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LAND USE AND LAND COVER CHANGE IN THE GREATER YELLOWSTONE ECOSYSTEM: 1975–1995

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Abstract. Shifts in the demographic and economic character of the Greater Yellowstone Ecosystem (GYE) are driving patterns of land cover and land use change in the region. Such changes may have important consequences for ecosystem functioning. The objective of this paper is to quantify the trajectories and rates of change in land cover and use across the GYE for the period 1975–1995 using satellite imagery. Spectral and geographic variables were used as inputs to classification tree regression analysis (CART) to find ''rules'' which defined land use and land cover classes on the landscape. The resulting CART functions were used to map land cover and land use across seven Landsat TM scenes for 1995. We then used a thresholding technique to identify locations that differed in spectral properties between the 1995 and 1985 time periods. These ''changed'' locations were classified using CART functions derived from spectral and geographic data from 1985. This was similarly done for the year 1975 based on Landsat MSS data. Differences between the 1975, 1985, and 1995 maps were considered change in land cover and use. We calibrated and tested the accuracy of our models using data acquired through manual interpretation of aerial photos. Elevation and vegetative indices derived from the remotely sensed satellite imagery explained the most variance in the land use and land cover classes (i.e., defined the ''rules'' most often). Overall accuracies from our study were good, ranging from 94% at the coarsest level of detail to 74% at the finest. The largest changes over the study period were the increases in burned, urban, and mixed conifer-herbaceous classes and decreases in woody deciduous, mixed woody deciduous–herbaceous, and conifer habitats. These changes have important implications for ecological function and biodiversity. The expansion of mixed conifer classes may increase fuel loads and enhance risk to the growing number of rural homes. The reduction of woody deciduous cover types is likely reducing population sizes for the numerous plant and animal species that specialize on this habitat type. Some of these species are also negatively influenced by the increase of rural homes in and near woody deciduous habitats.

Key words: classification and regression tree analysis; exurban development; fire; Greater Yellowstone Ecosystem; land use and land cover change; remote sensing; urbanization.

Introduction

The Greater Yellowstone Ecosystem (GYE), like many rural areas in the American West, is undergoing a transition in human demographics and economics. Yellowstone and Grand Teton National Parks and the surrounding public lands represent a large wilderness landscape (Schullery 1997). The area supports threatened species such as grizzly bear (*Ursus arctos horribilis*) and free-roaming populations of large ungulates including elk (*Cervus canadensis*) and bison (Yellowstone National Park 1997). The surrounding private lands include towns and small cities whose residents traditionally relied on natural resource industries such as farming, ranching, mining, and logging. In recent decades, however, the communities of the GYE have undergone rapid change (Rasker and Hansen 2000). The local economy has been shifting from traditional resource industries to a New-West economy based on high-tech firms, real estate, and recreational enterprises (Rasker and Glick 1994, Johnson and Rasker 1995). This has been driven in part by a population increase of 55% between 1970 and 1997 (Hansen et al. 2002). Some local communities are confronting traffic congestion and rural sprawl as major issues (Greater Yellowstone Coalition 2000).

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TABLE 1. Hierarchical classification of land use and land cover in the GYE.

Level A	Level B	Level B definition
Nonvegetation	soil/rock water‡ urban§/roads‖	lands including those within urban city boundaries, water bodies, barren areas, rock, and exposed soil
Agriculture†	agriculture	lands actively in field crops or fallow, hay, vegetables, grazing pastures, and feedlots
Vegetation	conifer	areas with >70% conifer species, primarily on forested land
	mixed conifer/ herbaceous	areas containing a mix of conifer with herbaceous shrub and grassy species with <70% conifer
	burn	areas of vegetation burned primarily by wildfire
	woody deciduous	areas containing >70% woody deciduous vegetation such as aspen, cottonwood, and willow species
	mixed woody deciduous/ herbaceous	areas containing a mix of woody deciduous vegetation and herbaceous species with <70% of the area woody deciduous
	herbaceous	areas containing >70% herbaceous species such as grasslands and sage brush dominated regions

† Agricultural cover class defined as privately owned grazed and cropped lands.
‡ Cover class defined from spectral thresholding.
§ Cover class defined as the area of incorporated cities and towns.
‖ Cover class defined from TIGER line data (US Department of Commerce 1999).

The shift to a New-West economy appears to be driving change in the land use and land cover regimes of the region. The pathways and rates of this change, however, are unknown. The suspected conversion of wild lands to rural residential and urban land uses may be detrimental to legally protected wildlife or to economically valuable game species. Moreover, changes in natural land cover may alter fire hazard to human property and safety. Changes in the distribution and types of agricultural lands and rural residences affect costs to local governments of providing services to citizens. If natural resource managers and local governments are to make informed decisions about land use policy in the face of change, they must be apprised of the geographic and temporal distribution of land use and land cover change in the GYE and the implications for ecosystem dynamics and native species.

Several previous efforts have mapped land cover, vegetation communities, and ecological units over portions of the GYE. The GYE was included within the 1975 NASA LULUC (Land Use and Land Cover Change) map of the United States (Anderson et al. 1976). This map was made at a relatively coarse scale, and accuracy for the GYE was not assessed. Vegetation communities on public lands in the GYE have been delineated from aerial photographs by the USDA Forest Service, U.S. Department of Interior Park Service, and the Grizzly Bear Interagency Study Team (e.g., Despain 1990). The U.S. Geological Survey/Biological Resources Division Gap Analysis Program[8] used 1991 Landsat TM imagery (30 m) to map land cover for the Montana and Idaho portions of the GYE (R. Redmond, *personal communication*) and for the Wyoming portion of the GYE. However, edges were not matched between Wyoming and the other states, resulting in discontinuous maps across the GYE. Other efforts to quantify vegetation cover with satellite imagery for smaller portions of the GYE included Turner et al. (1994), Jakubauskas (1996), Jakubauskas and Price (1997), Price and Jakubauskas (1998), Debinski et al. (1999), and Hansen et al. (1999). Burrough et al. (2001) used topoclimatic data to aid in mapping forest vegetation across a portion of the GYE. To date, however, a single accurate land cover map of the GYE has not been produced for even one time period, much less multiple time periods. Consequently, an analysis of change in land cover over time has not been done, and implications for ecosystem dynamics are unknown.

We present here the methods and results of a study of change in land cover and land use over the GYE for 1975–1995. The goal of this paper is to report on GYE-wide land use and land cover maps and patterns of change across the region over this time period as a basis for drawing implications for biodiversity and ecosystem processes. The specific objectives of the study were to (1) design and implement a methodology for statistical modeling of land use and land cover in conjunction with GIS data layers and Landsat MSS and TM satellite imagery; (2) use this methodology to produce GYE-wide land use and land cover maps for the years 1975, 1985, and 1995 at two levels of detail; and (3) perform change-detection analyses on the completed maps to quantify rates and pathways of change in land use and land cover over the 20-yr period and to interpret the implications of these changes for key habitat types and native species.

We created a hierarchical classification of land use and land cover for the GYE (Table 1) through statistical modeling of remotely sensed and GIS data. Two levels of detail were chosen to allow users to select the level of detail and accuracy that best meets their needs. The 20-yr time period 1975–1995 covered by the study was

[8] URL: ⟨http://www.gap.uidaho.edu/default.htm⟩

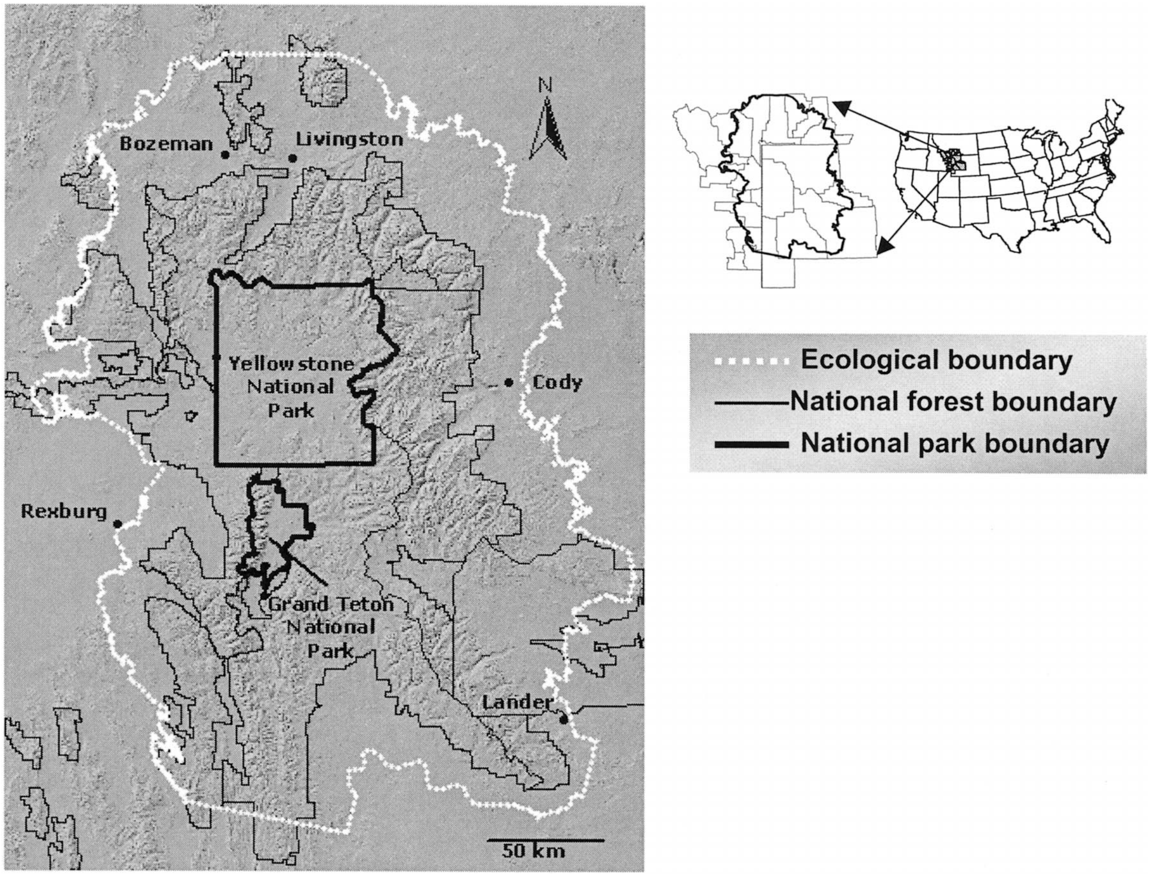

FIG. 1. Shaded relief map of the Greater Yellowstone Ecosystem, USA, with the study area boundary. The study area embraces Yellowstone and Grand Teton National Parks in the center with the surrounding national forests.

dictated by availability of satellite imagery (Landsat MSS since August 1972 and Landsat TM since 1982). Our method allows the inclusion of ancillary data in statistical classification using Classification and Regression Trees (CART).

STUDY AREA DESCRIPTION

The GYE is made up of Yellowstone and Grand Teton National Parks, seven national forests, 21 other federal and state jurisdiction areas, and surrounding private lands (Fig. 1). The national parks are at relatively high elevations, centered on the Yellowstone Plateau and surrounding mountain ranges. Other public lands are largely at mid-elevations on the flanks of the plateau. Private lands are primarily at lower elevations in valley bottoms and on the plains surrounding the public lands. Originally defined as the range of the Yellowstone grizzly bear (Craighead 1991), we delineated the GYE as the area of strong ecological and socioeconomic connection between the public lands and the surrounding private lands including the watersheds of the GYE down to the lower forest boundary and adjacent grasslands, which occur at elevations of 1280–1800 m.

The GYE has strong gradients in soils and climate. The Yellowstone Plateau was created through volcanic activity. Soils at higher elevations are largely nutrient poor rhyolites and andesites with low water-holding capacity (Davis and Shovic 1996, Rodman et al. 1996, Bowerman et al. 1997). Valley bottoms and floodplains contain glacial outwash and alluvium soils that are generally higher in nutrients and water-holding capacity. Climate severity increases with elevation (Despain 1990). Winters are characterized with mean temperatures below freezing and continuous snow pack. The growing season varies from two to three months at higher elevations, to five to six months at lower elevations.

Natural vegetation of the study area is a mosaic of forests, shrublands, and grasslands. Upland rhyolite soils support lodgepole pine (*Pinus contorta*) forests between 2000 and 2600 m (Despain 1990). Douglas-fir (*Pseudotsuga menziesii*) is common up to 2300 m on andesitic soils and in warmer microclimates. Above these elevations on both soil types, subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*) dominate. Sagebrush shrublands occur on dry, fine-textured soils from

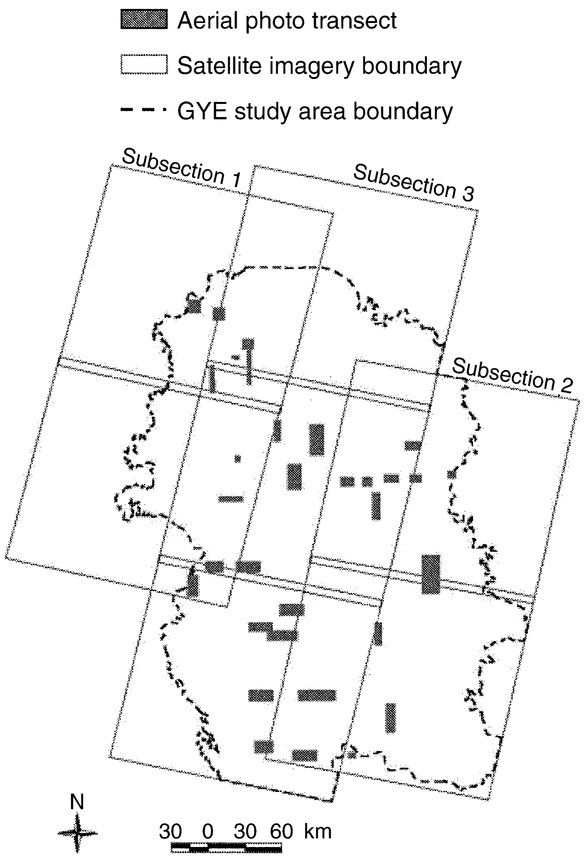

FIG. 2. Satellite imagery boundaries and the distribution of the air photo transects in the three subsections.

low to mid-elevations. Grasslands exist on fine-textured soils from valley bottoms up to mid slopes. Aspen (*Populus tremuloides*) is distributed in relatively small patches, primarily on moist toeslopes, on fractured rocks, or in thin transitional bands between upslope conifer forests and lowland grassland communities. Larger floodplains are dominated by black cottonwood (*Populus trichocarpa*) and narrowleaf cottonwood (*P. angustifolia*).

Typical disturbances on public lands in the GYE are fire and logging. Approximately 45% of Yellowstone National Park (YNP) burned during 1988. Logging was common on most of the national forests during 1960–1990. The most common land uses on the private lands of the GYE are agriculture, range, rural residential development, and urban development.

METHODS

Study design

We grouped each of the seven Landsat scenes covering the study area into one of three subsections comprised of two to three consecutive scenes each (Fig. 2). Land cover/land use classification was modeled separately for each subsection. Satellite data were obtained for the mid-1970s, mid-1980s, and mid-1990s for each scene (Table 2). We used images from two dates each year (June or July representing the early growing season and August or September representing the late growing season) for the mid-1990s and mid-1980s and one date during the growing season from the mid-1970s in the classification. All imagery was ≥90% cloud free.

First, the imagery from the mid-1990s was classified. We next implemented a change-detection method that identified pixels in the images from the mid-1980s and mid-1970s that had changed in the 1990s images. These change pixels were then reclassified using new CART models developed for the specific year. This methodology minimized classification error by focusing on changed area only, rather than creating independent classifications for each time period, each with their own error. By reclassifying only areas that had changed from the 1990s classified maps, areas of no change were consistent among all maps.

TABLE 2. Years and dates of satellite imagery and aerial photography.

Study area	Sensor, path/row	Image dates	Air photo years used	Air photo type
Subsection 1	Landsat 5—TM, 39/28, 39/29	28 Jun 1994	1995	color
		15 Aug 1994	1995	color
		19 Jun 1985	1984, 1981	color
		21 Jul 1985	1984, 1981	color
	Landsat 4—MSS, 42/28, 42/29	28 Sep 1976	1971, 1978	color
Subsection 2	Landsat 5—TM, 38/28, 38/29, 38/30	28 Jun 1995	1992, 1994	black and white
		12 Sep 1995	1992, 1994	black and white
		14 Jul 1985	1980, 1988	black and white, color
		16 Sep 1985	1988	black and white, color
	Landsat 4—MSS, 41/28, 41/29, 41/30	9 Sep 1976	1971, 1977, 1978	color
Subsection 3	Landsat 5—TM, 37/29, 37/30	30 Jun 1994	1990, 1994, 1996	black and white, color
		17 Aug 1994	1990, 1994, 1996	black and white, color
		21 Jun 1985	1981, 1980	color, color infrared
		8 Aug 1985	1981, 1980	color, color infrared
	Landsat 4—MSS, 40/29, 40/30	5 Sep 1975	1971, 1974, 1977	color, color infrared

Notes: Image dates were selected for optimal cloud-free conditions. Photo dates represent the closest possible match to image dates.

Reference data collection

We collected the land use/land cover reference data from aerial photos using a stratified random sampling design. Our objective was to obtain adequate samples of the range of variation in spectral properties of each cover type typical in the study area. The stratification criteria were elevation, aspect, cover type, and wide geographic dispersal. These data were collected along 32 aerial photo transects that were selected based on both the stratification criteria and the availability of photos for all years of interest (Fig. 2). All aerial photography used for reference data sampling was at a scale of either 1:15 840 or 1:24 000 and was purchased from the National Aerial Photography Field Office in Salt Lake City, Utah. The study used a combination of color and color–infrared photography, depending on availability.

Within the area of the photos, a stratified random sampling procedure identified locations of potential sample sites. Two elevation strata (below 2300 m and above or equal to 2300 m), two aspect strata (north–northwest from 211-20 azimuth degrees and south–southeast from 21-210 azimuth degrees), and seven cover type strata were used. Elevation and aspect were derived from digital elevation models (DEMs). Cover types were from existing sources (Gallatin National Forest Stand maps, Targhee National Forest Stand maps, and USGS/BRD Gap Analysis data from Idaho and Wyoming). This allowed for a possible combination of 28 stratified cover classes for sampling (two elevation classes $\times$ two aspect classes $\times$ seven cover classes). The rarest of these 28 cover classes was identified and a minimum of 200 randomly generated 2.25-ha sites were located within the area covered by this rarest class. The minimum mapping unit for this study was chosen to be $\sim$2.25 ha (22 500 m^2) because this is the smallest unit easily colocated on both the aerial photos and Landsat imagery at the classification levels of interest.

For the other 27 stratified cover classes, sites were located randomly in quantities proportional to the area each class covered within all combined transects. Sample sites were discarded if they fell on an edge between cover types or contained more than one cover type at level A. In total, $\sim$2000 2.25-ha usable sites were sampled across the three subsections for each of the three years to be used as reference data. The usable sites were then classified by a team of aerial photo interpreters for each year of aerial photos at each of the two hierarchical land cover/land use levels. When possible, the same sites were used for each of the three time periods, although in meeting classification criteria some sites were usable for only one or two of the three years. Additionally, $\sim$2000 2.25-ha sites were sampled across the three subsections for each of the three years at each classification level to be used as an independent validation sample for subsequent accuracy assessment.

Stratified reference sample sites were interpreted from the aerial photos at level A and classified either as natural vegetation, agriculture, or nonvegetation. For level B, all vegetated sites were interpreted as percent composition of the land cover types at that level by using a 20-dot matrix grid overlaid onto the photo. This allowed for classification of the sample sites in 5% increments of the level B land cover classes. Sites that were $\geq$70% pure for the given cover type were interpreted and classified as that cover type: conifer, herbaceous, agriculture, woody deciduous, or burned/cut at level B. Interpreted sites that were $<$70% pure at level B (e.g., 65% conifer and 35% herbaceous) were then classified as mixed conifer/herbaceous or mixed woody deciduous/herbaceous. Mixtures of conifer and woody deciduous were not present in enough abundance in the GYE to be sampled, and sample sites containing mixtures of three or more cover types were discarded. Therefore, at level B of the classification, there were fewer reference data sites interpreted and smaller sample sizes than at level A.

Nonvegetation classes included water, urban, soil, and rock. Of these nonvegetation types, reference data for soil and rock were interpreted from aerial photos and these land cover types were classified from satellite imagery. Water was determined by spectral thresholding of band 5 (infrared) in the Landsat TM imagery from 1995 (we assumed no major change in water bodies and used water classified from 1995 for all years of the study). Urban areas were manually digitized for each time period using known urban boundaries and road networks as guides. All classified data was entered into a database for each reference site and each year in the study. The same methodology was applied to the interpretation of validation sites.

Exurban development (rural homes at densities of less than one home per 20 ha) is an increasingly common form of land use in the study area. Because this development was not reliably detectable from Landsat imagery, we did not attempt to include this within our land cover classification. Data on rural home density was available from county well permit records, however. We found that the geographic distribution of the known home locations corresponded closely with the well permit locations. These data were in digital form for the Montana and Wyoming portion of the study area. The results of our analyses of these data were reported in Hansen et al. (2002) and are summarized in this paper.

Predictor variables

Potential predictor variables used in this study were spectral (derived from Landsat satellite imagery) and geographic (Table 3). Geographic variables were used only if data met resolution standards of 30 m and were geospatially continuous across the entire GYE. To georeference the satellite imagery one ''control'' image of each row and path was rectified to ground control points

TABLE 3. Greater Yellowstone Ecosystem-wide predictor variables for land cover modeling.

Source	Date	Scale/ resolution	Source	Derived layers
Landsat 5 TM	Jun 1994, Aug 1995, Jul 1985, Aug 1985	30 m	USGS EROS data center	tasseled cap indices 1, 2, and 3: brightness, greenness, wetness; spectral bands 1–7; seasonal difference in tasseled cap indices 1, 2, and 3
Landsat 4 MSS	Jul 1975	80 m	USGS EROS data center	tasseled cap indices 1 and 2: brightness, greenness; spectral bands 1–4
Digital elevation model	1997	30 m	USGS EROS data center	aspect, slope, elevation
Roads	1995	1:24 000	U.S. Census Bureau TIGER line	urban mask
Streams	1995	1:24 000	U.S. Census Bureau TIGER line	water bodies: lakes and rivers

(GCPs) digitized from 1:24 000 topographic maps. In all cases, the root mean square (RMS) error was <0.5 pixels. RMS error gives an indication of the variability of the resampled (new or ''moved'') pixel coordinates around their true coordinates. In general the lower the overall RMS value, the closer the coordinates of the output image will be to the real world. All other images from the same row and path but different dates were then rectified to the ''control'' image using the ITP FIND program (R. Kennedy, *personal communication*) resulting in RMS errors <15 m in all cases. The georectification allowed direct overlay of imagery from the same location with different dates.

Tasseled-cap brightness, greenness, and wetness indices were derived from each image in the 1990s and 1980s (Crist et al. 1986). Tasseled-cap indices were selected for use in this study because the tasseled-cap transformation, originally developed for Landsat MSS imagery and then redefined for Landsat TM imagery, particularly optimizes data for vegetation studies The linear tasseled-cap transformation rotates the data onto new axes which directly correlate to the physical characteristics of vegetation. In general, for Landsat TM data, the transformed index ''brightness'' is a measure of soil, ''greenness'' is a measure of vegetation, and ''wetness'' is a measure of soil moisture. Using the three tasseled-cap indices, the seasonal difference was calculated for 1985 and 1995 by subtracting the late-season date from the early-season date. For the MSS imagery, only the first two tasseled-cap indices of brightness and greenness were derived (Kauth and Thomas 1976). The third index, wetness, cannot be derived for MSS data. Because only one image date was used in the 1970s MSS imagery, the difference in tasseled-cap values could not be calculated. Spectral MSS imagery was also resampled to 30 m to make it compatible with all other data layers. All individual spectral bands (bands 1–7 for TM and 1–4 for MSS), the tasseled-cap indices (indices brightness, greenness, and wetness for TM and brightness and greenness for MSS) and the difference in tasseled cap (indices brightness, greenness, and wetness for TM only) were used in the input to the CART models.

Geographic variables used in the study were: elevation, slope, and aspect. Although other existing data sets of abiotic variables (such as precipitation, soil type, temperature, and parent material) were examined for inclusion in the study, none were at a comparable spatial resolution (all were 1 km or larger) and were therefore excluded from the study. We created a continuous DEM for the entire GYE by tiling all 7.5-min USGS DEMs within the study area boundary. Aspect and slope were then derived from the GYE DEM. A cosine transformation (Beers et al. 1966) was applied to the aspect variable to make the values continuous and then rescaled by multiplying the resulting cos(azimuth degrees) units by 1000 so that values ranged from 0 to 2000. This transformation emphasizes the north/south slope contrast that is critical in the GYE system.

Once data acquisition and preparation were complete for all of the predictor variables, a five-by-five mean pixel moving window filter was applied to all spectral and geographic layers. This moving window filter averages the 25 pixels in a five-by-five pixel neighborhood, replaces the center pixel with this mean value, and moves to the next pixel, repeating the process across the image to affect every pixel. The ''mean'' layers were then resampled (or aggregated) using a nearest-neighbor resampling method to five-by-five pixel ''blocks,'' or pixels that were 22 500 m^2 in size (2.25 ha). This effectively allowed for extracting the mean values for 2.25-ha areas from the predictor variable data layers for use in direct analysis with the response variable (2.25-ha photointerpreted plots).

Classification and regression tree analysis

Much land use and land cover class modeling has relied on supervised and unsupervised classification techniques. While effective at separating land cover classes with unique spectral properties, confusion often results when classes overlap spectrally (Lillesand and Kiefer 1994, Wright et al. 2000). Preclassification stratification or postclassification sorting using abiotic and geographic data is not uncommon (Vogelmann et al. 1998). These types of procedures might help to delineate confused classes but do not fully take advantage of information that is available in the abiotic data, as when such data are included in the classification models.

We used CART analysis to classify land use and land cover classes in the GYE. We felt the strong abiotic gradients in the study area would enhance the classification of cover classes beyond that based on spectral data alone. CART allows both spectral and ancillary data to be used to produce categorical rule-based models (Lawrence and Wright 2001). Although other models such as the maximum likelihood classifier also allow inclusion of ancillary data layers, CART has several advantages previously documented as part of this study (Lawrence and Wright 2001). CART creates a binary split of a single explanatory variable that best reduces deviance in the response variable after analyzing all predictor variables.

Modeling subsections 1 and 2: 1995

We used CART to model land use and land cover in 1995 for subsections 1 and 2 independently. Only the reference data from aerial photo transects located within a given subsection were used as the response variable for those areas. The binary decision trees for 1995 subsections 1 and 2 provided rules for classifying the landscape into three land cover classes at level A: vegetation, agriculture, and nonvegetated areas (rock). The spectral properties of urban areas overlapped with rock and bare ground. Thus, we identified urban areas visually on the satellite imagery with the use of road network density from TIGER line files and then masked these urban areas through on-screen digitizing. TIGER (topologically integrated geographic encoding and referencing) line files are a public product of the U.S. Census Bureau's database and include the geographic locations of streets, rivers, railroads, and other spatial features across the United States in digital format. We also masked large visible water bodies from classification by thresholding band 5 (mid-infrared) while we masked smaller rivers using TIGER line files. The TIGER lines therefore served as a useful abiotic ancillary variable for visual interpretation although they were not included as inputs to the CART model. Clouds and snow were not present in the imagery used for 1995 and were not classified. The ''rules'' from the level A CART decision trees for the two subsections were applied to the 1995 imagery. All areas classified as natural vegetation at level A were then subset and reclassified into level B classes. This process resulted in level A and level B land use/land cover maps of the two subsections which we then combined with the masked urban and water areas to create land cover maps for 1995.

Modeling subsection 3: 1995

To minimize edge effects of land cover classifications between the overlapping areas of subsection 1 and subsection 2 with subsection 3 (see Fig. 2), we used a methodology called applied radiometric normalization (Cohen et al. 2001) for the subsection 3 modeling. Instead of using the random stratified interpreted sites from aerial photos as the response variable to create an independent CART model, we chose random sites in the overlap areas between subsection 1 and subsection 3 and between subsection 2 and subsection 3 from the 1995 level A and level B modeled CART maps. In effect, the overlap areas were randomly sampled from the subsection 1 and 2 maps produced from the CART models and those samples were then used as the response variable for CART analyses at levels A and B for subsection 3. We then applied spatial modeling of the CART rules for subsection 3 in the same manner as for subsections 1 and 2. This process was used to capture the variability in vegetative cover across the GYE we saw in visual analysis of the subsection 1 and subsection 2 maps. All of the sites randomly generated in the stratified aerial photo transects and interpreted for subsection 3 were held aside to be used for validation. We found this technique to be successful upon visual analysis of the final mosaicked 1995 GYE land cover maps, where edge effects between the three subsections were minimal.

Modeling land cover change in 1985 and 1975

We used a ''thresholding'' technique to determine areas of land cover change in 1985 and 1975 from 1995 by using the 1995 modeled land cover as a base layer. Because imagery was available from different months, we used the tasseled-cap indices from the latest date for each year and subsection (August or September). A layer of change magnitude for 1985 was created using the equation

$$[(\mathrm{TC95}b1 - \mathrm{TC85}b1)^2 + (\mathrm{TC95}b2 - \mathrm{TC85}b2)^2 + (\mathrm{TC95}b3 - \mathrm{TC85}b3)^2]^{1/2}$$

where TC signifies late-date tasseled-cap indices, 95 and 85 the years 1995 and 1985 and $b1$, $b2$, and $b3$ represent the tasseled-cap indices brightness, greenness, and wetness, respectively. A layer of change magnitude for 1975 was developed using the equation

$$\sqrt{(\mathrm{TC95}b1 - \mathrm{TC75}b1)^2 + (\mathrm{TC95}b2 - \mathrm{TC75}b2)^2}$$

where TC signifies late-date tasseled-cap indices, 95 and 75 the years 1995 and 1975, and $b1$ and $b2$ represent the tasseled-cap indices brightness and greenness, respectively.

The equations created single-layer images showing the Euclidean distance in tasseled-cap-transformed spectral space between the two dates compared. The tasseled-cap indices were used because they represented a standardized response related to key variables (brightness, greenness, and wetness) correlated with land cover and land use. In the resulting images, pixels with low values (e.g., low Euclidean distances) were highly unlikely to have changed in land cover, and only pixels with relatively high values were logical candidates to examine for change.

We then visually examined these ''change magnitude'' data layers at varying levels for change/no change. Once we had determined the threshold value for each change-magnitude layer (using known areas of change as a guide), this value was used to mask no-change areas. For pixels of potential change, we developed CART models for levels A and B using the 1985 reference data for subsections 1 and 2 and we then applied these models only to these areas of change. We merged areas of no change from the 1995 map with the reclassified change areas to form land cover maps for 1985. Again, subsection 3 was modeled using randomly sampled sites from the overlap with the 1985 subsections 1 and 2 land and then modeled for change in the same manner as subsections 1 and 2. We repeated this procedure for 1975 data using MSS satellite imagery and a threshold ''change-magnitude'' layer calculated for 1995–1975.

We evaluated change across the GYE at level B. We generated matrices of change on a pixel-by-pixel basis for the change time periods 1975–1985, 1985–1995, and 1975–1995. These change matrices indicated the specific land cover classes the pixels changed from and to as well as the number of pixels that changed from one land cover class to another.

Final GYE land cover maps and accuracy assessment

We produced GYE-wide land cover maps by mosaicking all three subsections together for each level and time period. Our use of radiometric normalization minimized discontinuities at imagery scene boundaries. The final complete continuous maps that we produced were created and clipped to the GYE boundary for level A and level B for each of the time periods. We calculated accuracy assessments of each year and each level of the GYE land cover maps by using independent validation data sets interpreted from aerial photos. These validation data sets were assembled from sites sampled on aerial photographs using the same methodology applied in collecting the reference data. In further discussion of accuracies and results of these land cover maps, we will focus on the mosaicked GYE-wide data and not the individual subsections.

Results

Land cover area and change

Land cover/land use in the study area in 1995 was dominated by herbaceous (35%), conifer (30%), and mixed conifer (11%; Fig. 3, Table 4) cover types. Herbaceous vegetation occurred at all elevations, but was best represented at the lowest elevations in the higher altitude valleys and plains in the southern and eastern portions of the study area. Conifer and mixed conifer were primarily at mid and higher elevations. Burned areas were primarily associated with the 1988 wildfires that were centered on YNP. Woody deciduous and mixed woody deciduous areas covered only 3% of the study area and were primarily at mid-to-lower elevations on toeslopes and in riparian areas. Agriculture, including cropping and intensive livestock grazing, covered 11% of the area and was located in the broad valley bottoms on the north side of the GYE and in river bottoms elsewhere in the ecosystem where irrigation was possible. Urban area covered <1% of the GYE.

During the period 1975–1995, area in conifer decreased by 17%, while mixed conifer increased by 90%. Some areas in conifer in 1975 were burned or logged subsequently and became either burned, herbaceous, or mixed conifer by 1995 (Fig. 4). Wildfire was rare in the study area in the decade prior to 1975, so the 1988 wildfires in YNP resulted in a dramatic increase in burned area. Some of the land area burned in 1988 succeeded to other cover classes by 1995. Areas burned in 1988 but still lacking established vegetation in 1995 compose the great majority of the burned class in the 1995 maps (see Turner et al. [1994] for a map of the 1988 fires). The substantial increase in area of mixed conifer was primarily due to conifer being burned in 1988 and succeeding to mixed conifer by 1995. Some of the gains in conifer and mixed conifer were due to the encroachment of conifers into nonconifer habitats including herbaceous and woody deciduous. Woody deciduous and mixed woody deciduous declined over the 20-yr study period 1975–1995 by 46% and 24%, respectively, primarily by conversion to conifer, mixed conifer, and herbaceous. Area in agriculture over the 20-yr period decreased by 9%, primarily due to conversion to herbaceous under inclusion in the Conservation Reserve Program. Some agricultural lands also converted to conifer. The urban class expanded substantially in area (348%), at the expense of agriculture, herbaceous, and conifer cover types. Urban expansion was largely around the edges of cities and towns, although entirely new communities, like the ski resort town of Big Sky, Montana, were developed since 1975.

Examples of change in land cover and use in localized landscapes are depicted in Fig. 5. In and around the Targhee National Forest on the western border of Yellowstone National Park (Fig. 5a), clearcutting and wildfire altered conifer forests in the uplands while urbanization occurred in the recreational community of Island Park, Idaho. The Gallatin Valley surrounding Bozeman, Montana, exhibited substantial increase in urban areas and rural residences (Fig. 5b).

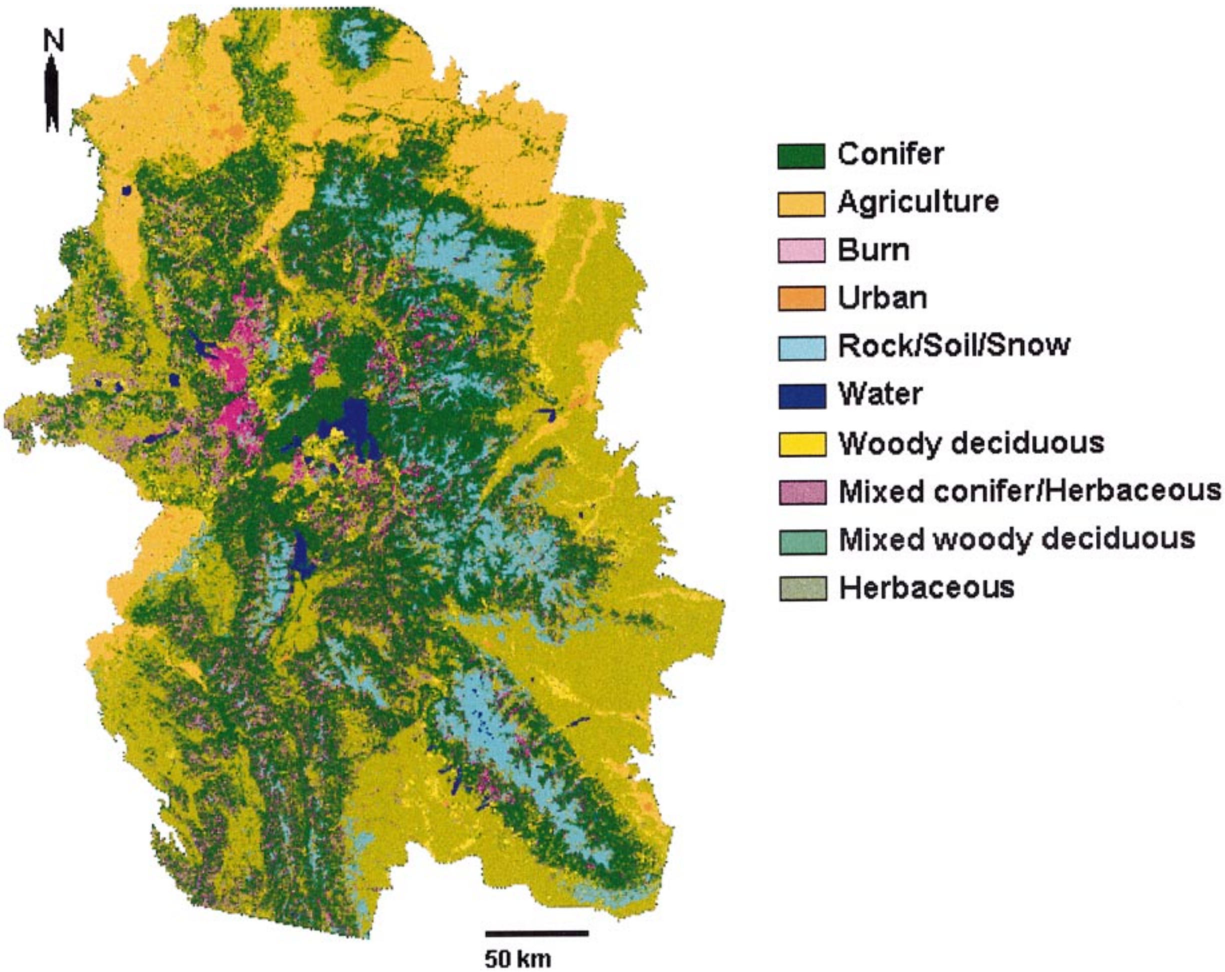

FIG. 3. Classified land cover map, level B, from 1995 imagery across the Greater Yellowstone Ecosystem.

Exurban development also increased dramatically during this time. The number of rural homes in the Montana and Wyoming portion of the study area increased by 402% during 1970–1997 (Hansen et al. 2002). This development was pronounced around population centers such as Bozeman, Montana, and Jackson, Wyoming. Exurban development also increased in relatively remote parts of the GYE, particularly along the major river valleys coming off the Yellowstone Plateau and the surrounding mountains.

Rates of change varied between the 1975–1985 and 1985–1995 time periods (Table 5). Most of the lost conifer area has occurred since 1985, most likely in association with the 1988 fire. Mixed conifer decreased in 1975–1985, possibly due to succession to conifer, but increased in 1985–1995 in association with postfire succession. Woody deciduous and mixed woody deciduous decreased more rapidly prior to 1985. Agriculture decreased in area during the first decade and expanded during the second decade. Rates of urban expansion were greater in 1975–1985 than in 1985–1995.

Accuracy assessment

Overall accuracy for 1995 level A was 97% (Table 6). Individual class accuracies ranged from 81% to 100% for producer's accuracy and 27% to 99% for user's accuracy. Producer's accuracy (or errors of omission) relates to the probability that a photo-interpreted reference sample will be correctly mapped on the classified image and user's accuracy (or errors of commission) relates to the probability that a pixel on the classified image actually matches the photo-interpreted reference data. Overall accuracy for 1985 level A was 95%. The producer's accuracies for individual classes ranged from 84% to 100% and the user's accuracies ranged from 71% to 97%. For 1975, the overall accuracy was 95%. Accuracies for individual classes in 1975 ranged from 63% to 100% for producer's accuracy and from 45% to 100% for user's accuracy. The greatest confusion occurred between agriculture and natural vegetation for all years, while the lowest accuracies were in the rock class.

Overall accuracy for 1995 level B was 83% (Table 7). Producer's and user's accuracies for individual

TABLE 4. Land cover/use change in the Greater Yellowstone Ecosystem for level B land cover/use classes for the period 1975–1995.

Class	Study area 1975 (%)	Total area (km²) 1975	Study area 1995 (%)	Total area (km²) 1995	Percent change 1975–1995	Total change in area (km²) 1975–1995	Pathways of change	
							Losses to (%)	Gains from (%)
ROCK SOIL	5.7	5437.12	6.8	6407.78	17.85	970.63	HERB (10.15) CON (6.36) MXCON (4.68)	CON (16.48) HERB (10.34) MXCON (5.76)
URBAN	0.1	49.13	0.2	220.03	347.8	170.89	HERB (1.85)	AG (48.7) HERB (21.13) CON (4.31)
WATER	0.9	881.46	0.9	846.86	−3.93	−34.60		
BURN	0.0	31.06	1.7	1573.76	4967.59	1542.70	HERB (40.51) MXCON (9.97) WD (7.07)	CON (76.76) HERB (13.51) MXCON (6.42)
AG	11.8	11 158.15	10.8	10 208.33	−8.51	−949.82	HERB (8.48) CON (4.64) URBAN (0.96)	HERB (5.73) CON (1.04)
CON	36.2	3438.10	29.9	28 344.45	−17.48	−6003.65	MXCON (10.02) HERB (7.62) BURN (3.50)	WD (5.40) HERB (2.47) AG (1.83)
WD	4.4	4197.77	2.4	2256.48	−46.25	−1941.29	CON (36.45) MXCON (17.24) HERB (12.63)	CON (29.24) HERB (6.58) MXCON (4.00)
HERB	33.6	31 911.58	35.1	33 302.79	4.36	1391.21	MXCON (6.69) CON (2.20)	CON (7.86) AG (2.84) MXCON (2.66)
MXCON	5.9	5690.29	11.4	10 845.08	90.59	5154.80	HERB (15.56) ROCK/SOIL (6.48)	CON (31.76) HERB (19.7)
MXWD	1.4	1245.78	0.8	944.92	−24.15	−300.87	HERB (32.23) MXCON (4.86) WD (4.98)	HERB (8.83) WD (7.20) AG (5.83)

Notes: MXCON, mixed conifer/herbaceous; MXWD, mixed woody deciduous/herbaceous; WD, woody deciduous; HERB, herbaceous; AG, agriculture; CON, conifer.

classes in 1995 range from 51% to 100% and from 52% to 100%, respectively. Overall accuracy for 1985 level B was 78%. The accuracies calculated for individual classes ranged from 25% to 100% for producer's accuracy and from 46% to 86% for user's accuracy. The lowest overall accuracy of 75% was in the 1975 level B land cover map. Producer's accuracies in 1975 for individual classes ranged from 22% to 100%. User's accuracies for individual 1975 classes ranged from 29% to 100%.

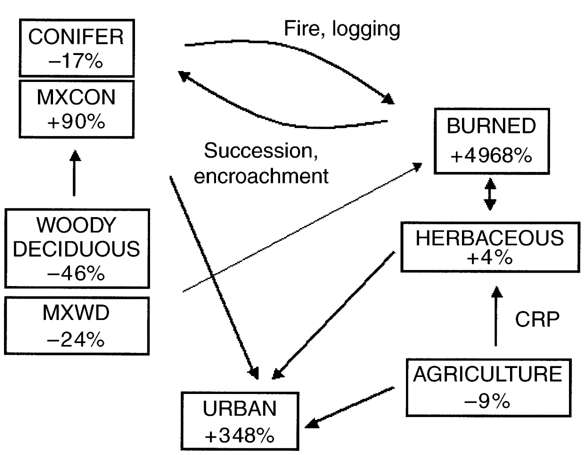

FIG. 4. Pathways of net gains and losses of percent cover change in the Greater Yellowstone Ecosystem, 1975–1995. MXWD = mixed woody deciduous/herbaceous, MXCON = mixed conifer/herbaceous.

The level B classes with the greatest extent in area had relatively high producer's and user's accuracies (70–100%). These included conifer, herbaceous, and agriculture cover/use types. The burn and urban classes also had high accuracies. The majority of confusion at level B in all three years occurred between related classes. The conifer/herbaceous mix (defined as a mix of herbaceous and conifer land cover with <70% conifer or <70% herbaceous) was most often confused with conifer and herbaceous cover types. The woody deciduous/herbaceous mix (defined as a mix of herbaceous and woody deciduous land cover types with <70% woody deciduous or <70% herbaceous) was most often confused with either woody deciduous or herbaceous cover types.

Although the overall magnitude of classification error was not determined, it should be noted that the classes of rock/soil and water had measurable changes in area that would not typically be expected over the 20-yr period of the study (Table 4). Although the rock/soil class increased ~970 km² during 1975–1995, it is likely that the apparent gain/loss (which occurred between the same cover classes of conifer, herbaceous, and mixed conifer) is due to classification error. Ad-

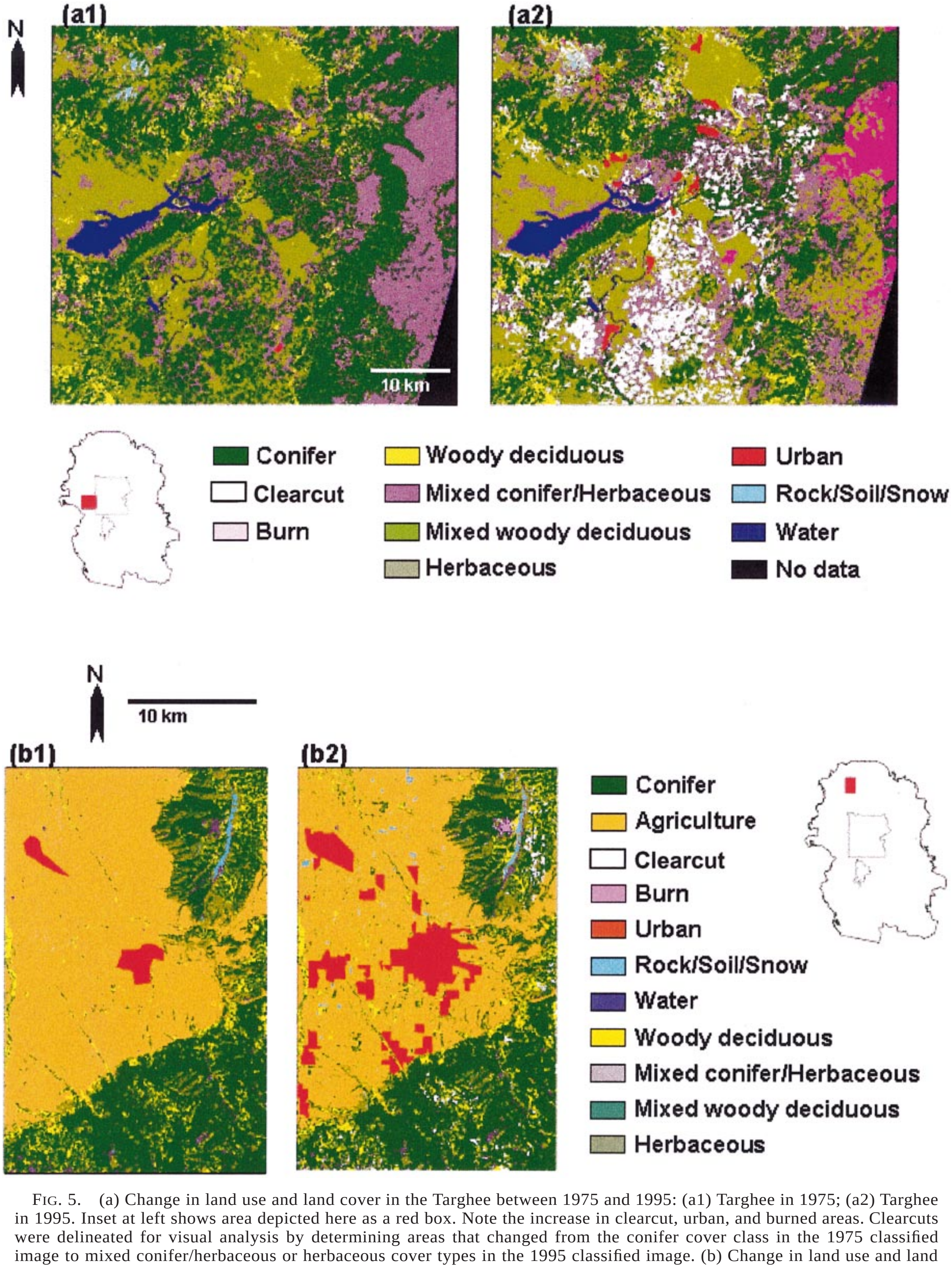

FIG. 5. (a) Change in land use and land cover in the Targhee between 1975 and 1995: (a1) Targhee in 1975; (a2) Targhee in 1995. Inset at left shows area depicted here as a red box. Note the increase in clearcut, urban, and burned areas. Clearcuts were delineated for visual analysis by determining areas that changed from the conifer cover class in the 1975 classified image to mixed conifer/herbaceous or herbaceous cover types in the 1995 classified image. (b) Change in land use and land cover in the Bozeman area between 1975 and 1995: (b1) Bozeman in 1975; (b2) Bozeman in 1995. Inset at right shows area depicted here as a red box. Note the increase in urban area.

TABLE 5. Rates of change in area of each cover class.

Class	Percent change in area 1975–1985	Percent change in area 1985–1995
Rock/soil	59.13	8.60
Urban	140.38	82.63
Water	−6.16	3.54
Burn	78.36	2759.86
Agriculture	−10.75	6.92
Conifer	2.79	−16.79
Woody deciduous	−39.54	−6.25
Herbaceous	6.35	−5.51
Mixed conifer/herbaceous	−36.77	92.06
Mixed woody deciduous/herbaceous	−32.12	−2.98

ditionally, water had a slight decrease in overall area over the study period (∼34 km^2) to multiple cover classes, none of which represented a significant ''gain to or loss from'' (Table 4) which may also be due to classification error. The changes seen in the rock/soil and water cover classes, therefore, may give a good estimate of the expected magnitude of error in the other classes.

DISCUSSION

Land cover, change, and ecological implications

The patterns of change in land cover and land use derive both from natural ecological processes and human demographic and socioeconomic processes. The largest change in aerial extent was conversion of conifer to mixed conifer, herbaceous, and burned classes. These changes were primarily driven by clearcut logging and by wildfire. Although we were not able to reliably separate logged areas from natural windthrow and insect mortality, other studies confirmed the large extent of logging in parts of the GYE (e.g., Fig. 5a). Within the Targhee National Forest west of Yellowstone National Park, some 38% of the area was logged between 1950 and 1990 (A. Hansen, *unpublished data*). Some of these logged areas remain in a herbaceous condition with tree seedlings and saplings present while the majority of these areas are now in a pole-age condition (mixed conifer in our classification system).

The large wildfires in 1988 also converted vast areas of conifer forest to earlier seral stages. These fires explained the dramatic increase in burned area during the time period 1985–1995. By 1995, however, vegetation growth in some burned sites (see Turner et al. 1997) led to them being classified as herbaceous or mixed conifer. Hence, the area classified as burned in 1995 was a subset of the actual area of the 1988 fires.

Vegetation history studies in the area indicate that forests of the GYE were dynamic in pre-Euro-American settlement times and driven by fire. Lower-elevation forests experienced relatively frequent (25–35-yr return intervals) and mixed severity fires (Littell 2002). Subalpine forests experienced high-severity fires at

TABLE 6. Error matrices for Level A Greater Yellowstone Ecosystem (GYE) land cover classification: 1995, 1985, and 1975.

	Rock	Urban	Ag	Veg	Row total	Producer's (%)	User's (%)
1995 Level A GYE accuracy assessment; overall accuracy, 97%							
Rock	6	0	0	16	22	100	27
Urban	0	21	0	2	23	81	91
Ag	0	4	118	15	137	90	86
Veg	0	1	13	1358	1372	98	99
Column total	6	26	131	1391	1554		
1985 Level A GYE accuracy assessment; overall accuracy, 95%							
Rock	5	0	0	2	7	100	71
Urban	0	25	0	4	29	100	86
Ag	0	0	272	43	315	84	86
Veg	0	0	51	1486	1537	97	97
Column total	5	25	323	1535	1888		
1975 Level A GYE accuracy assessment; overall accuracy, 95%							
Rock	5	0	0	6	11	63	45
Urban	0	8	0	0	8	100	100
Ag	0	0	366	68	434	91	84
Veg	3	0	37	1587	1627	96	98
Column total	8	8	403	1661	2080		

Note: Abbreviations are defined as follows: Ag, agriculture; Veg, natural vegetation.

TABLE 7. Error matrices for Level B Greater Yellowstone Ecosystem (GYE) land cover classification: 1995, 1985, and 1975.

	Rock	Urban	Burn	Ag	Con	Wd	Hb	MXCON/ Hb	MXHW/ Hb	Row total	Producer's (%)	User's (%)
1995 Level B GYE accuracy; overall accuracy, 83%												
Rock	6	0	0	0	0	0	0	0	0	6	100	100
Urban	0	21	0	0	0	0	0	0	0	21	81	100
Burn	0	0	43	0	1	0	0	0	0	44	74	98
Ag	0	4	0	118	0	2	4	0	2	130	96	91
Con	0	1	3	1	357	23	13	29	1	428	94	83
Wd	0	0	2	0	0	37	1	2	5	47	44	79
Hb	0	0	8	3	3	11	223	12	1	261	89	85
MXCON/Hb	0	0	2	0	20	5	8	44	1	80	51	55
MXHW/Hb	0	0	0	1	0	7	2	2	11	21	52	52
Column total	6	26	58	123	381	85	251	87	21	1038		
1985 Level B GYE accuracy; overall accuracy, 78%												
Rock	5	0	0	0	0	1	2	0	0	8	100	63
Urban	0	25	0	0	0	0	4	0	0	29	100	86
Burn	0	0	0	0	0	0	0	0	0	0	NA	NA
Ag	0	0	0	170	0	5	26	0	3	204	78	83
Con	0	0	0	4	563	12	14	86	5	684	92	82
Wd	0	0	0	3	2	75	2	2	8	92	59	82
Hb	0	0	0	41	27	12	329	26	2	437	83	75
MXCON/Hb	0	0	0	0	19	3	17	40	0	79	25	51
MXHW/Hb	0	0	0	0	1	20	2	3	22	48	55	46
Column total	5	254	0	218	612	128	396	157	40	1581		
1975 Level B GYE accuracy; overall accuracy, 75%												
Rock	4	1	0	0	2	0	2	0	0	9	100	44
Urban	0	8	0	0	0	0	0	0	0	8	89	100
Burn	0	0	0	0	0	0	0	0	0	0	NA	NA
Ag	0	0	0	241	1	3	20	1	4	270	97	89
Con	0	0	0	0	445	23	17	83	5	573	88	78
Wd	0	0	0	1	7	92	6	5	14	125	62	74
Hb	0	0	0	6	7	10	199	17	10	249	72	80
MXCON/Hb	0	0	0	0	37	3	29	30	3	102	22	29
MXHW/Hb	0	0	0	1	4	17	3	2	21	48	37	44
Column total	4	9	0	249	503	148	276	138	57	1384		

Note: Ag, agriculture; Con, conifer; Wd, woody deciduous; Hb, herbaceous; MXCON/Hb, conifer/herbaceous mix; MXHW/Hb, herbaceous/woody deciduous mix; NA, not applicable.

~250-yr intervals (Romme and Despain 1989). Between 1880 and 1988, fire was rare in the GYE, likely due to human exclusion. During this time, mature and old-growth conifer forests expanded substantially in area and patch size (Gallant et al. 2003). Since 1950, logging has reversed this trend of mature conifer expansion in parts of the GYE. In the Targhee National Forest, such logging has produced spatial patterns that were outside the historic range of variation (since 1705).

Thus, the reduction in closed conifer forest documented in this study represents a period of natural and human disturbance that was in contrast to the previous century of conifer forest expansion. While the 1988 fires are thought to be typical of those in pre-Euro-American settlement times (Rome and Despain 1989), the logging in the Targhee National Forest since 1950 was a departure from these presettlement patterns. It is apparent that these forests are highly dynamic over time. Efforts to predict ecological dynamics in this system (e.g., fire behavior, carbon storage, hydrological budgets) need to take into account this variability.

Another trajectory of change was from herbaceous and woody deciduous to conifer and mixed conifer. This observation is consistent with studies of matched sets of aerial photographs from the late 1800s and late 1900s (Greull 1983, Meagher and Houston 1998). Encroachment of conifer trees into conifer-free habitats is not uncommon in the Yellowstone region (Jakubos and Romme 1993) and is fairly dramatic on some of the 100-yr photo retakes as well as sufficiently fast to be detected in our 20-yr time period. This encroachment was most evident in the study area at the lower forest ecotone with grasslands. Frequent fires prior to Euro-American settlement are thought to have inhibited conifer forest in these settings (Gruell 1983). Fire exclusion by humans (due to both fire suppression and reduction of fuels through livestock grazing) in the 20th century might have allowed conifers to establish in these locations. Climate change over the past 100 years might also have favored conifer encroachment (L. Graumlich, *personal communication*). Conifer encroachment has considerable implications for fuel loadings and risk of fire, for carbon sequestration, and for wildlife habitats. We are currently working on more detailed studies of rates and consequences of conifer expansion in the GYE.

The loss of deciduous woodland and mixed-deciduous woodland in the study area is notable. The results indicated a 46% decline for the pure class and a 24% decline for the mixed class for 1975–1995. Close examination of the change maps leads us to believe that some of this change is real and some of it was due to classification error. Classification accuracy of these two classes was lower than many of the other classes due to the spectral similarity of deciduous woodlands to conifers and herbaceous vegetation and their distribution in small, narrow patches. We believe that the woody deciduous class was systematically misclassified as conifer in a northern portion of the study area west of Red Lodge, Montana, in 1995. Otherwise, classification error is not obviously aggregated spatially across the study area. While the results do not indicate precisely the rate of loss of aspen, other studies collaborate that aspen is declining across the GYE and that the rate is substantial. The Northern Range of YNP has experienced a 95% decline in aspen area since the 1870s (Kay and Wagner 1996). In the Centennial Range to the west of YNP, aspen forests declined by 84% since 1850, largely due to succession by conifers (Gallant et al. 2003). Further study is now underway to better quantify rates of loss of the woody deciduous cover type.

Loss of deciduous woodlands has important implications. These aspen, willow, and cottonwood forests are keystone habitats in the conifer-dominated Rocky Mountain ecosystems. The palatable foliage, relatively soft wood, and high rates of primary productivity result in these being required habitats for several species of plants, invertebrates, and vertebrates (Hansen et al. 2000). These woody deciduous habitats support the highest diversity of bird and shrub species among cover types of the GYE (Hansen et al. 1999). They may also serve as population source areas for some species that maintain sink populations in conifer and other less productive habitats across the ecosystem (Hansen and Rotella 2002). The type of change in deciduous woodlands documented in this study represents an important ecological concern. Public land managers are beginning to use prescribed fire and silviculture to restore aspen communities as it becomes clear that more research and adaptive management strategies are needed on this issue.

Agricultural area decreased by 9% during the study period. Our measure of agriculture is crude because it combines both cropping and more intensive livestock grazing. Separating these two types of agriculture would allow for clearer interpretation of possible drivers of agricultural change. Nonetheless, our study supports the conclusion that the loss of agricultural lands in the GYE was due to both the placement of marginal upland grain fields in the Conservation Reserve Program and to urban and rural residential expansion (Maxwell et al. 2000).

Perhaps the most interesting change documented in the study was the expansion of urban area and exurban development. The urban boundaries of many of the towns and small cities in the GYE expanded and, in a few cases, entirely new communities were built since the early 1970s. Similarly, rural home development occurred at a rapid rate on many of the private lands across the GYE.

Although private lands cover just 28% of the GYE, development on these lands may have a disproportionate effect on biodiversity due to the location of the development. Because of the harsh climate and infertile soils over most of the GYE, many native species are concentrated in small hotspots at lower elevations with good soils and moderate climate (Hansen et al. 2002). These hotspots are primarily on or near private lands. Exurban development has been disproportionately centered on these biodiversity hotspots. Domestic pets, exotic predators, and native predators often expand near human settlements and have negative effects on some native species (Odell and Knight 2001). In the northwest part of the GYE, Hansen and Rotella (2002) found that some bird species in hotspots had very low rates of reproduction, likely due to the effects of rural homes. The study suggested that exurban development near low elevation hotspots cause these places to change from population source areas to population sinks, thereby increasingly the likelihood of extinction within Yellowstone National Park. Urban and exurban development may also destroy native habitats (Oeschli 2000), alter flow levels and nutrient concentrations in rivers and lakes, create barriers to movement of native species, and modify fuel loads thus increasing the risk of severe fire.

Classification models

A separate CART model was produced for each level of classification, for each year in the study, and for each subsection resulting in a total of 18 models. The contribution of spectral and geographic predictor variables varied by model in both the number of variables that were included as well as by the type of variables that were used (Table 8). One pattern that emerged, however, was that for each of the 18 CART models some combination of both spectral and geographic variables was used to form the ''rules'' for classification. Elevation was the geographic variable that contributed most often to the models, while tasseled-cap bands (either difference in tasseled cap or the individual tasseled-cap bands) and the raw spectral bands of near-infrared for TM and red and green for MSS contributed most often as spectral variables (Table 8). Further analysis of the contributions of individual variables to the CART models is discussed in Lawrence and Wright (2001).

TABLE 8. Spectral and geographic variables used in the CART models.

	1995		1985		1975	
Location	Level A	Level B	Level A	Level B	Level A	Level B
Subsection 1	tcap diff 1, 2, 3	tcap diff 1, 2, 3	tcap diff 1, 3	tcap diff band 3		
				tcap 1, 2	tcap 1, 2	
	elevation		elevation, slope		elevation, slope	elevation, slope, aspect
	June 4, 5, 6	June bands 3, 4	June bands 3, 4, 6	June bands 3, 5		
		June tcap 1, 2		June tcap 1, 2		
	Aug band 5	Aug tcap 2, 3	July band 5	July band 4	Sep band 1 tcap 1, 2	Sep bands 1, 2 tcap 2
Subsection 2	tcap diff band 3					
	elevation	elevation, slope	elevation	elevation, slope	elevation	elevation, slope
		June band 1				
	June tcap 2	June tcap 1, 2, 3				
	Aug band 4	Aug bands 3, 4, 5, 7		Aug band 7	Sep band 1	Sep band 2
		Aug tcap 2	Aug tcap 2	Aug tcap 1, 2	Sep tcap 2	Sep tcap 1, 2
Subsection 3	elevation	elevation, slope	elevation, aspect	elevation, slope	elevation, slope	elevation, slope, aspect
	Sep bands 3, 4, 5	Sep bands 1, 3, 4, 5, 6, 7	Aug bands 3, 6	Aug bands 1–7	July bands 1, 4	July bands 1–4
	Sep tcap 2	Sep tcap 1, 2, 3	Aug tcap 1, 2, 3	Aug tcap 1, 2	July tcap 1, 2	July tcap 1, 2

Note: tcap diff, seasonal tasseled cap index; tcap, tasseled cap index.

Classification accuracy

The overall accuracies of the level A classification (>94%) were very high. The lower accuracies seen in the level B maps (overall accuracy >74%) compared with level A maps were expected because of the increased detail of the cover classes.

The lower accuracies at level B were largely the result of spectral confusion between related classes. The fine spatial patterning of some cover classes relative to the resolution of the analysis also lead to lower accuracies for some classes. The woody deciduous habitats of cottonwood, aspen, and willow often occurred as narrow linear patches along streams, or as small irregular patches within conifer. Many of these small and/or narrow patches were missed at the 2.25-ha resolution of our classification. This was especially true for the Landsat MSS imagery used for the mid-1970s classification. Additionally, CART analysis does not incorporate spatial context (i.e., pattern) but acts only on individual pixels. The result is that patterns that might be noticeable to a human interpreter are not considered.

Evaluation of reference data approach and sample sizes

Due to the short growing season in the GYE, only three to four dates during the years of interest were captured with the Landsat satellites. We were limited further in the available imagery because it was essential to use cloud-free imagery for modeling land cover and it was therefore not possible to use the same months of imagery for each year. Other ancillary data layers that might have helped eliminate some of the confusion between classes, such as soil and climate (precipitation, snowfall, and temperature), were available only at unsuitably coarse resolutions.

The land cover in the GYE also presented some physical limitations to the study design. Given the 2.25-ha sample unit size and model development resolution used in this study, it was difficult to generate enough reference and validation samples of the most rare cover classes, especially woody deciduous. Woody deciduous areas most often occur in the GYE in either long linear patches along riparian zones or in patches often smaller than 2.25-ha at the forest/grassland boundary. It was not possible to model areas of woody deciduous vegetation smaller than 2.25-ha because of the resolution and RMS error associated with the satellite imagery rectification as well as the resolution of the aerial photos from which the reference data were interpreted. A combination of spectrally mixed pixels and shadowing may have contributed to the problems of modeling woody deciduous vegetation.

The use of CART was advantageous for incorporating ancillary data into the land cover models but might have been limiting in its ''best split'' nature. Because CART only picks the very best binary split at each level of the tree while reducing variance, other ''second best'' splits are ignored that might lead to patterns missing in the present maps. CART, like many statistical models, is sensitive to large variances or discrepancies within the reference data. Reference data should be collected from relatively homogenous areas and must include both the range of physical environments present for each cover class within the study area, as well as all types of land cover known to be present. The land cover classes most often confused in this study (mixed woody deciduous/ herbaceous, and mixed conifer/herbaceous) were, by definition, not homogenous and therefore not surprisingly misclassified most often. It was also not possible or practical to sample every type of vegetative land cover across the GYE. This might have added to spectral confusion when unknown cover types were present and forced into one of our defined cover classes.

Contextual evaluation of GYE land cover change

Overall, our results are consistent with those of other change-detection efforts documenting land use intensification in rapidly growing areas of the United States and around the world. Most rural counties in the United States are growing rapidly in human population density (Johnson 1998). This is driving considerable change in land cover and use. Across the United States, area classified as urban grew by 13–24% between 1982 and 1992 within each region of the country (Flather et al. 1999). Within Colorado, for example, rural development increased by over 240 km^2 annually between 1960 and 1990, a rate exceeding the combined rates for urban, suburban, and ranch development (Theobald 2000). Preliminary results from a set of case studies funded by the NASA Land Cover Land Use Change Program[9] indicate high rates of change since the 1970s in several places in the world.

Collectively, these studies of landscape change reveal very high rates of human population growth, land use intensification, and loss of natural habitats around the world. Studies such as ours of land cover and land use change hold promise of informing citizens and governments of rates of change and allowing for better-informed land use policy decisions.

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[9] URL: ⟨http://lcluc.gsfc.nasa.gov/⟩

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