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Change in the forested and developed landscape of the Lake Tahoe basin, California and Nevada, USA, 1940–2002

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Abstract

The current ecological state of the Lake Tahoe basin has been shaped by significant landscape-altering human activity and management practices since the mid-1850s; first through widespread timber harvesting from the 1850s to 1920s followed by urban development from the 1950s to the present. Consequences of landscape change, both from development and forest management practices including fire suppression, have prompted rising levels of concern for the ecological integrity of the region. The impacts from these activities include decreased water quality, degraded biotic communities, and increased fire hazard. To establish an understanding of the Lake Tahoe basin's landscape change in the context of forest management and development we mapped, quantified, and described the spatial and temporal distribution and variability of historical changes in land use and land cover in the southern Lake Tahoe basin (279 km^2) from 1940 to 2002. Our assessment relied on post-classification change detection of multi-temporal land-use/cover and impervious-surface-area data that were derived through manual interpretation, image processing, and GIS data integration for four dates of imagery: 1940, 1969, 1987, and 2002. The most significant land conversion during the 62-year study period was an increase in developed lands with a corresponding decrease in forests, wetlands, and shrublands. Forest stand densities increased throughout the 62-year study period, and modern thinning efforts resulted in localized stand density decreases in the latter part of the study period. Additionally forests were gained from succession, and towards the end of the study period extensive tree mortality occurred. The highest rates of change occurred between 1940 and 1969, corresponding with dramatic development, then rates declined through 2002 for all observed landscape changes except forest density decrease and tree mortality. Causes of landscape change included regional population growth, tourism demands, timber harvest for local use, fire suppression, bark beetle attack, and fuels reduction activities. Results from this study offer land managers within the Lake Tahoe basin and in similar regions a basis for making better informed land-use and management decisions to potentially minimize detrimental ecological impacts of landscape change. The perspective to be gained is based on quantitative retrospection of the effects of human-driven changes and the impacts of management action or inaction to the forested landscape.

Keywords: Land-use and land-cover change; Forest dynamics; Fire suppression; Lake Tahoe basin; California

1. Introduction

The Lake Tahoe basin landscape has been greatly changed since Euro-American settlers first arrived in the region in the 1850s. Timber was harvested for local use starting in 1861 and gave way to widespread cutting to fuel Nevada's Comstock Lode silver mining from 1873 to 1898 leaving 60% of forests in the basin clearcut (Leiberg, 1902). Small-scale logging resurged in 1910 for local needs and continued through the 1960s (Lindström, 2000). Sheep and cattle overgrazed deforested lands through the 1930s hindering much of the second-growth forest regeneration (Strong, 1999).

Urban development in the early 1900s consisted of small vacation resorts and a few communities until the post-World War II era of urbanization. With the transportation infrastructure in place by the 1930s allowing access to the basin by northern California's growing and economically prosperous population, the shift from a resource-extraction-based economy to one dependent on recreation and tourism was complete. The demands of this economy have continued to increase over time (Strong, 1984). Loosely regulated residential and commercial development increased through the 1950s to accommodate more visitors and a greater permanent population.

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The basin continues to be known for Lake Tahoe's deep, clear water and the surrounding forested mountain landscape; in fact much of the region's popularity as a tourist destination is based on the perception of a healthy environment (Elliot-Fisk et al., 1996). However, there is evidence that changes in land use and land cover, particularly to the vast forested expanses within the Lake Tahoe basin, over the past 150 years of human activity and especially since the onset of urbanization may have brought about undesirable ecological conditions in the present day. In the Lake Tahoe basin disturbance increases sediment and nutrient availability and may increase other inputs that result in degraded water quality and clarity (Reuter and Miller, 2000; Goldman, 1994; Byron and Goldman, 1989). Conversion of vegetative natural land-cover types, including forests, wetlands, and riparian zones to urban uses may have adverse impacts on biotic communities (Manley et al., 2000). Changes in forest characteristics and extent may increase fire hazard, posing risk to property, public safety, and natural resources themselves (Taylor, 2004; Stephens et al., 2004; Manley et al., 2000). As land managers, policy makers, conservation groups, and scientists seek to minimize the detrimental effects of past and future changes to the natural communities of the Lake Tahoe basin, an understanding of the characteristics of change over time and across the landscape is needed.

While much of the Lake Tahoe basin is forested, its landscape is comprised of numerous different vegetative communities that can be characterized into unique, descriptive land-cover categories. Similarly where development has occurred the landscape can be described in terms of its land use. Together, land use and land-cover categorization provides a means to identify spatial and temporal changes using a simple and common organization structure. Several studies have sought to characterize or classify land use/cover in the Lake Tahoe basin at varying spatial scales and thematic detail for a single date. The US Western Federal Regional Council (1979) presented some of the first quantified estimates of land-use/cover change in the basin using zoning and water quality management data to classify land disturbed as of 1976. The study estimated that 15% of forests, 5% of shrublands, 35% of stream zones, 50% of meadows, and 75% of marshes have been lost to development since 1900. The Tahoe Regional Planning Agency (TRPA) has utilized land classification systems to address planning issues starting with a system developed by Bailey (1974) that classified land based on geology according to the capability of an area to tolerate a level of use without sustaining permanent damage. In 1989 the TRPA implemented the Individual Parcel Evaluation System (IPES), which built upon Bailey's system to prevent development of the steepest, most erodible slopes (TRPA, 2004). The California Tahoe Conservancy (CTC) mapped ten classes of ground cover in 14 riparian zones using 1996 digital videographic imagery for a riparian assessment (Butt et al., 1998). Cablk and Minor (2003) derived a basin-wide binary raster impervious-surface layer from 2002 IKONOS imagery using image processing and geographic information system (GIS) data integration. Dobrowski et al. (2006) mapped vegetation in the basin using 2002 IKONOS imagery and spatial modeling. The Lake Tahoe Total Maximum Daily Load (TMDL) study mapped land use using current imagery, parcel data, and impervious-surface area as an input to a watershed model (Riverson et al., 2005). Much of the previous characterizations were not focused on the greater forested landscape, rather they were focused on discrete landscape elements in an effort to directly cope with development pressure. These efforts were conducted without an accounting of the surrounding forest matrix which has regenerated since the basin was clearcut in the late 1800s.

Despite efforts to understand the extent to which the Lake Tahoe basin has been affected by human activities, a quantitative assessment of multi-temporal land-use/cover change for the urbanization era had not been conducted. Nechodom et al. (2000) observed that "there is no geography of settlement over time that can be used to isolate the effects of building on the [basin's] biophysical system" and that "this could be accomplished by constructing a series of maps that describe the geography of built and modified surfaces as they have accumulated over time." Elliot-Fisk et al. (1996) identified a need to complete a more thorough analysis of the basin's historical record that is, in part, archived in written and graphic form. The geographic application we developed and present here was implemented in part as a step towards filling this data gap and to consider landscape change and management in the context of the Lake Tahoe basin's forests.

The purpose of this study was to assess landscape changes in the southern Lake Tahoe basin (SLTB) during the era of regional urbanization in the physical context of the surrounding forested land. In particular our objectives were to quantify the spatial and temporal distribution and variability of change within the SLTB (Fig. 1). We used these results to describe how and to what degree different types of anthropogenic influences may have contributed to landscape change and corresponding trends. An important step in understanding the impacts of landscape change is to determine the characteristics of change over time and across the landscape as well as the possible causes and implications of those changes. Additionally this study provides quantitative data that may be useful in formulating land-use, water quality, and forest management policy aiming to alleviate adverse impacts of past and future landscape changes.

2. Methods

2.1. Study area

The Lake Tahoe basin (latitude 39.07° N, longitude 120.00° W) lies in the central Sierra Nevada physiographic province split by the California–Nevada state border and contains portions of six counties, three national forests, and ten state parks. The steep hydrographic basin covers 1311 km^2 of the montane and subalpine zones from 1900 to 3050 m with the surface area of Lake Tahoe accounting for 38% (498 km^2) of the basin. Average temperatures range from 20 °C from June through September to −4 °C from December through March. Average annual precipitation ranges from over 76 cm on the eastern side of the basin increasing to about 178 cm on the western side and occurs mostly as snow from November

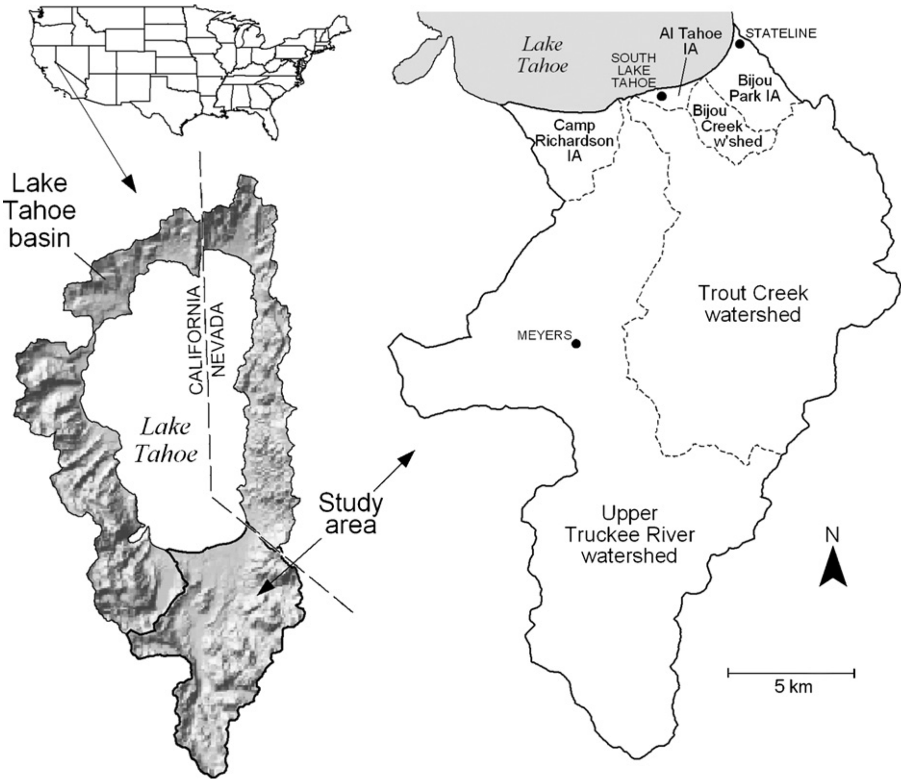

Fig. 1. The southern Lake Tahoe basin study area (279 km^2), California and Nevada, USA. On the right, the study area is divided by hydrographic boundaries between watersheds and intervening areas (IA).

through April (Rowe et al., 2002). Our study area in the southern portion of the basin consists of 34% (279 km^2) of the basin's terrestrial area and includes the Upper Truckee River, Trout Creek, and Bijou Creek watersheds and three intervening areas that drain directly into the lake. Varying landscape conditions and levels of human disturbance occur in the SLTB, representing a range of land-use/cover types that occur throughout the entire basin, from old-growth forest stands to the most urbanized areas in the basin flanking the lake.

Natural vegetation in the Lake Tahoe basin is dominated by coniferous forest, much of which is still undergoing succession after intensive logging during the Comstock period. White fir (*Abies concolor*) and red fir (*Abies magnifica*) dominates mesic sites while Jeffrey pine (*Pinus jeffreyi*) dominates xeric sites below 2000 m. In general, these three species are the most abundant but are also found intermixed together as well as with other conifer species (Graf, 1999). Density of more shade-tolerant white fir has increased over Jeffrey pine throughout the basin as a result of fire suppression activities (Elliot-Fisk et al., 1996). Lodgepole pine (*Pinus contorta* var. *murrayana*) dominates forests on harsh or wet sites in the subalpine zone (Taylor, 2004). Shrublands include montane chaparral, alpine scrub, and Great Basin sagebrush communities that often represent successional stages following fire, cutting, or other disturbances. Wetlands occur as riparian zones, meadows, and marshes and are dominated by quaking aspen (*Populus tremuloides*), black cottonwood (*Populus balsamifera*), and willow (*Salix* sp.).

Similar to the rest of the basin, public lands make up the majority of the SLTB. Approximately 78% of the SLTB is administered by the U.S. Forest Service (USFS) Lake Tahoe Basin Management Unit. Twenty-one percent of the SLTB is in private ownership while 1% is under State of California-administration as parks or recreation areas. The SLTB includes three county jurisdictions in California and Nevada. Urban development in the basin is regulated by the TRPA, a bi-state regional land-use and environmental planning agency.

The Lake Tahoe basin economy revolves around recreation and tourism, and currently there is a robust planning partnership called Pathway 2007 to simultaneously sustain a healthy environment and a healthy economy. In 1998, lodging, eating and drinking establishments, and recreation providers together accounted for 52% of the employment and 44% of the total earnings in the basin (Nechodom et al., 2000). More than eight million people live within a few hours drive to Lake Tahoe and this proximity to the San Francisco, Sacramento, Reno-Carson City, and even Los Angeles urban areas results in a steady flow of tourists drawn to seasonal and perennial recreational activities such as hiking, skiing, biking, water sports, sightseeing, shopping, and casino gaming. The basin supports a permanent population of approximately 55,000 and on any given weekend the population can swell to over 200,000 with over 23 million visitors annually (Elliot-Fisk et al., 1996).

2.2. Imagery and data

No large-scale multi-temporal thematic land-characterization data existed for any part of the Lake Tahoe basin at the onset of this study, so a comprehensive data collection and production effort was required. We built a database of vertically integrated historical and current imagery from which land-use/cover data could be derived using manual photo interpretation and image processing techniques. Archived black and white aerial photos dated 13 July 1940 and 16 August 1969 and natural color aerial photos dated 27 July 1987 were processed to produce digital orthophotos with a 1-m horizontal scale (Raumann et al., 2004). IKONOS multispectral satellite imagery was acquired on 19 July 2002 for a project total of four individual dates and three periods for analysis.

We mapped land use/cover from the four dates of imagery using manual, or visual, interpretation techniques in a GIS. Image interpretation was performed systematically by a skilled group of six individuals with an average of 20.5 years of image interpretation experience. The interpreters adhered to strict quality-control protocols including peer review to minimize subjectivity and assure consistency. The minimum mapping unit (MMU) was 0.4 ha and the minimum polygon width was 18 m for ground features. Land use and land cover was classified using a thematic hierarchy rooted in the Anderson et al. (1976) system that we modified to better characterize Lake Tahoe basin land-use/cover types. In total, 43 classes were defined and mapped for the SLTB up to a Level III-equivalent thematic resolution. The Level I, or major, classes were based on definitions presented by Loveland et al. (2002) that describe general land-use change with land cover serving as a surrogate for land use. The data was compiled into one master vector data layer that contained all land-use/cover polygons and respective class codes for each year as separate attributes. We dissolved polygon boundaries in the master data layer based on identically classified adjacent polygons for each of the four dates to create unique data layers for each imagery date.

The five major natural-cover classes were forest, grass/shrubland, wetland, barren, and water. The forest class was defined as land with a tree canopy-cover density greater than 10% and was further separated into subclasses based on a canopy-cover threshold of 50%. Separation of the forest class into the two canopy-cover categories, 10–50% or >50%, was made by ocular estimation with reference to visual examples of known forest densities. Reliability of our density delineations is based on stringent mapping protocols and the relative broadness of the two canopy-cover categories. The grass/shrubland class was comprised of vegetative cover with less than 10% tree canopy-cover density and greater than 10% coverage of small tree and shrubs including evergreen and deciduous species of true shrubs, desert scrub, and chaparral. Grasslands within the grass/shrubland major class were covered by herbaceous plants with the total of all tree and/or shrub canopy cover being less than 10% and included most ski runs with regrowth following initial clearing. Wetlands were defined as lands where the water table is at, near, or above the land surface for a significant part of most years with associated vegetation that covers more than 25% of the land surface. Naturally occurring unvegetated lands consisting primarily of exposed rock outcrops at higher elevations and sand beaches, including human-made beaches, were classified as barren. The water class included any areas of open water that met the MMU requirements. Dead upland and dead wetland vegetation was classified for those areas that met the MMU requirements.

The major developed land-use class includes all residential, commercial, industrial, transportation/roads, utility, and recreational subclasses. Land use took precedent over land cover when criteria were met for more than one class definition. For example a residential subdivision that occurred in a forest setting was classified as 'developed, residential' even though the natural-cover type met the classification criteria for the forest class. Human-induced transitional cover types fell into the mechanically disturbed major class. These lands were unimproved and in an altered and usually unvegetated state. Some ski runs with minimal to no vegetation regrowth due to higher intensity of use were classified as mechanically disturbed. The final classification is presented below with our results.

In order to better characterize developed land use we visually estimated impervious-surface area created by paved roads, parking lots, driveways, and building footprints. Impervious-surface area is a quantifiable land-cover component of developed land use. Each land-use/cover polygon contained a separate attribute that was an estimate of impervious-surface area from 0% to 100% in 5% increments where 100% indicates that the area of a polygon was entirely impervious. These estimates were interpreted for every polygon for each date of imagery regardless of whether the area of a polygon and/or land-use/cover class changed between imagery dates.

2.3. Data accuracy

Although it was not possible to conduct a statistical accuracy assessment of the multi-temporal data layers because historical ground-truth data was not available in form or content, we were able to compare the manually interpreted 2002 impervious-surface area estimates in the land-use/cover data layers with a separate basin-wide raster impervious-surface data layer that was directly but independently derived from the same 2002 IKONOS imagery on a per-cell basis using image processing and GIS data integration (Cablk and Minor, 2003). This impervious-surface data layer (1-m^2 cell size) had an overall 92% accuracy. Two statistical models, one discrete and one continuous, were developed based on the empirical relationship between the 1-m^2 data layer and the manually interpreted estimates. The discrete best-fit model was then applied to the four dates of visually interpreted impervious-surface area estimates. This method proved successful in minimizing error in the manually interpreted impervious estimates (Cablk and Raumann, unpublished data).

2.4. Change detection and measurement

The four dates of the vector land-use/cover data layers were converted to raster layers with a 4 m × 4 m cell size for change detection by post-classification comparison. We calculated total area and area changed by land-use/cover class for each period and used cell-by-cell change data to detect, quantify, and determine the direction ('from' and 'to' classes) and context of land-use/cover 'conversions' (i.e., urban development) and 'modifications' (i.e., forest density increase), which together we referred to as *changes* (Coppin et al., 2004).

We ranked individual land-use/cover changes between major classes and subclasses for the 62-year study period based on the total changed area during each period:

$$\text{Total changed area} = \text{Area}\Delta_{1940-1969} + \text{Area}\Delta_{1969-1987} + \text{Area}\Delta_{1987-2002}$$

We ranked the total changed area from greatest to least total area changed in addition to existing literature and knowledge of the SLTB to group similar individual changes into descriptive groupings (e.g., development or forest density increase). We selected average annual rate of change as a metric to describe land-use/cover trends because it effectively normalizes the results for each period to an annual scale. This method is useful for analyzing multi-temporal data as it eliminates confusion that can result from looking at the total amount of change in each period when period durations are varied. Annualized rate of change is calculated by dividing the area changed between two dates by the period duration in number of years.

3. Results

Fig. 2 illustrates an example of mapped land use/cover for a portion of the SLTB. In 2002 the SLTB was dominated by forest (68.5%) with developed (8.9%), grass/shrubland (8.2%), wetland (7.2%), and barren (5.3%) land-use/cover types comprising the majority of the remaining area (Table 1). These major class totals, as well as composition of some subclasses, vary from the totals in 1940 and the corresponding rates of change have fluctuated throughout the 62-year study period. The forest, developed, and grass/shrubland classes were the most dynamic in terms of gross area changed which includes both gains and losses of class area (Fig. 3). The culmination of net area changed (area gained minus area lost) over time shows that in general all classes underwent the most change before 1987 after which time rates of change began to level off (Fig. 4).

The dominant change in terms of areal extent during the 62-year study period was the conversion of all undeveloped land to developed land uses (Table 2). In 1940 the SLTB developed lands covered only 0.4% of the total area. By 1969, development had increased at an average rate of 47.3 ha per year and developed lands increased to 5.3% of the SLTB. Between 1969 and 1987 the development rate slightly increased to 49.3 ha per year. Of the 887.1 ha developed during this 18-year period, 15% of the area was gained from lands already mechanically disturbed as of 1969 while the remaining 85% was gained from undisturbed vegetated lands. From 1987 to 2002, development continued to increase but at a slower annualized rate of 8.9 ha per year.

Approximately 935 ha of impervious surfaces were added to the SLTB from 1940 to 2002 accounting for an increase in imperviousness from 0.1% to 3.5%. As of 2002, 43% of all impervious surfaces in the Lake Tahoe basin were located within the SLTB as shown by the 1-m^2 impervious-surface data layer (Cablk and Minor, 2003). Predictably, the spatial and temporal variability of impervious-surface increase was similar to that of all developed lands throughout the 62-year study period with a much higher rate of increase from 1940 to 1969 (17.9 ha per year) and 1969–1987 (19.6 ha per year) than from 1987 to 2002 (4.1 ha per year).

Area lost from the forest class accounted for 2054.9 ha gained by development or disturbance from 1940 to 2002 (Table 3). In total 12.7% of wetlands, 9.9% of forests, and 8.5% of grass/shrublands were lost to the major developed class, mechanically disturbed class, and, in some cases, the water class which together can be considered all direct human-induced disturbances. As development rates slowed from 1987 to 2002, so did the rate of natural-cover loss accordingly, and in the case of wetlands practically no class area (0.2 ha) was lost to development during the 1987–2002 period.

Development in the SLTB radiated from the town of Meyers, the intersection of Highways 50 and 89, along Highway 50 in the City of South Lake Tahoe between "The Y" (junction of Highways 50 and 89) and Stateline, NV, and to a lesser degree along Pioneer Trail (Fig. 5). Residential areas lined the fringe of and often encroached upon wetlands while 50% of all developed lands and impervious surfaces occurred within 2.5 km of the Lake Tahoe shoreline. Commercial and residential areas were developed on average slopes of 10.2° and 5.4°, respectively and together primarily occupy the SLTB's lower elevation range of 1900–2793 m with a mean of 1935 m.

Approximately 2195 ha of conifer forest with a canopy-cover density of 10–50% transitioned to a canopy-cover density of >50%. Total area of conifer forest with a canopy-cover density >50% increased by 22%. The annualized rate of forest densification was much higher from 1940 to 1969 (62.3 ha per year) than from 1969 to 1987 (13.7 ha per year) and 1987–2002 (9.4 ha per year). The geographic distribution of forest densification was relatively dispersed throughout the SLTB with 73.4% occurring below 2300 m (Fig. 6A). The density of forest cover in the SLTB had also decreased in some areas as indicated by the transition of 792.2 ha of conifer forest with a canopy-cover density >50% to a canopy-cover density of 10–50%. About half (49%) of this land-cover modification occurred most recently during the 15-year period from 1987 to 2002 and the remainder was split between the 1940 and 1969 (25%) and 1969–1987 (26%) periods. Forest converted to grass/shrubland at a rate of 13.6 ha per year from 1940 to 1969 and slowed to less than half that rate thereafter. The geographic distribution of density decrease (Fig. 6B) and forest conversion to grass/shrubland (Fig. 6C) appeared to be localized.

The extent of forest cover also increased in some areas as 981.0 ha of the major grass/shrubland class and 121.0 ha of scrub/shrub and herbaceous wetlands changed to forest and forested wetlands classes, accounting for a 35.1% loss of grass/shrubland and 6.3% loss of non-forested wetlands to forest totaling a 5.3% gain of forest from these classes since 1940. This expansion of the forest class occurred at its greatest rate

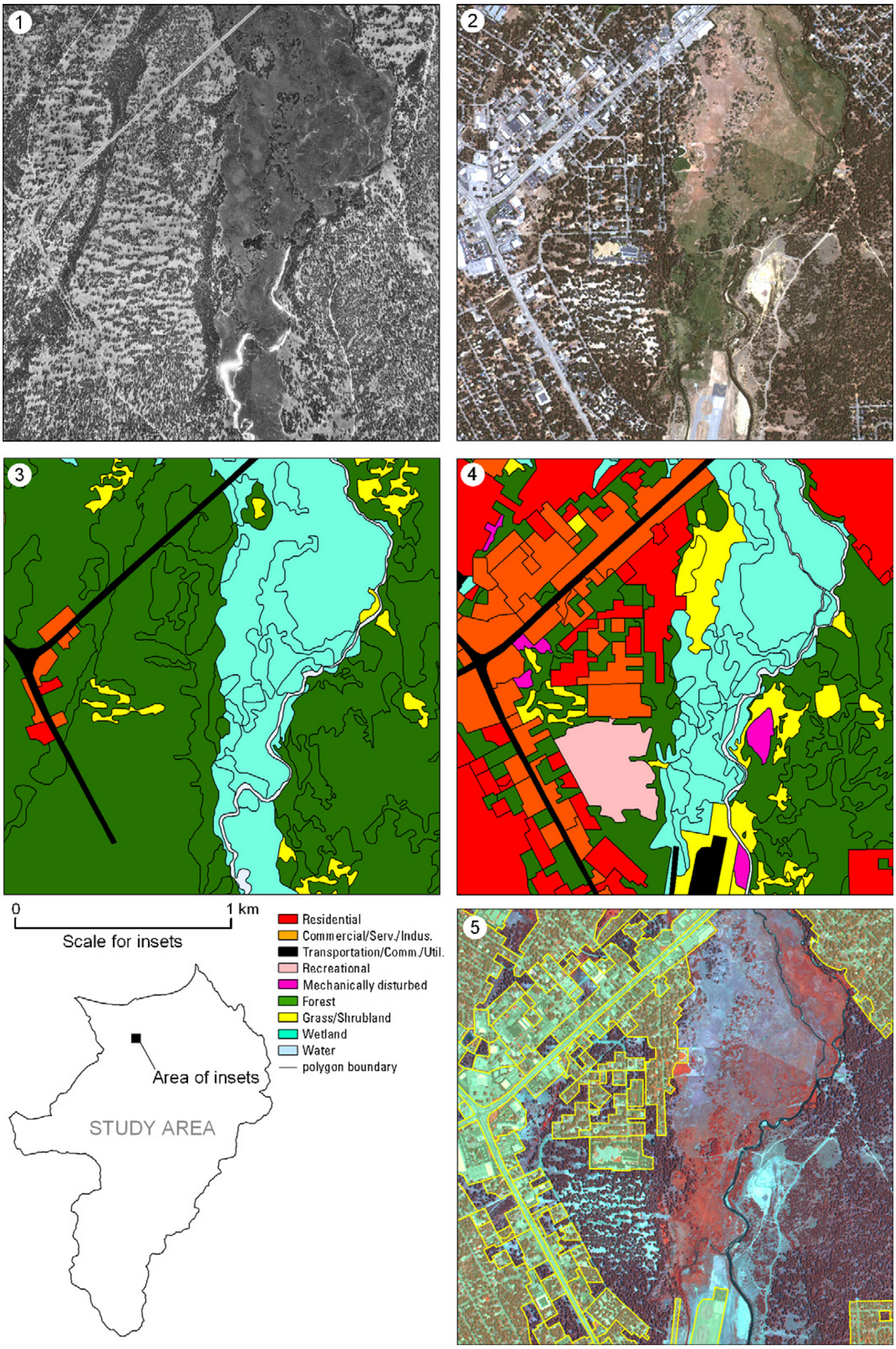

Fig. 2. Example of land-use/cover mapping and change for the same 410-ha area in the southern Lake Tahoe basin. Content of insets are: (1) 1940 digital orthophoto; (2) 2002 IKONOS imagery, false natural color composite (bands 3-2-1); (3) 1940 and (4) 2002 major land-use/cover classes; and (5) urban classes overlying 2002 IKONOS imagery, near-infrared composite (bands 4-2-1). Polygon boundaries within major classes in (3) and (4) represent higher thematic resolution subclasses.

from 1940 to 1969 and has decreased since. From 1969 to 2002, 23.0% (98.5 ha) of the area that changed to forest from grass/shrubland and wetlands occurred in areas of forest loss between 1940 and 1969, with the remaining majority occurring in undisturbed areas. The geographic distribution of forest expansion was dictated by the locations of grass/shrubland and wetland cover types, and in some cases, previous disturbances (Fig. 6D).

Table 1
Land-use/cover class area by year as a percent of total area of the southern Lake Tahoe basin (27,946 ha)

	1940	1969	1987	2002	Net change (1940–2002)	
Land-use/cover class	%	%	%	%	ha	%
Developed major class	0.4	5.3	8.5	8.9	2391.8	2234.2
Residential	0.2	3.3	6.1	6.4	1741.9	2997.6
Commercial/services/industrial	0.1	0.9	1.1	1.2	307.6	1742.7
Transportation/communication/utilities	0.1	0.6	0.7	0.7	170.9	606.5
Recreational	0.0	0.5	0.6	0.6	171.3	5502.1
Mechanically disturbed major class	0.0	1.0	0.3	0.2	58.5	835.0
Mining major class	0.0	0.0	0.0	0.0	6.7	n/a
Forest major class	74.4	70.7	69.0	68.5	−1644.9	−7.9
Conifer forest, 10–50% canopy cover	59.9	51.1	50.1	50.8	−2546.1	−15.2
Conifer forest, >50% canopy cover	14.4	19.5	18.9	17.6	889.9	22.1
Other (deciduous, mixed, planted)	0.1	0.1	0.1	0.1	11.3	50.5
Grass/shrubland major class	10.0	9.0	8.3	8.2	−508.8	−18.2
Herbaceous	1.3	1.9	1.5	1.5	66.4	18.2
Brush/shrubland	8.7	7.2	6.9	6.6	−575.2	−23.6
Wetland major class	8.9	7.4	7.3	7.2	−485.3	−19.5
Herbaceous wetland	4.5	3.0	2.5	2.5	−572.7	−45.5
Scrub/shrub wetland	2.4	2.4	2.6	2.6	48.4	7.2
Forested wetland	2.0	2.0	2.1	2.1	39.0	7.0
Barren major class	5.4	5.3	5.3	5.3	−17.4	−1.2
Water major class	0.9	1.2	1.3	1.2	103.7	43.1
Dead vegetation major class	0.0	0.0	0.0	0.3	95.8	n/a
Dead upland vegetation	0.0	0.0	0.0	0.2	67.6	n/a
Dead wetland vegetation	0.0	0.0	0.0	0.1	28.2	n/a
Total, major classes	100.0	100.0	100.0	100.0		

n/a: class area was zero in 1940, so a percent change value could not be calculated. Subclasses are listed and indented below major classes. Negative net change values indicate a net decrease in area of a particular land-use/cover class. Positive net change values indicate a net increase in area of a particular land-use/cover class. Net change values for subclasses may be greater than that of corresponding major classes due to fluctuations between subclasses. Impervious surfaces are not included in the developed major class totals as the impervious surfaces estimate further describes land already classified within the developed class. Net change shows the amount of class area changed (in ha and as a percent of 1940 class area) overall during the 62-year study period.

Between 1987 and 2002, 67.6 ha of forest and 28.2 ha of forested wetlands transitioned to dead vegetation classes. We detected a negligible amount of tree mortality before 1987. The 2002 land-use/cover data showed locations of most patches of dead trees in and along the border of wetland areas in Washoe Meadows State Park at the confluence of Angora Creek and the Upper Truckee River and also on USFS land along upper Trout and Saxon creeks (Fig. 6E).

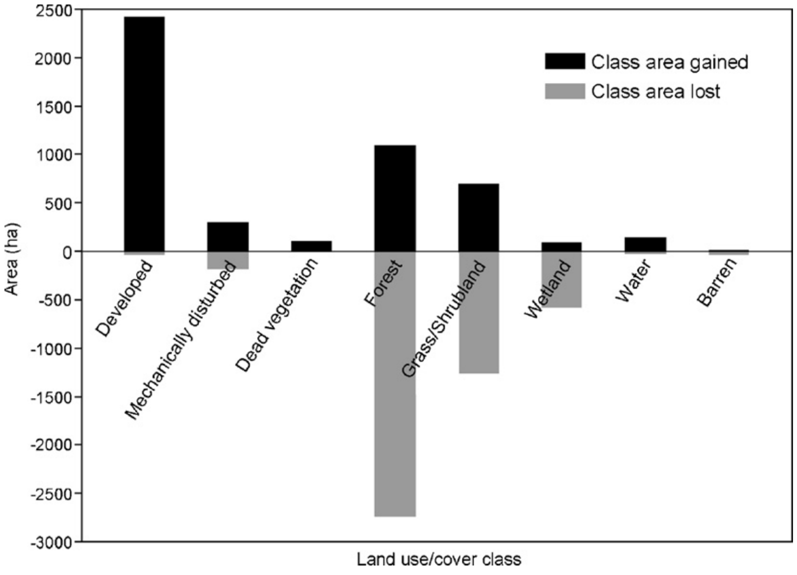

Fig. 3. Area lost and gained (i.e., gross change) by land-use/cover class from 1940 to 2002 in the southern Lake Tahoe basin.

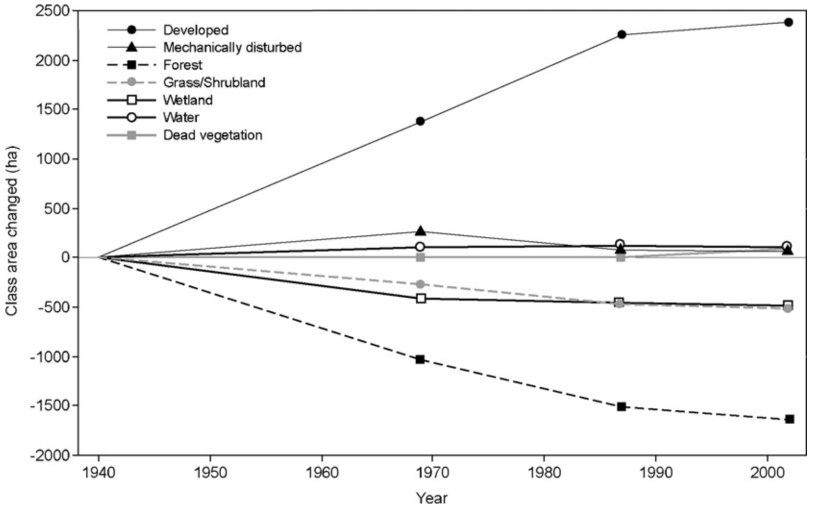

Fig. 4. Cumulative net area changed by major land-use/cover class from 1940 to 2002 in the southern Lake Tahoe basin. The steepness of each line serves as a proxy for rate of change with a steeper line indicating a higher rate of change and a flatter line representing a lower rate of change.

Table 2

Ranking of individual land-use/cover changes by total area changed for changes affecting greater than 25 ha from 1940 to 2002 in the southern Lake Tahoe basin

Rank	From class	To class	Area (ha)	% of all changes
1	Forest 10–50%, canopy cover	Forest, >50% canopy cover	2195.2	27.7
2	Forest	Developed	1926.6	24.3
3	Grass/Shrubland	Forest	1001.8	12.6
4	Forest, >50% canopy cover	Forest, 10–50% canopy cover	792.2	10.0
5	Forest	Grass/Shrubland	560.4	7.1
6	Grass/Shrubland	Developed	205.1	2.6
7	Mechanically disturbed	Developed	153.8	1.9
8	Wetland	Developed	134.3	1.7
9	Wetland	Mechanically disturbed	130.8	1.7
10	Forest	Mechanically disturbed	128.3	1.6
11	Wetland	Water	125.2	1.6
12	Wetland	Grass/Shrubland	106.4	1.3
13	Forest	Dead upland vegetation	71.4	0.9
14	Wetland	Forest	48.6	0.6
15	Forest	Wetland	34.7	0.4
16	Wetland	Dead wetland vegetation	29.2	0.4
Total			7643.9	96.5

4. Discussion

The Lake Tahoe basin landscape, like any other natural system, is dynamic and as such it responds to alterations from human activities evidenced by changes to the forest canopy, succession, tree mortality, and development among others. The ecology of the basin likewise reflects these changes and has been measured in terms of changes to water quality, sedimentation, air quality, and other biotic and abiotic metrics. The changes within the forested and natural vegetation communities over time showed effects from both active management practices and from policy, such as fire suppression and implemented bans on controlled burns along with other regulations on private landowners related to tree removal and view enhancement. These management practices and policies were set into place as development including infrastructure expansion grew to meet the demands of the growing tourist and recreation economy of the region particularly in the mid-1900s. Management and policies changed the structure of the forests which, being interconnected in the landscape matrix, ultimately affects other vegetation communities and landscape elements such as riparian zones, water bodies, wetlands, and shrublands. The results from our change analysis show the vectors of change and for forests, documents recent historical impacts of management and policy evidenced by changes in density and extent.

4.1. Development trends

Most of the development in the SLTB occurred between 1940 and 1987 as forest land conversion. The main type of development was residential and the SLTB saw a concomitant increase in infrastructure between 1940 and 1969 to support community expansion. The rate of commercial development was also highest from 1940 to 1969 and by 2002 was the second largest developed land use next to residential. The increase in

Table 3
Annualized rates of change (ha per year) by period and overall amounts of change for the entire 62-year study period in the southern Lake Tahoe basin

Change	Land-use/cover class		Period			
	From class	To class	1940–1969 29 years (ha per year)	1969–1987 18 years (ha per year)	1987–2002 15 years (ha per year)	1940–2002 62 years (ha)
Development	Undeveloped classes	Developed	47.3	49.3	8.9	2391.8
	Pervious land	Impervious surfaces	17.9	19.6	4.1	935.7
Natural-cover loss	Forest	Developed	43.7	37.3	7.7	2054.9
	Grass/Shrubland	Developed	4.2	5.3	1.5	238.9
	Wetland	Developed, water	10.3	1.0	0.0	315.3
	Total		58.1	43.6	9.2	2609.0
Forest density increase	Forest 10–50% CC	Forest >50% CC	62.3	13.7	9.4	2195.2
Forest expansion	Grass/Shrubland	Forest	21.2	15.1	6.3	981.0
	Non-forested wetland	Forest, forested wetland	1.8	2.5	1.5	121.0
	Total		23.0	17.5	7.9	1102.0
Forest loss	Forest	Grass/Shrubland	13.6	5.7	4.2	560.4
Forest density decrease	Forest >50% CC	Forest 10–50% CC	6.9	11.4	25.9	792.2
Tree mortality	Forest	Dead upland vegetation	0.1	0.0	4.4	67.6
	Forested wetland	Dead wetland vegetation	0.0	0.0	1.9	28.2
	Total		0.1	0.0	6.2	95.8

CC: canopy cover. Development includes all developed classes and the transitional mechanically disturbed major class. The wetland-to-water conversion represents 50.6 ha of wetlands dredged and filled during the construction of the Tahoe Keys residential development.

development corresponded to regional population increases and the subsequent demands of recreation and tourism. Population growth trends for the entire Lake Tahoe basin and more locally for the City of South Lake Tahoe, incorporated in 1965 and located within the SLTB, mirrored development increases with a relatively constant rate of increase through the mid-1980s, after which both population and development rates began to slow considerably (Fig. 7).

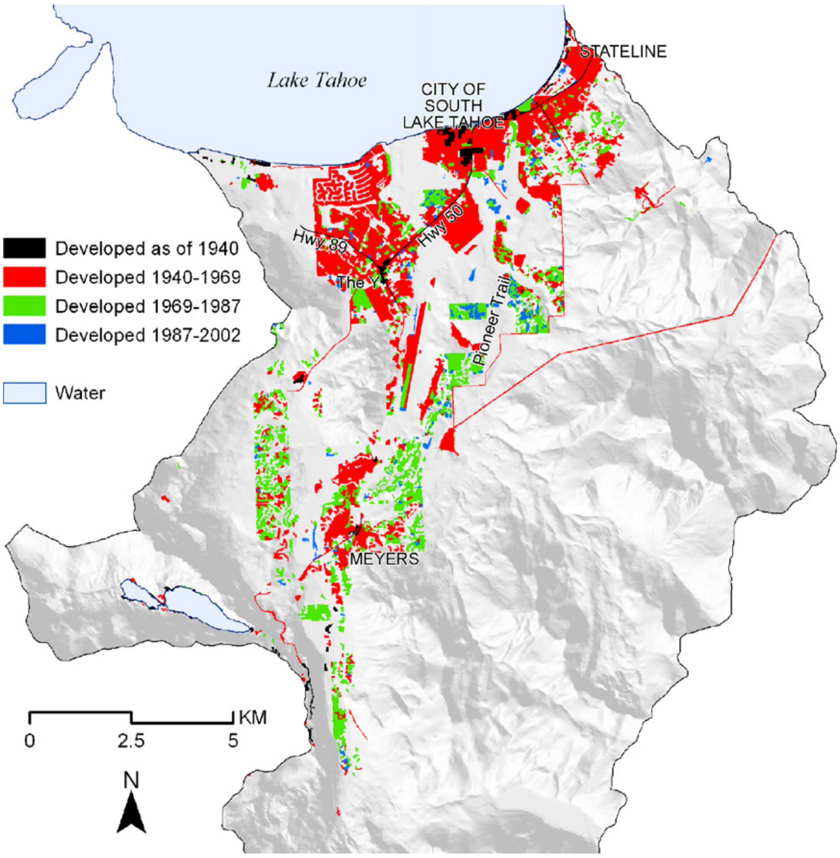

Fig. 5. Spatial and temporal distribution of land developed from 1940 to 2002 in the southern Lake Tahoe basin. Development that occurred during each period cumulatively comprises the footprint of development as of 2002. The only roads shown are sections of highway that meet the 18-m minimum polygon width.

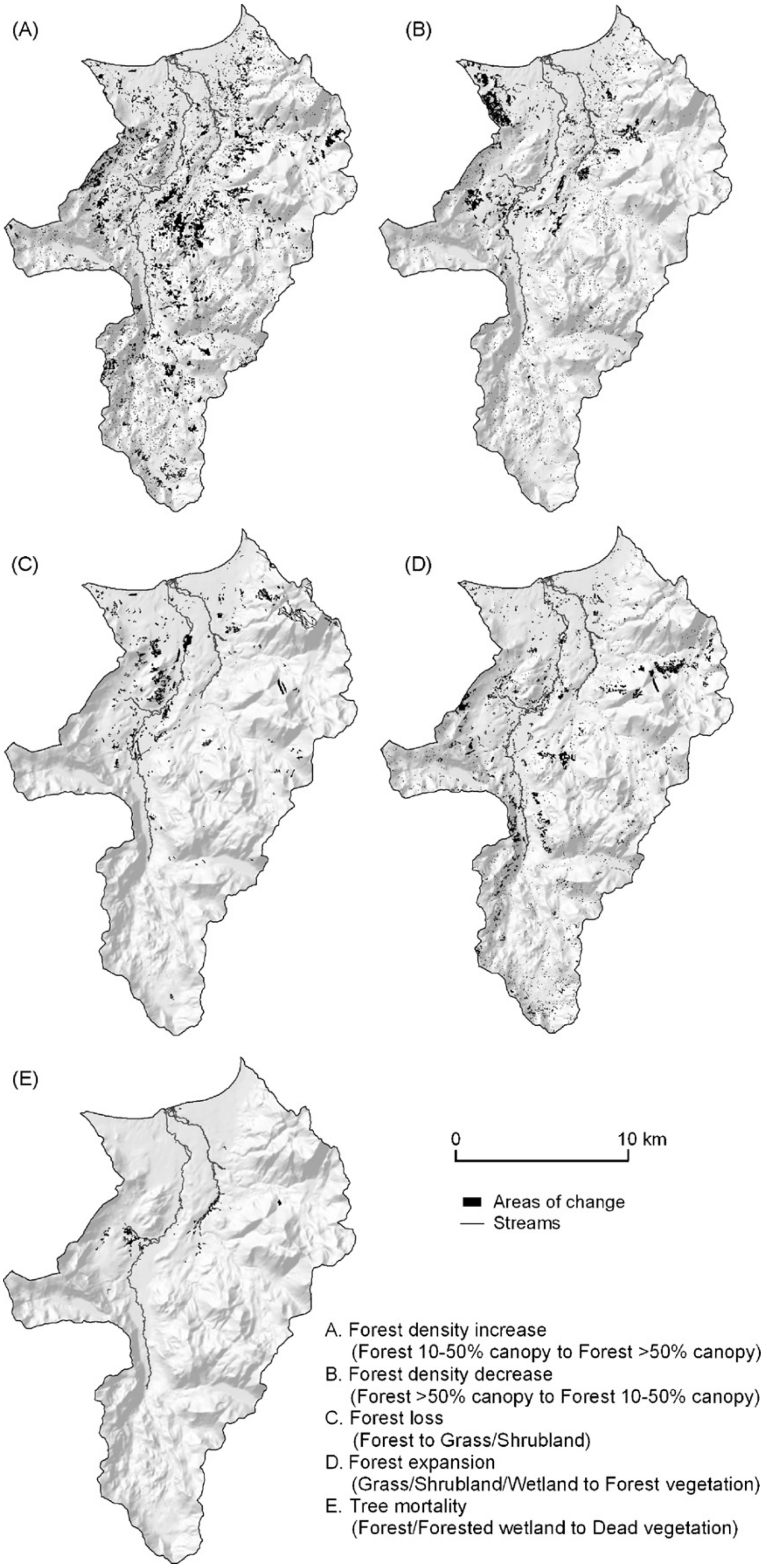

Fig. 6. Spatial distribution of land-cover changes occurring in undeveloped areas from 1940 to 2002 in the southern Lake Tahoe basin. Each change is represented by black patches on the corresponding maps.

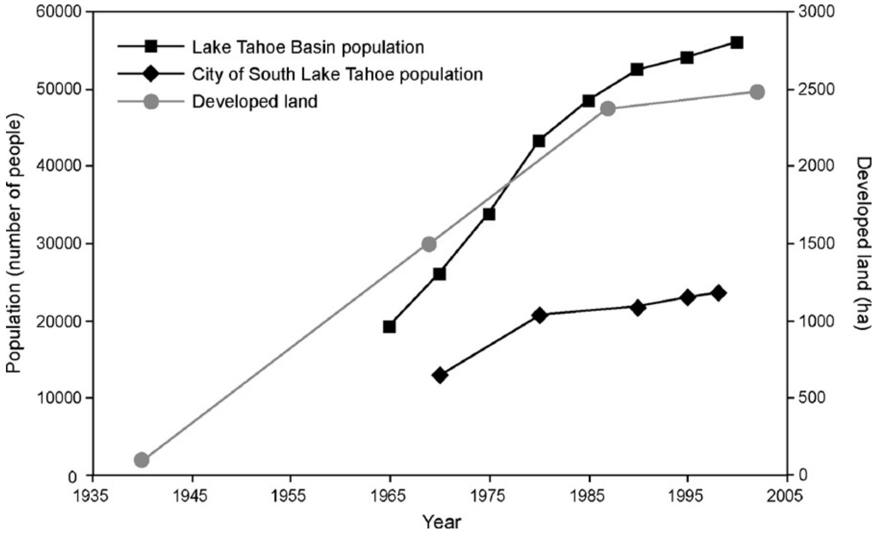

Fig. 7. Population growth in the Lake Tahoe basin and City of South Lake Tahoe and developed land increase in the southern Lake Tahoe basin. Lake Tahoe basin population data from Nechodom et al. (2000); City of South Lake Tahoe population data from California Department of Finance city and county profiles, 1999.

After 1987 development rates dropped significantly, presumably for two main reasons. The first may have been due to constraints on land availability. There is a finite amount of land in private ownership in the SLTB and by 1987 much of the private land that was available for development was developed. During the 1930s only about 15% of total terrestrial area in the entire Lake Tahoe basin was under public ownership (Strong, 1999). In the 1950s public ownership, primarily by the USFS, stood at 20% of the basin, and urban development during this time prompted increased public land acquisition as the resulting ecological impacts focused attention on acquisition of sensitive lands in urban areas. The Land and Water Conservation Fund Act of 1965 increased the ability of the USFS to carry out exchanges and purchases of private land holdings, increasing federal holdings to 65% by the early 1970s. Between 1982 and 1999 lands in public ownership further increased to 87% as $187 million was spent purchasing 2422 ha through the federal Santini-Burton Act, Lake Tahoe Acquisition Bond Act in CA, and Nevada Tahoe Basin Act in NV (Nechodom, 2000). The California Department of Parks and Recreation (CDPR) has also been acquiring lands since 1927 complementing the efforts of the USFS. Overall the 100-year history of public land acquisition in the basin has reduced private ownership to 12% basin-wide and reflects changes in public policy regarding recreation, environmental protection, and availability of purchase funds (Elliot-Fisk et al., 1996). Public land acquisition has been a significant factor contributing to the declining trend of development through the decrease of private lands available for subdivision and subsequent development. Furthermore, acquisition efforts created the unique mosaic pattern of ownership in urban areas of scattered publicly owned lots within privately owned subdivisions.

The second main contributing factor was the change in attitude of the resident and policy communities who began to see the negative impacts of unregulated development on the ecological quality of the basin as early as the 1960s as shown by scientific studies. These changes in cultural attitudes and values invoked the evolution of a strict regulatory environment marked by the formation of the TRPA in 1969. In 1982 the TRPA established environmental carrying capacity thresholds for the categories air and water quality, soil conservation, vegetation, noise, wildlife, fisheries, recreation, and scenic resources and may be expanded in the future to include socio-economics, transportation, and fuels. Each category includes explicit indicators as metrics of environmental condition and most of these indicators to varying degrees are affected by landscape change. To allow additional time to prepare and adopt a regional plan, the TRPA enforced development moratoria between August 1981 and August 1983 and between August 1983 and April 1984 (Lucero and Soule, 2002). The TRPA adopted a regional plan to attain threshold standards in 1987, and from 1987 to 2002 the annualized rate of land converted to development decreased to 82% of the 1969–1987 annualized rates. This rate decrease is likely strongly related to the pursuit of threshold attainment as well as other regulatory limits on development.

Urban development has been a significant contributing factor to the deterioration of environmental quality in the Lake Tahoe basin. The direct conversion of natural cover to varying intensities of developed lands translates to habitat loss, fragmentation, and degradation contributing to decreased biological integrity of floral and faunal communities (Manley et al., 2000). In the SLTB natural land cover was lost to many types of development including road building, residential, commercial, and infrastructure construction, and development of recreational facilities such as ski areas, marinas, golf courses, and campgrounds. As in similar regions, development on a relatively small amount of private land may have a disproportionate effect on biodiversity as many native species occur on these lands, especially development in wetlands which tend to have higher species diversity (Parmenter et al., 2003). Furthermore, landscape fragmentation affects diversity throughout trophic levels. Forest health is largely a function of the biotic components of that system and landscape fragmentation brings changes in biotic composition. Therefore the increase in development may also affect the health of the upland communities in ways that are not directly measurable with multi-temporal photographs or imagery. The ecological effects of fragmentation in terms of species richness, exotic species invasion, impacts on rare, threatened, or endangered species or on endemic species in the Lake Tahoe basin have not yet been evaluated.

Land disturbance, including the emplacement of impervious surfaces, coupled with the effect of environmental variables have contributed to the degradation of tributary stream- and lake-water quality and clarity by affecting nutrient and sediment input (Reuter and Miller, 2000; Byron and Goldman, 1989). Impervious surfaces prevent ground percolation and effectively increase runoff velocity, peak flows, stream-water temperature, erosion potential, and non-point source pollutant concentrations (Slonecker et al., 2001; Brabec et al., 2002). Increased runoff in concentrated locations during storm events subsequently increases the sediment load in streams that empty into the lake. Nutrients carried in those storm pulses contribute to algal blooms (Taylor, 2002), which are a significant contributor to decreased water clarity in the lake (Goldman, 1988). The increase in development is considered to be the most important contributor to the documented loss of water clarity at least since 1967 when lake clarity measurements began (Goldman, 1994; Jassby et al., 1999; Reuter and Miller, 2000). In addition the sediment record shows conclusively that human activity during the urbanization era has caused a great deal more erosion and nutrient loading in the basin than during the Comstock era (Heyvaert, 1998).

4.2. Wetlands, urbanization, and environmental quality

Wetlands experienced the greatest loss relative to class area from 1940 to 2002 (485.3 ha, 19.5%). During this time, 45.5% of all herbaceous wetlands were lost, and about half of this loss was the result of conversion to developed land uses. The remaining half of all herbaceous wetlands lost underwent succession to other natural-cover classes. Furthermore, in 1940 the total area of all wetlands was greater than developed lands by a ratio of 23.3 to 1, but by 2002 developed land outnumbered wetland area by a ratio of 1.2 to 1. In response to rapid wetlands loss the TRPA established stream environment zones (SEZs) in 1981 and has enforced a prohibition on development within SEZs since that time. Most of the wetlands mapped in this study are located within SEZ boundaries and the effectiveness of this restriction was demonstrated by the loss of only 0.2 ha of wetland area during the 1987–2002 period.

The substantial loss of wetlands, as with other vegetated cover, is problematic in part because of the importance of wetlands to Lake Tahoe water quality. Functional wetlands filter runoff through nutrient uptake and by trapping sediments. This function is compromised when wetlands are drained, altered, or encroached upon (Weller et al., 1997) and therefore the loss of wetlands in the SLTB may be a contributing factor to water quality and clarity issues of the lake itself. One notable case occurred between 1940 and 1969 as 50.6 ha of wetlands were lost to the Tahoe Keys residential development. This project was completed in the late 1960s and included the dredging, filling, and development of a substantial amount (40.2%) of what was the largest marsh (416.5 ha in 1940) in the Lake Tahoe basin for the creation of a residential neighborhood, artificial lagoon, and marina.

4.3. Forest trends and changes to undeveloped natural areas

Although urban development may be the most recognizable and conspicuous change that occurred within the SLTB since

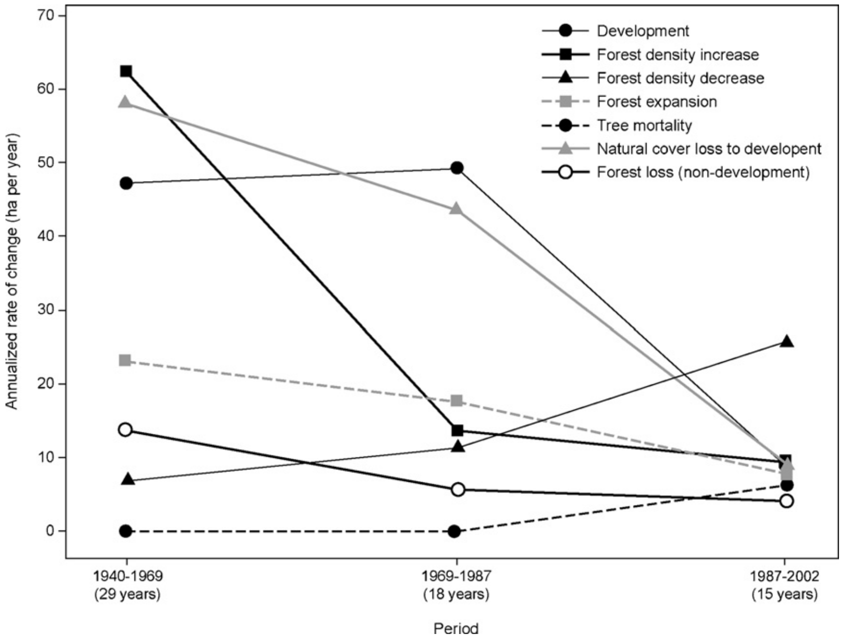

Fig. 8. Annualized rates of land-use/cover change for the southern Lake Tahoe basin.

1940, significant fluctuations between and within vegetative natural-cover classes have occurred as well. In terms of areal extent, forest densification was the dominant change observed among natural-cover changes (Fig. 8). Effective fire suppression as mandated by state and federal policy since the 1920s has played a significant role in shaping the forests of the Lake Tahoe basin including densification (Elliot-Fisk et al., 1996; McKelvey et al., 1996; Manley et al., 2000). Presettlement fire return intervals from 1500 to 1850 have been determined to range from 5 to 29 years on the west side of the Lake Tahoe basin (Elliot-Fisk et al., 1996) to 3–8 years for sites on the east side (Taylor, 2004). In contrast we detected no fires in the SLTB during our 62-year study period, and USFS fire perimeter data shows that only one small fire event (4.8 ha in 1987) occurred between 1930 and 19 July 2002 in the SLTB which we determined to be unmappable.

Forest densification was detected at elevations up to 3000 m, however the majority (73.4%) occurred below 2300 m, which coincides with the approximate upper elevation limit of Jeffrey pine–white fir forests. Similarly Taylor (2004) found that fire suppression has resulted in greater changes, including increased density, in Jeffrey pine–white fir forests than for other forest types since Euro-American settlement on the east side of the Lake Tahoe basin. While the species composition of these forests allows for growth resulting in denser stands, anthropogenic variables should also be considered in that most of the developed areas within the basin are at lower elevations. Therefore development has occurred in forest stand types conducive to increased density, and forest policy has emphasized public safety thus increasing fuel loading in and around developed areas. This interplay between development patterns, forest stand types, fire suppression, and forest management policy sets the stage for catastrophic loss when fire occurs.

Forest stands in the SLTB are much denser than would be expected under a natural fire regime for the Lake Tahoe basin (Manley et al., 2000). The few old growth stands of forest remaining in the basin as well as a reconstruction of presettlement forest conditions (Taylor, 2004) give us a view of the open forests that would be expected without fire suppression. Similar effects of fire suppression and fire exclusion have been documented in the western U.S. (Taylor, 2000; Gallant et al., 2003). The implications of increased forest density include increased total biomass as well as tree mortality due to greater inter-tree competition, insect attack, disease, and storm damage (Oliver et al., 1996) leading to important fire-related consequences. Fire-related consequences were realized in the SLTB with the 24 June 2007 human-caused 'Angora Fire' which burned over 1200 ha of land owned by the USFS, CTC, and El Dorado County. An additional 92 ha of private property burned in the fire with a loss of over 250 structures including primary homes. The USFS post-fire assessment report on fuel treatment effects (Murphy et al., 2007) echoes our findings regarding the basin's recent landscape history and states that "a century of fire exclusion has interrupted the natural fire cycle resulting in dramatic changes in the forest. Tree density has increased... and surface fuel has accumulated." The implications are that fire must be a managed element of forested landscapes which evolved with fire even where development occurs.

A great deal of the increase in forest extent from 1940 to 1969 is from regeneration after timber harvest that occurred prior to the onset of our study period. Although some of the forest expansion after 1969 was also regeneration post-timber harvest, the majority of forest expansion after 1969 (77%) occurred in undisturbed areas as succession. Encroachment of conifer forest into undisturbed shrubland, scrub/shrub wetlands, and herbaceous wetlands shown in our results may also be attributed to fire suppression. Shrub communities in the basin such as montane chaparral have been shown to require recurring high-severity fire for establishment and persistence, and that fire suppression has allowed conifers to encroach upon chaparral stands leading to eventual replacement of chaparral by forest (Nagel and Taylor, 2005). Climate change in the form of reduced winter severity and a longer growing season may also be a contributing driving force of conifer encroachment in the SLTB as may have been the case in the Greater Yellowstone Ecosystem (Gallant et al., 2003; Parmenter et al., 2003). The climate of the Sierra Nevada since 1850 has been warmer and wetter than the period from 1650 to 1850 (Stine, 1996), and these conditions might have favored conifer growth and forest expansion. Because the grassland class usually represents a forest disturbance in the SLTB, such as ski runs and chairlift paths, conversion of grasslands to shrublands and ultimately to forests in these cases are expected stages of succession after human-induced disturbance. A small amount (9.8 ha) of change was forest regeneration on avalanche-cleared slopes.

Tree mortality mapped from the 1987 to 2002 period was likely the result of trees already weakened by environmental stresses such as drought lasting from 1987 to 1992 and forest densification succumbing to tree-killing bark beetle infestation (Ferrell et al., 1994). The observed geographic distribution of tree mortality suggests that stands of relatively moisture-sensitive trees along the forest-forested wetland interface may have been weakened by greater competition for water and light brought on by increased stand density further amplified by drought. These conditions may have left these stands of trees more susceptible than upland stands to widespread bark beetle attacks. Although we mapped only contiguous patches of dead trees >0.4 ha, drought and bark beetle related tree mortality was seen at varying degrees throughout the Lake Tahoe basin and by 1991 an estimated 300 million board feet of timber were dead or dying in the basin (Elliot-Fisk et al., 1996).

4.4. Responses to forest change

Forest densification, forest expansion, and tree mortality all documented herein contribute to fuels and increased fire hazard and the likelihood of high-severity fire (Manley et al., 2000). In response to these changes, land managers began mechanical and hand thinning activities in the 1980s in order to reduce hazards and create stands structurally similar to inferred presettlement conditions (Christopherson et al., 1996; McKelvey et al., 1996). Thinning activities were reflected by our results showing decreasing forest density between 1969 and 2002. Some of the density decrease from 1969 to 1987 was due to commercial logging early in this period, but most of the density decrease later in this period and likely all of the density decrease from 1987 to 2002 was the result of thinning for fuels management by the USFS and on a smaller scale by the CDPR and CTC. This distribution of timber harvesting and thinning generally agreed with the spatial and temporal distribution of our mapped areas of density decrease for the entire study period as shown by GIS overlay.

The anticipated results of thinning include reduction of fuels and fire hazard, regulation of species composition, promotion of large tree development, wood production, and regulation of understory shrub and tree regeneration (Oliver et al., 1996; Weible et al., 2005). Thinning activities often focused on the removal of dead or dying trees, and the resulting slash was disposed of through commercial sale of wood, chipping and removal, or prescribed burning of slash piles. Pile burning is controversial as it impacts air quality (Cliff and Cahil, 2000). Ground burns as a fuels management strategy are rarely practiced in the basin because they are considered difficult to control, pose a risk to property, and impact air quality.

Conversion of forest to grass/shrubland and forest density decrease from 1940 to 1969 was likely caused by small-scale selective commercial timber harvesting driven primarily by local lumber needs generated by urban growth as well as to a lesser degree by clearing for ski runs. Cutting began in 1946 in the upper Trout Creek watershed and from 1950 through the 1970s in stands along Trout Creek, upper Saxon Creek, and around Meyers (Lindström, 2000). Forest density decrease early on during the 1969–1987 period was also likely due to commercial logging with the rest of the density decrease during this period the result of thinning. At least two patches were cleared of trees by an avalanche between 1969 and 1987.

Overall our results show that the highest rates of landscape change occurred from 1940 to 1969 and rates have declined through 2002 for all changes with the exception of two (Fig. 8). Interestingly the two changes with an increasing rate through 2002, forest density decrease and tree mortality, were driven partially in response to land-use/cover changes that occurred earlier in the study period. Tree mortality occurred in response to environmental stresses including forest density increase while forest density decrease as caused by thinning was driven by the need to alleviate the fire hazard caused by forest density increase and tree mortality. Forest dynamics in the SLTB are in part directly and indirectly linked to on-the-ground practices driven by policy.

4.5. Temporal sampling considerations

It is important to note that due to the length and unequal durations of the temporal sampling intervals between the land-use/cover data layers, some considerations regarding the temporal resolution of change detection should be identified and discussed. Significant class transitions may have been missed within periods, especially within the 29 years separating the 1940 and 1969 data, a period representing the greatest amount of urban development in the history of the SLTB, and in turn the highest likelihood of the appearance of transitional classes. Transitional, or disturbed, classes usually represent disturbances that are not climax landscape types but rather indicate a temporary state of land cover. Typically, mechanically disturbed lands transitioned into developed lands, and in this study that was the case 63% of the time. However, even though it was impossible to capture every occurrence of temporary disturbances, it was still vital to map the disturbance classes when possible as the disturbed land-cover state represents a period of high sediment availability and potentially high erosion rates that can affect water quality.

5. Conclusions

The SLTB landscape underwent significant changes from 1940 to 2002 which were primarily the result of varying types and intensities of human activity. Changes that occurred were the result of direct anthropogenic activity, such as construction, or were from indirect drivers such as fire policies and drought. Many of the issues and controversies surrounding the ecology of the Lake Tahoe basin today are likewise the result of changes in land use/cover that occurred at the greatest intensity early in the basin's modern (post-1940) use history. During the mid to late 1800s much of the basin was clear-cut and historical photos show much of the basin to be almost treeless, and contemporary forests are second, third, or later generation regrowth. The regeneration of the basin's forests was shaped through management and much of the management post-1940 centered on policy aimed at reducing perceived threat from the natural fire cycle. Public discovery of the basin as a destination for recreation in the mid-1900s subsequently changed the landscape again, but by different mechanisms. The results of our analysis of multi-temporal discrete periods show the trends in development, land management, and forest succession during the most intensive development period for the SLTB. The changes that occurred, the reasons for those changes, and the fulfillment of damage and loss from the resulting fire risk, as with the Angora Fire, can play out in similar regions wherever fire suppression and development scenarios are supported.

As management strategies in the Lake Tahoe basin begin to reflect the move into the era of restoration and renewal (Murphy, 2000), results from this assessment of landscape change may be used in future studies requiring a dynamic landscape component, allow decision makers to anticipate possible consequences of forest management and policy as it relates to land use, and support the development of policies focused on minimizing these consequences. Furthermore, although we produced the multi-temporal land-use/cover data to fulfill the needs of this study, we consider this study to be the initial application in anticipation of a wide variety of future uses for these data including watershed/water-quality modeling among others. In part because manual image interpretation is a costly and time-consuming approach, it is beneficial to the research and management community that the usefulness of data across disciplines is considered and even made a priority in studies such as this.

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