental gradient analyses

The greater rate of tree invasion on north-facing slopes versus south-facing slopes clearly shows the importance of aspect on the rate of tree invasion (Tables 5–7). When analyzing change on north-facing slopes at the Eldorado Springs sites, an average of 47% of north-facing slopes shifted from grassland habitat to tree cover from 1937 to 1988 (Table 6). In comparison, an average of 22.7% of south-facing slopes at Eldorado Springs sites shifted from grassland to tree cover during the same period (Table 7). These results support the theory that the rate of tree invasions into grasslands would be greater on north-facing slopes due to moister conditions.

At the North Boulder site, the majority of tree cover occurred on the moister north-facing slopes, with 32.1% of the north-facing slopes in continuous tree cover from 1941 to 1990 (versus an average of 9.2% of north-facing slopes in continuous tree cover at Eldorado Springs study sites) (Table 6). An additional 15.1% of the north-facing slopes at the North Boulder site shifted from tree cover in 1941 to grassland in 1953 (possibly due to fire) then back to tree cover by 1990. Only 7.8% of north-facing slopes at the North Boulder site shifted from grassland in 1941 to tree cover in 1990 (versus 47% of the north-facing slopes in Eldorado Springs study sites). The lower percentage of north-facing slopes that changed from grassland to tree cover at the North Boulder site, as compared with north-facing slopes at

Table 9
Results from the GIS analyses for changes in tree cover and urban areas, from 1942 to 1965, for the Eldorado Springs Quadrat Topographic Maps

Cover type	Hectares
Both urban or buildings	52.20
Both lakes	3.60
Both tree cover	8342.28
Tree cover to lakes	136.80
Non-wooded to buildings	63.00
Both non-wooded	2806.92
Tree cover to non-wooded	739.08
Buildings to tree cover	103.32
Both buildings	39.24
Tree cover to buildings	106.92
Non-wooded to tree cover	2102.40
Non-wooded to urban	84.24
Both urban	13.32

Table 10
Results from the GIS analyses for changes in urban areas and buildings, from 1942 to 1971, for the Eldorado Springs Quadrat Topographic Map

1942 Cover	1965 Cover	1971 Cover	Hectares
-	Building	Urban	56.16
-	Building	-	113.40
-	-	Building	153.36
-	-	-	13908.96
-	-	Urban	71.28
Building	Building	Building	24.84
Building	Building	-	27.36
-	Urban	Building	1.44
-	Urban	-	51.12
-	Urban	Urban	32.76
Building	-	Building	28.08
Building	-	-	115.56
Urban	-	-	10.80
Urban	-	Urban	2.16
Urban	Urban	-	1.44
Urban	Urban	Urban	10.44

Fig. 3. GIS results for 1942 versus 1965 cover types based on the Eldorado Springs, Colorado, Quadrat Topographic Map. Cover categories include black (meaning non-woodlands to woodlands) and hatch (meaning nonurban to urban).

the Eldorado Springs sites, is due in part to the large percentage (32.1%) of area in continuous tree cover, but may also be attributed to a percentage (26%) shifting from tree cover in 1941–1953 to grassland by 1990. This loss of tree cover since the 1950s may be linked to fires and increased human settlement in the north Boulder area.

In contrast to north-facing slopes, only 5.5% of south-facing slopes at the North Boulder site remained in continuous tree cover, while 43.3% remained in continuous grassland cover (Table 7). Of the south-facing slopes at the North Boulder study site, 19.1% shifted from grassland in 1941 to tree cover in 1990, similar to the percentages on south-facing slopes in Eldorado Springs study sites.

4.3. Tree invasion and settlement pattern analyses

GIS analyses of the final combined maps, summarized in Tables 8–10 and Fig. 3, support the aerial photo image processing results. Overall, the GIS tree invasion and settlement pattern results for the Eldorado Springs Quadrangle topographic map area clearly show an increase in woodland areas where there formerly existed grasslands. The amount of land that experienced a shift from grassland to woodland cover represents 14% of the total study area, an increase of 2102 ha over the 23 year period from 1942 to 1965 (Table 9).

Similarly, the GIS settlement change analyses also identified areas experiencing an increase in settlement, both in wooded and non-wooded areas (Tables 8 and 10). The results of the urban-wildland settlement show that 26 ha had urban development in 1942, with 117 ha of urban areas by 1971 (a 457% or 91 ha increase in urbanization since 1942).

5. Discussion

Results from the landscape-scale analyses illustrate a spatial pattern of increased tree cover since the 1930s. Image processing of digital aerial photography and GIS analyses of topographic maps identified areas of change in tree cover and quantified locations and total hectares of tree invasions. The greatest increase in tree cover into former grassland areas occurred from 1971 to 1988 in the Eldorado Springs study site. This result agrees with stand structure analysis that indicates substantial seedling establishment in the 1970s and 1980s (Mast, 1993). Increases in ponderosa pine establishment in the 1970s–1980s correspond to periods of above average precipitation. In addition, fire suppression since the early 1900s and decreased grazing pressure in the 1970s–1980s favored ponderosa pine establishment at lower timberline. These changes in disturbance regimes, together with moister springs/early summers, created favorable conditions for the increase in extent of ponderosa pine at lower timberline ecotone.

For all areas analyzed, results show the importance of environmental gradients at the lower timberline ecotone such as terrain aspect. The general trend of greater tree cover on north-facing slopes occurred on all air photograph results. For Eldorado Springs areas, the majority of change from grassland to tree cover occurred on north-facing slopes, while south-facing slopes remained non-forested in most areas. One possible explanation suggests that periods of spring/early summer drought would result in an even greater negative impact on tree seedling establishment and survival on south-facing slopes, normally drier and warmer than north-facing slopes. As a result, tree invasions at lower timberline appear more successful on north-facing slopes. Similarly, in the region north of Boulder, Colorado, the north-facing slopes included the majority of tree cover, yet also experienced a significant loss of tree cover from 1950s to 1990 (possibly due to fires running up ridge slopes and increased human settlement in these areas).

When compared to the original vegetation cover maps, the filtered vegetation maps contain more grassland pixels since smoothing eliminates pixels that are different from the neighboring pixels values. Yet, the results of the moving filter maps paralleled that of the non-filtered vegetation cover maps and GIS tree cover-settlement analyses. All clearly show a consistent quantitative change in the ecotone boundary from grassland to forests at a landscape scale. Overall, quantitative measures of change through landscape analyses indicate increased tree establishment and a major regeneration pulse along the ecotone between grassland and forests along the Colorado Front Range.

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