Targeting Conservation Action through Assessment of Protection and Exurban Threats

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Abstract: *Landscape-level assessments of biodiversity strive to guide land-use planning and conservation activities by providing information about areas of high biodiversity value and low protection status. I developed a methodology to assess the level of threat to conservation of biodiversity to help guide conservation action. This method incorporates socioeconomic indicators of risk, including developed and roaded areas, and measures the proportion of conservation lands affected by developed areas. In addition, I developed a metric called conservation potential to measure the degree of fragmentation of patches caused by development. As an illustration I applied this methodology to Colorado (U.S.A.). Protection levels were determined by examining land ownership, resulting in protected lands (status levels 1 and 2) and unprotected lands (status levels 3 and 4). Areas were considered threatened (at risk) if a land-cover patch had >20% roaded area, >15% developed area, or was highly fragmented. Although 24 of 43 natural land-cover types were unprotected (49% of the state), 9 additional types were threatened. Combining conservation-status protection levels with patterns of threat targets the geographic area where conservation action is needed, provides a way to determine where so-called protected areas are at risk, and allows conservation strategies to be better refined.*

Orientación de Acciones de Conservación a Través de Evaluación de la Protección y Amenazas Exurbanas

Resumen: *Las evaluaciones de biodiversidad a nivel de paisaje se esfuerzan por proporcionar información para la planificación del uso del suelo y actividades de conservación mediante datos sobre áreas de alto valor de biodiversidad y bajo estatus de protección. Desarrollé una metodología para evaluar el nivel de amenaza para la conservación de la biodiversidad para ayudar a guiar acciones de conservación. Este método incorpora indicadores socioeconómicos de riesgo, incluyendo áreas desarrolladas y con caminos, y mide la proporción de tierras de conservación afectadas por áreas desarrolladas. Adicionalmente, desarrollé una medida llamada potencial de conservación para cuantificar el grado de fragmentación debido al desarrollo. Como un ejemplo, apliqué esta metodología a Colorado (E. U. A). Los niveles de protección se determinaron examinando la propiedad, resultando en tierras protegidas (niveles 1 y 2) y no protegidas (niveles 3 y 4). Las áreas se consideraron amenazadas (en riesgo) si tenían >20% de su superficie con caminos, >15% del área desarrollada o si estaban muy fragmentadas. Aunque 24 de los 43 tipos de cobertura natural no estaban protegidos (49% del estado), 9 más estaban amenazados. La combinación de estatus de conservación y niveles de protección con patrones de amenazas identifica al área geográfica donde se requieren acciones de conservación, proporciona una forma de examinar donde están en riesgo las llamadas áreas protegidas y permite que las estrategias de conservación sean mejor ajustadas.*

Introduction

Land-use planning and conservation activities should be guided by the best available information about areas with high biological significance. Conservation assessments are critical to identify areas of high biodiversity value and low protection status (Burley 1988). Conservation assessments have been conducted at a variety of scales. For example, the World Wildlife Fund and The Nature Conservancy have sponsored ecoregional assessments

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throughout the world (e.g., Ricketts 1999; Groves et al. 2002), and Pressey et al. (2000) have conducted numerous assessments in New South Wales, Australia.

A leading cause of species imperilment is land use associated with residential development and roads (Wilcove et al. 2000). If these threats to species and habitat are not considered, conservation resources may not be properly prioritized (Cassidy et al. 2001) to achieve the greatest benefit for the most species (Scott et al. 1993). A number of efforts have incorporated threats to biodiversity to prioritize conservation action (e.g., White et al. 1997; Pressey & Taffs 2001). Cassidy et al. (2001) incorporated threats in assessing conservation priorities in the state of Washington (U.S.A.), but they relied only on land-cover mapping to identify locations of human activities. Reyers et al. (2001) developed a coarse-scale approach to identifying priority areas in South Africa that incorporated threats associated with roads. Margules and Pressey (2000) argued for the need for systematic conservation planning and provided a framework that recognizes two main dimensions to prioritizing conservation action: vulnerability and irreplaceability. Vulnerability is defined as the likelihood of destruction or alteration of native vegetation, and irreplaceability is a measure of how much land of a particular type remains (Margules & Pressey 2000).

In the United States, the main conservation assessment program is the U.S. Geological Survey's Gap Analysis Program (GAP). The GAP uses biological survey data and geographic information systems (GIS) to detect conservation "gaps" (Scott et al. 1993). There is a major opportunity to refine GAP analysis by integrating socioeconomic factors to better assess levels of protection and risk, particularly on private lands (McKendry & Machlis 1993). These refinements are especially useful for informing local land-use planners and decision-makers (Theobald et al. 2000).

Incorporating information about private lands into the GAP methodology is important for a number of reasons. First, private lands contain disproportionately high levels of biodiversity and habitat for rare species (Bean & Wilcove 1997). For example, fewer than 10% of U.S. endangered species occur exclusively on public land (General Accounting Office 1994). Second, many of the important causes of habitat loss and fragmentation stem from changes of land use on private lands, especially conversion of agricultural (including grazing and pastureland) to residential development. Third, private lands vary greatly in degree of human-induced impacts on habitat. It follows that land-use planning affecting private land is fundamentally important to conserving biodiversity nationwide (Dale et al. 2000).

The GAP methodology evaluates vulnerable plant communities and vertebrate species by comparing land cover and species distributions to land stewardship categories (Scott et al. 1993). I use the term *stewardship* because management of land does not always correspond directly to land ownership. The primary criterion in assigning the stewardship category or status is whether land is managed for permanent biodiversity maintenance through some legal and institutional mechanism. This approach is similar to the World Conservation Union's process of examining protected areas, although the categories are different (Davey 1998). The standard stewardship, or status, categories are (1) permanent protection from conversion of natural land cover, with natural disturbance events allowed; (2) some suppression of natural disturbance; (3) some extractive uses permitted; and (4) no protection from conversion of natural land cover (Csuti & Crist 2000).

As a first step, GAP methodology identifies land-cover types and species distributions that are particularly vulnerable given the current array of land ownership and management. A main drawback to identifying status categories is the coarse categorization of potential land-use activities that are weakly associated with species vulnerability (Stoms 2000). That is, status categories are indictors of vulnerability but need to be refined to more closely reflect the relationship between particular land-use activities and associated species responses. Some types of human activities affect broad expanses of the landscape and result in land-cover conversion (e.g., monocrop agriculture and urban uses), and these activities are typically well documented through land-cover maps. However, low-intensity land uses (e.g., low-density rural residential development) are more difficult to map and are typically not included in land-cover data. Also, land-cover maps reflect a single, typically current situation and do not recognize likely future changes caused by population growth. Compiling data that more directly relate to impacts on biodiversity associated with land use is challenging (Stoms 2000) but offers a straightforward and reasonable means by which to identify threats to biodiversity, although demonstrating species responses to land-use activities is challenging (Theobald et al. 1997). There is a growing research literature, however, that examines species-specific responses to exurban and urban land uses (e.g., Blair 1996; Theobald et al. 1997; White et al. 1997; Maestas et al. 2001; Marzluff et al. 2001; Odell & Knight 2001).

Another way to refine status categories is to move beyond using them solely to identify unprotected lands (status levels 3 and 4). Finding the proportion of a species' habitat that is not protected is an important first step but is not sufficient to fully facilitate conservation planning. A refinement to identifying vulnerability is to differentiate areas on the landscape threatened by current or future land-use activities associated with human development (e.g., urbanization, intensive agricultural practices, logging). I maintain a distinction between threat and protection level to explicitly recognize that many so-called protected areas, even U.S. wilderness areas, are subject to internal and external threats (Cole & Landres 1996).

It follows that a major opportunity for innovation in GAP methodology is to move from assessing protection levels to targeting areas by their level of risk so that threats to biodiversity are more fully incorporated into biological assessments. I refined the identification of vulnerable (unprotected) areas to consider what lands are threatened by various human uses, especially those that are likely to have significant impacts and those that are growing rapidly through urbanization and rural residential development. My overall research objectives were to incorporate information about land use on private lands in the assessment of protection levels on private (and adjacent public) lands and to forecast future levels of development to identify areas most at risk from potential private-land development. I then designated conservation triage levels with information about protection levels and future risk to protected lands. I organized my research around the following questions: (1) What useful socioeconomic indicators can be developed from readily available data to assess potential risk to conservation land? (2) How do standard gap status levels compare to indicators of risk? (3) How can indicators of risk be used to better target where conservation action should occur?

Methods

First, I examined possible socioeconomic indicators and identified two useful, easily mapped indicators of risk. Next, I compared these measures to standard GAP stewardship protection categories. Finally, I assessed which land-cover types are particularly at risk and where land is threatened by development. I illustrate these methods through a threat assessment of Colorado (U.S.A.), and I used the land-stewardship, land-cover, and species-distribution maps produced by the Colorado Gap Analysis Project (Schrupp et al. 2000). The land-stewardship map was derived from land-ownership maps and updated to differentiate federal lands (U.S. Department of Agriculture national forests, wilderness areas, and research natural areas), state lands (parks, wildlife areas), and private lands. The land-cover map was produced through interpretation of Landsat TM imagery (30-m resolution) and distinguishes 54 cover types with a 100-ha minimum-mapping unit. The species-distribution maps were modeled through use of species-cover associations derived from expert opinion for each species.

Study Area

In the Rocky Mountain West, the foremost threat to high-quality habitat is conversion of agricultural to residential land uses and encroachment of development on public lands. Not only is the West's population growing two to three times faster than that of most of the rest of the United States (Baron et al. 2000; U.S. Census Bureau 2000), but demographic and economic trends are changing the pattern and location of development (Riebsame et al. 1997). As a result, more than 60% of the West's counties are experiencing "rural sprawl," where rural areas (outside city and town limits) are growing at a faster rate than urban areas. In Colorado, population growth rates in nearly one-fifth of the counties exceeded 5% from 1990 to 1997, and this growth has caused large expanses of low-density, exurban development. Also, even though much of the West is publicly owned, the most productive land that supports particularly rich biodiversity is privately owned, and because private land ownership typically follows valley bottoms, a large proportion of the western landscape is close to private lands. For instance, roughly two-thirds of western Colorado is publicly owned, and nearly 80% of forested land is within 3 km of private land.

Socioeconomic Indicators

Assessing trends in biological diversity requires, in addition to information about habitat and ecological processes, information about the location and trends of human activities on the land (Davis et al. 1990). McKendry and Machlis (1993) describe a general framework to include socioeconomic indicators such as population change, economic trends, government policies, and land-use conversion in gap analysis. Few methods have been developed that use socioeconomic indicators in conservation planning. Recently, Stoms (2000) compared three indicators of development—permitted land use, roaded areas, and human population growth—to stewardship status for two pilot-study areas in California and found large differences between these more direct indicators and the general proxy of status or protection level. Reyers et al. (2001) also used the roaded-areas approach in their conservation assessment of South Africa.

A number of possible indicators of human development have been suggested, but to provide a general method that can be applied easily to regional and national extents, the indicator must be readily mapped from existing, commonly available, digital data sources. Human population density (e.g., McKendry & Machlis 1993; Merrill et al. 1999), housing density (e.g., Theobald 2001), and road density (e.g., Moyle & Randall 1998; Mladenoff et al. 1995; Merrill et al. 1999) are commonly used indicators of the intensity of human land-use activities and can be easily derived from nationwide, detailed data from the U.S. Census Bureau and U.S. Geological Survey. In contrast, although detailed maps depicting allowable densities and types of human activities on private lands (i.e., zoning maps) and management zones on public land would be useful, these data are demanding to compile and are typically unavailable for regional- or national-level studies (e.g., White et al. 1997; Theobald & Hobbs 2002).

The effects of roads on biodiversity and ecological integrity have been well documented (e.g., Forman & Alexander 1998). Because road and population density are often thought to be highly correlated, I calculated their correlation by converting roads on the U.S. Geological Survey's Digital Line Graph (DLG) map at a 1:100,000 scale to a 30-m grid and then finding the proportion of a 1-km circle occupied by roads, resulting in a map with units in kilometers per square kilometer. The statewide correlation was 0.533 and was particularly poor in urban and rural areas. Although population density is often used to map human activity patterns, census population data are tied to the primary place of residence and so underestimate potential effects on land in areas with a high percentage of second and vacation homes (Theobald 2001). Moreover, potential impacts on land, such as removal of native vegetation, alteration of vegetation structure for wildfire protection purposes, and introduction of exotic species are more closely related to housing density than population density (Theobald et al. 1997). Therefore, I selected two socioeconomic indicators to use in the assessment: roaded areas and housing density.

Roaded Areas

I created a roaded-areas map following the methodology of Davis et al. (1996) and Stoms (2000), also used by Reyers et al. (2001), which considers roads not as linear features but estimates their footprint or areal extent. A measure of roaded areas, in contrast to one of road density, accounts for spatial pattern and thus does not suffer from bias introduced when road density is calculated in locations where many roads that are close together result in very high road densities. Moreover, it provides a straightforward way to depict the effects of roads on biodiversity by linking the size (or use) of a road to its potential biological impact. The roaded index estimates the proportion of an area (e.g., watershed, county, status category) affected by roads. Roads were converted to a grid with a 30-m resolution and then were buffered based on road use (Table 1). For example, the roaded area or footprint for a primary highway was a 500-m-wide swath, centered on the highway.

Table 1. Roaded areas in Colorado.

Road description	*Buffer width (m)**	*Total width, actual (m)*	*No. grid cells*
Primary: limited access or interstate highway	500	1000 (990)	16
Primary: other U.S. or state highway	250	500 (510)	8
Secondary (state and county)	100	200 (210)	3
Local	100	200 (210)	3
Vehicular (four-wheel drive)	25	30	0
Other—hiking	0	0	0

**Buffered roads have a specified width based on their road type. Total width of affected roaded portion is twice buffer width, and a 30-m grid was used. Actual width is slightly different because of 30-m cell size (Davis et al. 1996; Stoms 2000).*

Housing Density

To create a map of housing density, I used housing counts from the 2000 U.S. Census that were aggregated into census blocks, which are fine-grained, spatially detailed data. A typical block in the United States contains <100 housing units and ranges in size from a few hectares in urban areas to thousands of hectares in rural areas (U.S. Census Bureau 2000). In Colorado the 2000 census mapped over 140,000 blocks. The average number of housing units is 20.9, and the average area of blocks in rural areas is 415 ha. Because private housing does not occur on public land, I removed the public-land portions of blocks, reducing the average block to 248 ha.

To ease the description and portrayal of development patterns, I classified housing density into four general classes (Theobald 2001): urban, suburban, exurban, and rural. Urban densities are typically defined as areas with >386 people/km^2 (1000 people/square mile). Assuming an average of 2.5 people per housing unit, this translates to roughly 1.7 units per ha (0.7 units/acre). Urban housing density is defined as at least 1.2 units per ha (0.5 units/acre). Suburban density ranges from 0.25 up to 1.2 units per ha (0.1 to 0.5 units/acre). Exurban density ranges from 0.06 up to 0.25 units per ha (0.025 to 0.1 units/acre). Rural density occurs below 0.06 units per ha (0.025 units/acre).

Forecasting Growth Patterns

Understanding the drivers and consequences of land-use and land-cover change (LUCC) was a major focus of the International Geosphere-Biosphere Programme (Riebsame et al. 1994; Turner et al. 1995), and this program has spawned numerous modeling approaches to land-cover change, including agricultural changes, deforestation, and urbanization (Veldkamp & Lambin 2001). Many of these efforts have modeled urbanization with maps of land-cover types classified from satellite imagery and occasionally from high-elevation aerial photography (e.g., Brown et al. 2000). For example, Meaille and Wald (1990) combined satellite imagery, GIS, and numerical modeling to predict urban growth in France. Workers on the California Urban Futures Model (Landis 1995) used a multinomial logit procedure to predict the probability of agricultural to urban conversion. A related model estimated the impacts of urban growth (>7.4 units per ha) on agriculture in the central valley of California (Bradshaw & Muller 1998). Models such as What If? (Klosterman 1999) allow users to specify demand for land but require more complex, spatially detailed data sets, generally derived from parcel maps. Cellular automata (CA) methods have been used to model urban form (Batty 1997). For example, Clarke and Gaydos (1998) developed a CA-based model to predict urban growth in San Francisco and Baltimore. Stoms (2000) distributed population growth in California with a rule-based approach that arbitrarily limited growth to within 8 km of urban cores.

In sum, most land-use modeling efforts have concentrated on forecasting urban growth and have ignored conversion of land to residential uses at lower than urban densities (Theobald & Hobbs 1998; Theobald 2001). As Pond and Yeates (1993) showed through their work in Canada, methods that examine only urban-nonurban changes are unsatisfactory because they only account for direct conversion to urban uses. Also, lower native species richness occurs in exurban density developments (Maestas et al. 2001). It follows that forecast models targeted to regional planning uses should be able to represent changes for large spatial extents, represent growth patterns and densities beyond urban areas into the exurban and rural fringe, and examine patterns 20–50 years in the future.

The approach I pursued was to create a straightforward, easy-to-interpret model, which is a key consideration when models are to be used by decision-makers and the general public (Theobald et al. 2000). My model is a simplified version of a supply/demand/allocation model, which is not driven by a particular economic theory but is rooted in the practical assumptions and limitations of development (Klosterman 1999). The number of units available to be developed in an area is described by the supply component, and the demand component defines the number of units likely to be needed in the future to meet the demands of a projected population. The locations where new housing units will be placed first, assuming that supply exceeds demand, are identified within the allocation component.

A number of coarse-grain factors help determine whether land can be developed and thus determines the supply of developable land, defined here as private land excluding water bodies. Additional fine-scale factors are typically considered, including hazardous areas (e.g., floodways, steep slopes, unstable soils) and provision of basic services (e.g., domestic wells or water and septic or sewer), although I did not consider these here.

Initially, I assumed that all developable land was suitable for housing development. A critical factor in accurately portraying the spatial pattern of growth, however, is to consider the maximum density that an area will attain. A typical, recurrent characteristic of settlement is that housing density is roughly homogeneous at a scale that corresponds roughly to subdivision scale (100–300 ha), which is often controlled by land-ownership patterns and land-use regulations. Zoning regulations typically restrict the land use and intensity of use (i.e., housing density) that can occur on a given parcel. In lieu of zoning data, I assumed that future development will continue to occur in a similar pattern as it has in recent years. That is, in any given decade, a block group's density will not exceed the average density of its neighboring blocks. This allows urban areas to expand organically and spread outward over time, and both the average density and location of new units are calculated locally (i.e., within the neighborhood), so within-county growth patterns can be markedly different. I used county-level population projections developed by the Colorado state demographer to allocate new housing units on the landscape.

The forecast model consisted of three computations for each time step in the forecast model. First, I calculated where new units will be located that are required to meet the demand of new residents. The number of housing units in each block group (u) is

$$u_t = u_{t-1} + N_t.$$

The number of new units at a given time step (N_t) is computed by

$$N_t = (P_t - P_{t-1})(u_{t0}/p_{t0})((u_{t-1} - u_{t-2})/U_{t-1}),$$

where P is the county population, p is the block-group population, and U is the number of units in the county. The number of new units for each block group reflects the previous increase in units and the county population growth rate. Time (t) is usually measured in decades, and $t0$ indicates the initial time step of the forecast model.

Second, I calculated the maximum density (M) allowed in each block group by finding the area-weighted average of the number of housing units in the n adjacent block groups using

$$A = \sum_{i=0}^{n} a$$

$$M = \frac{\sum_{i=0}^{n} ua}{A},$$

where a is the area of a block group and A is the area of all adjacent block groups. Third, I removed the excess units (u') and distributed them to adjacent block groups. This was an iterative process because excess units were distributed until block groups were found that had not reached their maximum capacity. When $u > M$,

$$e = u_t - M_t,$$

so that each adjacent block group received additional housing units, proportional to their area

$$u = u + u' \times \left(\frac{a}{A}\right).$$

Status and Threat Analyses

I compared land-protection status categories with the indicators of threat described above. I designated a land-cover class as threatened if more than 20% was roaded area, if more than 15% of a land-cover class coincided with exurban or greater density development in 2020, or if it was within 1 or 2 km of exurban or greater development in 1990. These designations exceed the 10% threshold established by GAP project thresholds and the conservative goal set by the World Conservation Union of 10% of country area (WCED 1987). To measure how well the indicators identified not only vulnerability and threat, I cross-tabulated the area of each indicator with the status category for all of Colorado, for each county, and by watershed.

I then spatially overlayed the indicators to identify land-cover types that were particularly threatened. Also, to further target specific locations where conservation activity should be located, I prioritized individual patches within a land-cover type by computing its "conservation potential." The spatial pattern of a threat within a patch is important to understanding its potential impacts. The conservation potential of a patch is lower if the threatened area is dispersed throughout a patch or if the patch has a thin shape. It is higher if the threatened area is concentrated in one corner of the patch or if the patch has a relatively compact shape. For each grid cell within a patch, I computed the distance from roaded areas, developed areas, or the patch edge in a process similar to GISFrag (Ripple et al. 1991; Theobald & Hobbs 2002). I then summed the cell values and normalized the total distance-from-nearest-edge value by dividing it by the value computed for the original patch without considering the roaded or developed areas. Critically low conservation potential was reached if the value was <30%, falling within the 10–40% range where most rapid ecological change occurs (Reyers et al. 2001).

Based on protection status and risk indicators, I separated locations in a landscape into four "conservation triage" levels in an attempt to partition conservation effort to avoid targeting lands that will likely be too compromised regardless of protective measures (Myers 1979). Level 1 indicates areas that are not protected and at risk and so would require new (and likely substantial) effort to conserve them. Level 2a indicates areas protected and at risk, and level 2b areas not protected but not at risk. These areas are likely to be conserved with some effort, but otherwise might be compromised, although the conservation strategies would clearly be different. Level 3 areas are protected but not at risk and require less effort to conserve.

Results

Indicator Maps

The total land base of Colorado is 269,590 km^2. At the time of the study, Colorado had 269,773 km of roads and 21.6% of the state was roaded (Fig. 1). The roaded proportion varied widely by watershed, from 6.1% to 40.9% ($\bar{x} = 20.7\%$). By county, percent roaded area ranged from 5.8% to 55.5% ($\bar{x} = 22.4\%$). As expected, urban counties such as Denver (55.5%) and Jefferson (37.2%) had a high percentage of roaded area, but several rural counties also had a fairly high percentage of roaded area: Costilla (36.5%) and Rio Blanco (49.7%). Both of these counties were subdivided in the 1970s for rural, large-lot subdivisions. Land managers often assume that public land protects areas from roads, but I found a poor relationship ($R^2 = 0.21$) between percent roaded area and the proportion of public land in a county.

About 3.9% of Colorado was developed in 2000 (Fig. 2a), but development will likely expand to 8.1% by 2020 (Fig. 2b). Because of the fragmented land-ownership pattern, however, 13.8% of Colorado was within 1 km of developed areas in 2000, and 23.1% was within 2 km. Urban densities occupied 1513 km^2 in 1990 and were projected to enlarge to 2397 km^2 by 2020. Exurban and higher densities (including urban) occupied 6184 km^2 and will likely expand to 12977 km^2 by 2020. The locations at risk of future development tended to be along the foothill areas of the Front Range and in mountain valleys.

Protection Status

Roughly 10% of Colorado is protected (defined as status 1 and 2), and the remainder has little or no protection (Fig. 3). All private lands were assigned status 4, about 64% of the state. Twenty-four of 43 natural land-cover types are vulnerable (status 3 and 4), representing nearly half the state (Table 2). Nine of the 43 cover types were "non-natural" cover classes, such as urban or cropland, where human activities dominate.

Threat Assessment

In addition to the vulnerable land-cover types, four land-cover types—ponderosa pine (*Pinus ponderosa*), bristlecone pine (*Pinus aristata*), shrub-dominated wetland, and prostrate shrub–tundra—were identified as threatened by roads (Table 2). Only three additional cover types were identified as threatened by development in 2000 (tallgrass prairie, xeric upland shrub, and barren lands), and two additional types (foothills-mountain grasslands and bristlecone pine) were identified as threatened by future development in 2020. Assuming that effects of development in 2000 extended up to 1 km, then 14 land-cover types would be threatened; 28 would be threatened if the threats of development extend 2 km from development. A number of land-cover types within 1 km of development were threatened but were not identified as vulnerable, most notably water, spruce fir, Douglas fir, ponderosa pine, bristlecone pine, forest-dominated wetland, and most tundra cover types.

Nineteen cover types had low conservation potential (<30%). In the conservation triage levels, protection status and threat were combined to better identify locations where conservation action should be placed

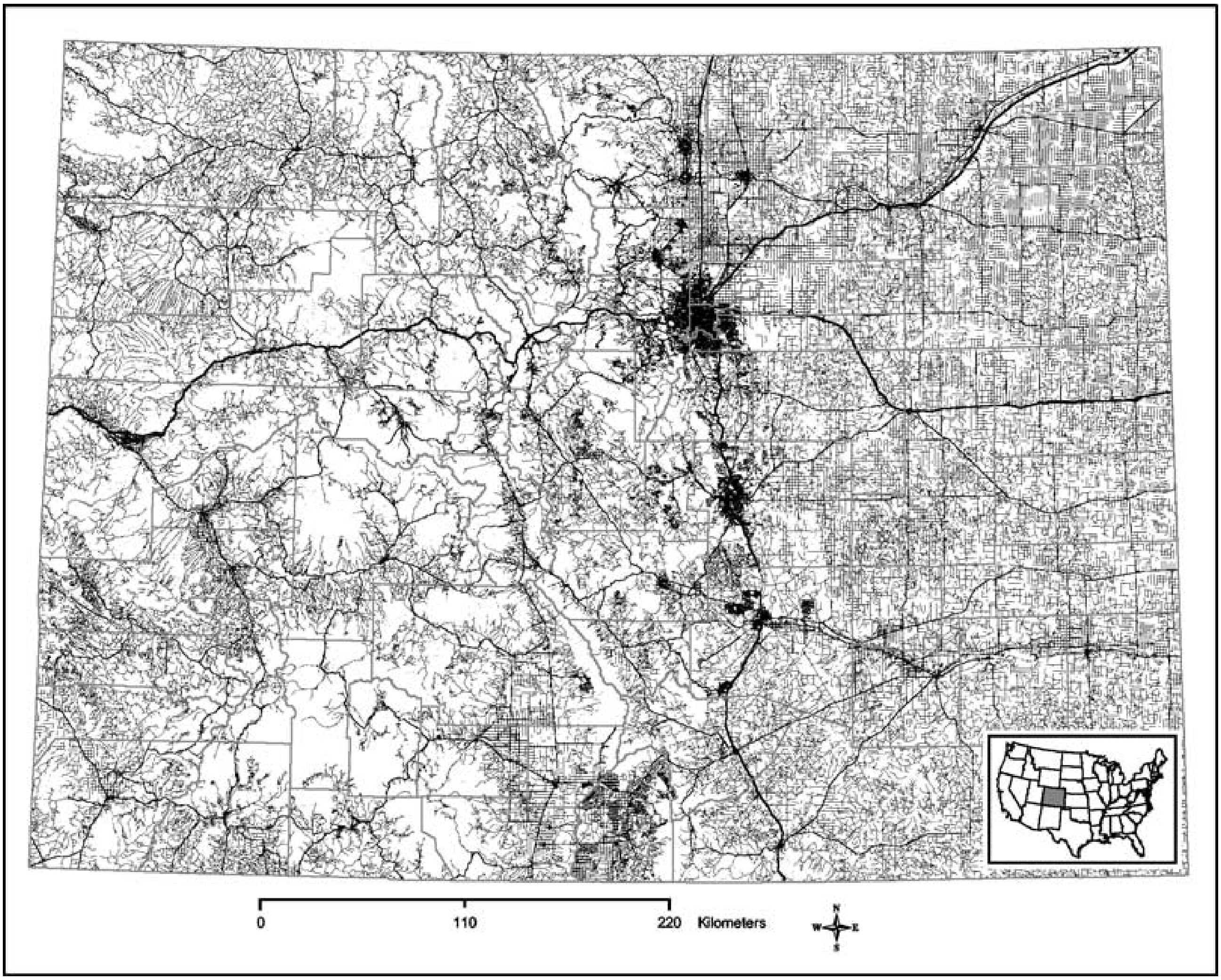

Figure 1. Roaded areas in Colorado (U.S.A.). Inset map (lower right) shows the location of Colorado within the conterminous United States.

(Fig. 4). Patches of natural land cover not protected and at risk (level 1) occupied about 43% of the state. Land-cover types protected but at risk (level 2a) occupied about 2%, and areas that were not protected and not at risk (level 2b) occupied 25%. About 8% of Colorado was protected and not at risk (level 3).

Discussion

Although 10% of Colorado was protected, I determined that the proportion of roaded area on protected lands averaged 13.5%. With identification of the location and relative magnitude of the roaded and developed areas, conservation activities can be targeted. For example, stratifying protected areas by watersheds revealed 71 separate protected areas larger than 1000 ha (totaling 28,610 km^2). However, identifying areas with more than 10% roaded area significantly reduced the area of concern to 2097 km^2. Incorporating indicators of risk into an analysis of protected status allows conservation efforts to be focused on mitigation in particularly threatened areas and highlights nonthreatened but vulnerable areas where protection could be enhanced.

Twenty-four of 43 land-cover types were identified as vulnerable, but incorporating threats helped narrow the areas where conservation effort would potentially be most effective. A number of types of lower-montane forest cover were not identified as vulnerable but as threatened because of their proximity to development and the possibility of edge effects on adjacent public lands. For example, ponderosa pine was not identified as vulnerable, and it appears that large patches are well-represented across the state. However, management of forest fires is being influenced by residential development encroaching on the forest fringe (e.g., Jehl 2000). So although ponderosa pine occupies 5.1% of Colorado, patches can be prioritized based on the metric of conservation potential.

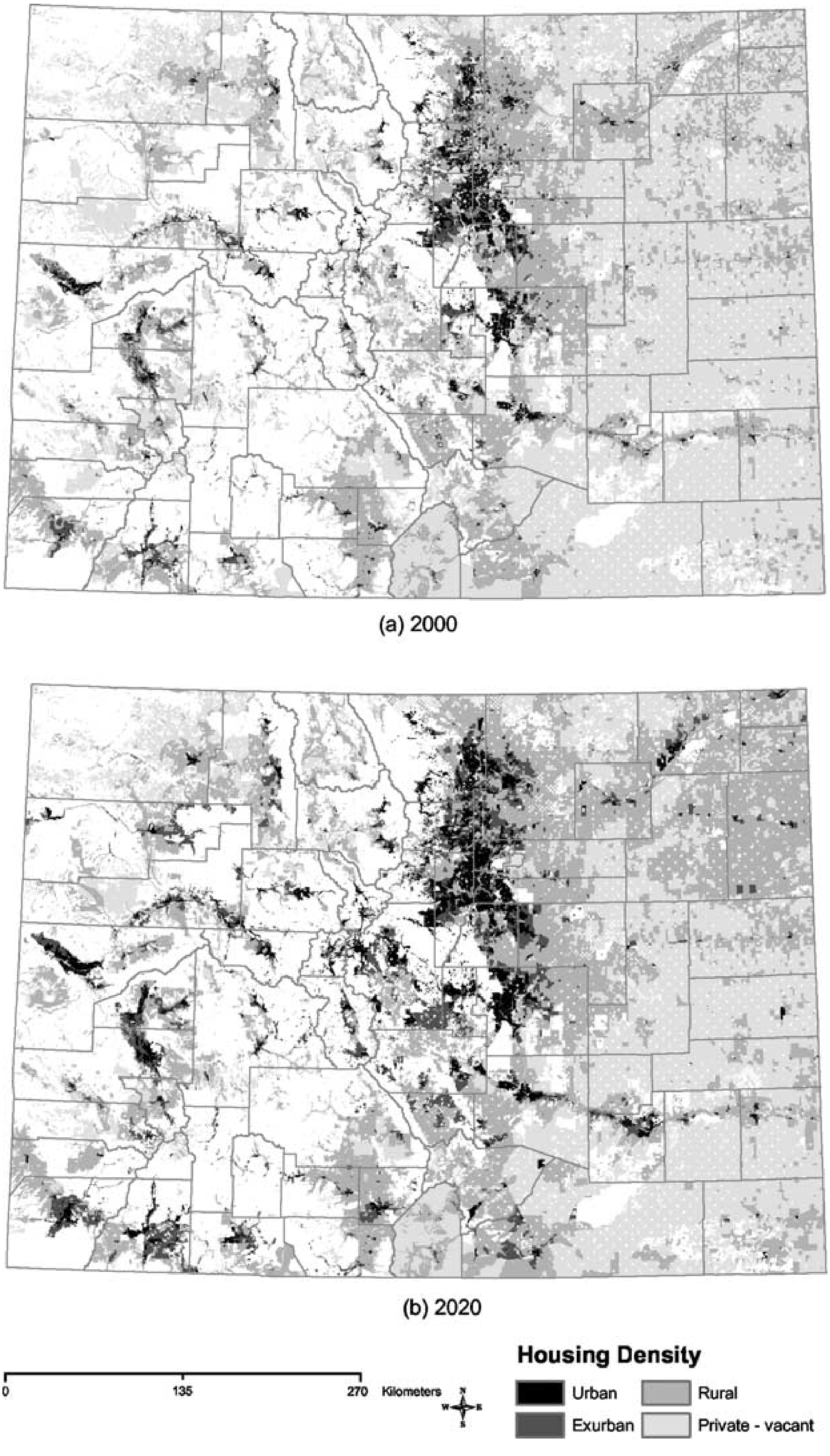

Figure 2. Housing density in Colorado (U.S.A.) in (a) 2000 and (b) 2020.

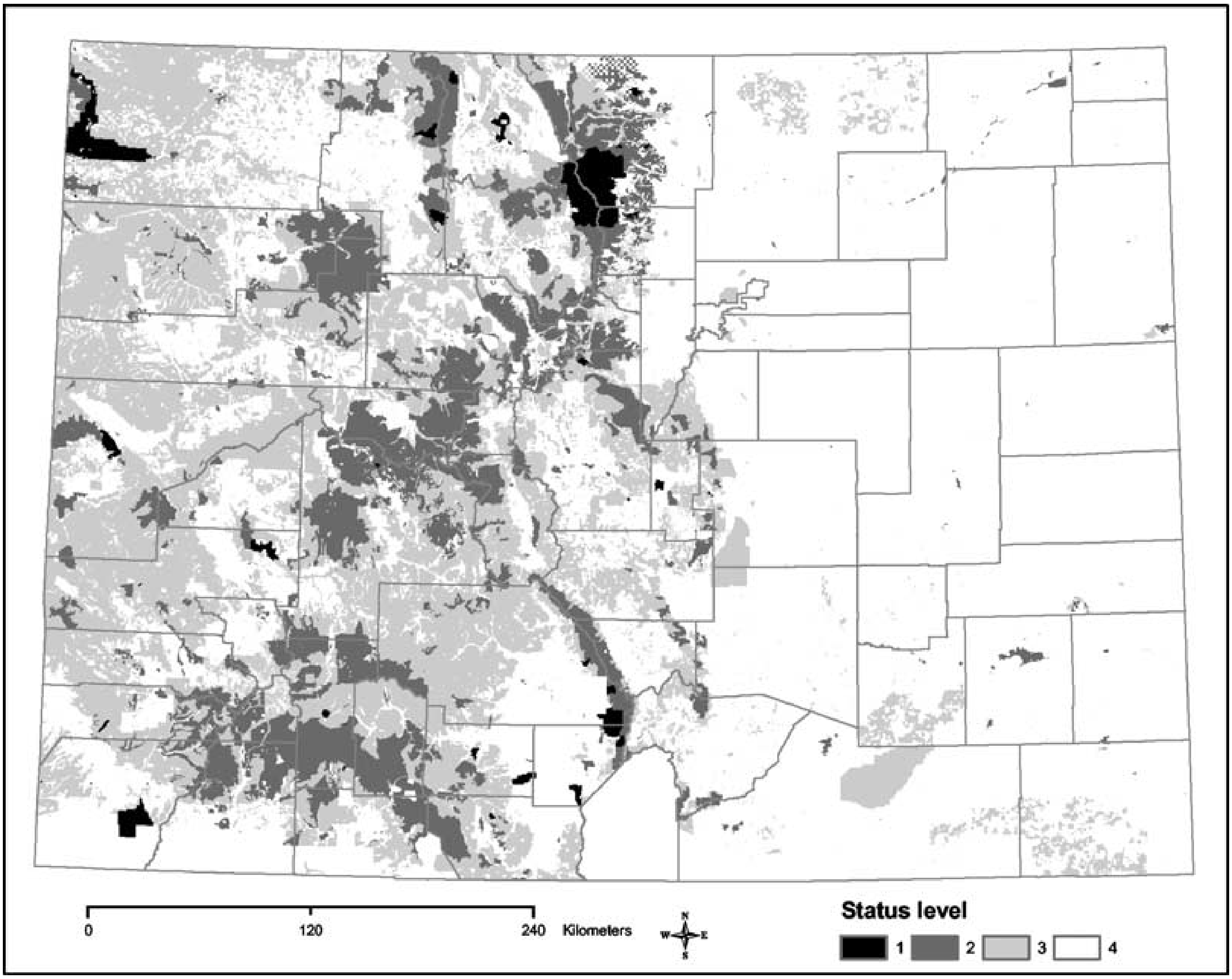

Figure 3. Map of Colorado Gap Analysis Program land-protection status. Protected land is composed of land status 1 and 2; vulnerable land is comprised of land status 3 and 4 (adapted from Schrupp et al. 2000).(Land status codes defined in text.)

One-tenth of the ponderosa pine has a conservation potential value of 50% or more, and higher-valued locations are located in the southern portion of the state.

Another important use of the triage levels is that different conservation strategies can be aligned with different situations. For example, it is likely that level 1 lands (at risk but not protected) will require acquisition of land or conservation easements, which is generally expensive. A number of land-cover types designated as triage level 1 are potentially threatened by new development occurring by 2020. In particular, these areas are located in Douglas, Elbert, and El Paso counties (tallgrass-prairie cover type), with smaller patches in northeastern Park County (bristlecone-pine cover type). For level 2a lands (at risk but protected), minimization of impacts from human activities through management is required, and some natural processes should be allowed to occur without interference. For level 2b lands (not at risk and not protected), strategies such as tax incentives to keep land zoned as open space can be employed. And finally, for level III lands (not at risk but protected), relatively little immediate conservation effort is required.

Ascribing a vulnerable or threatened condition to a land-cover type based on development presupposes that the current extent is adequate to retain the viability of a species for that ecosystem. But some land cover types such as midgrass prairie have already lost the majority of their original extent. Therefore, protecting at least 10% of their current extent may be better than nothing, but the proportion that should be protected to maintain biological viability may in fact be higher.

Biodiversity is threatened by human land-use activities, particularly conversion of agricultural to residential land use, throughout the western United States (Wilcove et al. 2000; Hansen et al. 2002). As a result of these changes, citizens, planners, and decision-makers are challenged to identify areas of land that offer the greatest benefits for conservation of species and that are also at greatest risk

Table 2. Proportion of each land-cover type in Colorado that is protected, roaded, and developed.

Land cover	Area (km^2)	State (%)	Protected (%)	Roaded area (%)	Developed (%) in 2000	Developed (%) w/in 1 km	Developed (%) w/in 2 km	Developed (%) in 2020	Conservation potential[a]
Urban or built-up lands[b,c]	2,172	0.81	0.19	84.44	71.3	95.7	98.1	83.2	—
Dryland crops[b]	36,882	13.70	0.07	23.71	1.3	6.0	11.7	3.6	—
Irrigated crops[b]	19,007	7.06	0.01	37.32	15.0	42.1	57.8	30.4	—
Orchard[b]	2	0.00	0.00	29.73	51.3	100.0	100.0	98.6	—
Confined livestock feeding[b]	4	0.00	0.00	45.41	0.0	7.9	69.7	0.0	—
Tallgrass prairie (e.g., *Andropogon gerardii*)[c]	2,024	0.75	0.04	25.28	15.5	35.7	54.3	31.0	11.4
Sand dune grassland (e.g., *Calamovilfa longifolia, Andropogon hallii*)[d]	537	0.20	0.00	14.70	1.1	6.3	13.0	3.4	33.3
Midgrass prairie (e.g., *Bouteloua curtipendula, Pascopyrum smithii*)[d,e]	4,949	1.84	0.31	24.36	5.3	16.4	27.4	8.9	26.7
Shortgrass prairie (e.g., *Bouteloua gracilis, Buchloe dactyloides*)[d,e]	40,291	14.96	0.19	23.14	0.5	2.7	6.1	1.4	18.0
Foothills/mountain grassland (e.g., *Danthonia parryi*, *Festuca* spp.)[d,e]	6,707	2.49	2.30	29.24	6.9	26.7	44.3	22.9	14.7
Mesic upland shrub (*Acer glabrum, Amelanchier* spp.)[d,e]	1,160	0.43	3.26	22.86	9.5	26.9	36.7	13.6	27.6
Xeric upland shrub (*Cercocarpus* spp.)[d,e]	584	0.22	4.61	29.97	17.9	46.5	62.1	25.4	23.4
Gambel oak (*Quercus gambelii*)[b]	8,490	3.15	4.85	19.58	2.4	12.2	23.8	6.8	30.0
Bitterbrush shrub (*Purshia tridentata*)[d,e]	740	0.27	1.67	26.97	0.2	2.7	8.1	0.3	28.5
Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*)	944	0.35	19.05	15.65	1.0	5.6	11.0	1.9	49.4
Wyoming big sagebrush (Artemisia tridentate ssp. wyomingensis)[d,e]	443	0.16	0.00	24.03	0.0	0.4	1.6	0.0	28.1
Big sagebrush (*Artemisia tridentata* ssp. *tridentata*)[d,e]	16,798	6.24	3.49	26.66	1.6	10.3	20.4	4.1	21.3
Desert shrub (e.g., *Altriplex canescens*)[d,e]	4,323	1.61	1.48	27.87	1.2	9.9	21.0	3.1	17.8
Saltbush shrub (e.g., *Atriplex* spp.)[d]	4,840	1.80	2.01	19.68	1.2	6.6	13.0	4.9	17.9
Greasewood fans and flats (*Sarcobatus verniculatus*)[d]	2,198	0.82	4.83	23.25	2.1	9.2	18.0	8.2	18.7
Sand dune shrub (e.g., *Artemisia filifolia*)[d,e]	10,807	4.01	0.45	23.21	0.3	2.2	5.9	1.5	19.5
Disturbed shrub (e.g., *Chrysothamnus* spp.)[d,e]	11	0.00	0.00	47.79	0.0	7.3	22.7	0.0	24.1
Aspen (*Populus tremuloides*)	12,660	4.70	21.99	11.60	1.6	10.7	20.8	4.7	54.4
Spruce fir (*Picea engelmannii, Abies lasiocarpa*)	18,719	6.95	46.53	9.14	0.8	8.5	18.5	2.1	57.9
Spruce-fir clearcut[b]	92	0.03	8.38	29.68	0.0	0.2	2.9	0.0	—
Douglas fir (*Pseudotsuga menziesii*)[e]	4,323	1.61	14.13	14.69	5.3	25.2	42.4	9.3	22.2
Lodgepole pine (*Pinus contorta*)	8,723	3.24	34.44	15.31	4.5	19.3	33.0	7.4	41.1
Lodgepole pine clearcut[b]	162	0.06	5.74	26.51	0.3	5.9	15.4	0.3	—
Limber pine (*Pinus flexilis*)[d]	12	0.00	0.08	18.34	2.5	16.7	49.5	2.9	47.2
Ponderosa pine (*Pinus ponderosa*)[e]	13,883	5.16	12.68	20.96	11.7	33.5	49.3	20.9	16.2

Table 2. (continued)

Land cover	*Area (km²)*	*State (%)*	*Protected (%)*	*Roaded area (%)*	*Developed (%) in 2000*	*Developed (%) w/in 1 km*	*Developed (%) w/in 2 km*	*Developed (%) in 2020*	*Conservation potential*[a]
Blue spruce (*Picea pungens*)	29	0.01	46.53	2.79	0.4	7.2	26.6	2.9	68.6
White fir (*Abies concolor*)[d,e]	40	0.01	0.00	26.99	0.0	0.0	0.0	0.0	67.9
Juniper woodland (*Juniperus* spp.)	4,664	1.73	12.16	15.34	0.7	3.8	7.4	1.5	47.6
Pinyon juniper (*Pinus edulis, Juniperus* spp.)[d,e]	25,038	9.30	7.24	17.93	1.8	11.9	23.0	6.4	29.8
Bristlecone pine (*Pinus aristata*)[e]	228	0.08	10.31	28.85	11.8	42.6	61.8	42.2	18.9
Mixed conifer	1,832	0.68	24.19	15.11	1.7	13.6	29.0	3.1	43.3
Mixed forest	831	0.31	16.25	15.70	0.4	3.8	9.2	1.0	46.1
Open water	907	0.34	13.47	16.69	7.3	36.8	53.3	12.4	38.7
Forest-dominated wetland (e.g., *Populus* spp.)[d,e]	1,144	0.42	9.16	27.79	7.2	34.7	51.6	15.6	27.5
Shrub-dominated wetland (e.g., *Alnus incana*, *Betula* spp., *Salix* spp.)[e]	522	0.19	13.77	21.38	3.8	17.0	24.8	9.1	54.9
Graminoid- and forb-dominated wetland (e.g., *Scirpus americanus*, *Carex* spp.)[d,e]	454	0.17	6.70	27.87	1.7	12.5	22.7	9.1	48.2
Barren lands	169	0.06	1.74	56.45	68.9	88.9	90.5	75.8	2.5
Unvegetated playa	3	0.00	0.00	8.76	0.0	0.0	0.0	0.0	—
Sandy areas other than beaches	180	0.07	0.00	13.98	0.5	1.8	4.3	0.5	97.2
Exposed rock[b]	460	0.17	50.78	4.22	0.1	5.7	11.9	0.7	—
Mining operations[b]	69	0.03	1.13	8.66	9.9	31.6	45.3	26.0	—
Prostrate shrub and tundra (*Salix* spp.)[e]	1,271	0.47	74.53	44.66	0.4	5.3	12.0	0.8	76.4
Meadow tundra (e.g., *Agrostis* sp., *Carex* spp.)	1,834	0.68	62.92	2.64	0.3	5.4	13.4	1.1	73.8
Subalpine meadow (e.g., *Agrostis* spp.)	2,047	0.76	28.28	4.50	2.5	14.4	25.5	6.9	49.5
Bareground tundra	2,001	0.74	81.59	18.33	0.28	6.3	15.1	2.9	74.6
Mixed tundra	2,999	1.11	66.47	0.92	0.5	7.8	16.8	1.3	72.9

[a] *Conservation potential measures the fragmentation of a patch and is computed as the average distance from developed areas, roaded areas, or patch edge divided by the average distance from the edge of the original patch without developed or roaded areas.*
[b] *Human-modified land-cover types.*
[c] *Percent developed is <100% of the urban and built-up class because industrial and commercial areas have low housing densities and therefore are not identified in the housing-density map.*
[d] *Vulnerable native land-cover types have <10% protected in status land (land status defined in text).*
[e] *Threatened native land-cover types have >20% roaded area, >15% developed area, or <30% conservation potential.*

of harm from encroaching development (Theobald et al. 2000). Given the proximity of much of public land to private land, management activities on public land increasingly must take into account adjacent private land uses, especially low-density exurban development.

I have described a methodology to extend typical gap analysis by incorporating socioeconomic factors to differentiate threatened locations. Both the roaded and housing-density indicators were useful in characterizing potential impacts from human land use. These indicators were used to refine analyses of vulnerability to include level of threat. The data to produce these layers were readily available, and methods to convert them into reasonable indicators were straightforward. Moreover, research is emerging that directly examines the possible effects of these indicators on native habitat (e.g., Forman & Alexander 1998; Marzluff et al. 2001). There is a strong need to incorporate additional spatial data that provide detailed information on private lands, such as zoning, the location of conservation easements, and private-land open space. It would be useful to differentiate different types of uses and patterns within the exurban development category and to incorporate a number of additional land uses associated with humans, such as grazing, logging, oil and gas wells, and fire suppression. In addition, an important refinement of assessments would be to understand the sensitivity of the prioritization results to alternative patterns of growth. One useful way to accomplish this would be to conduct assessments with a range of alternative scenarios of land-use patterns developed from a variety of models derived from land-use and land-cover change.

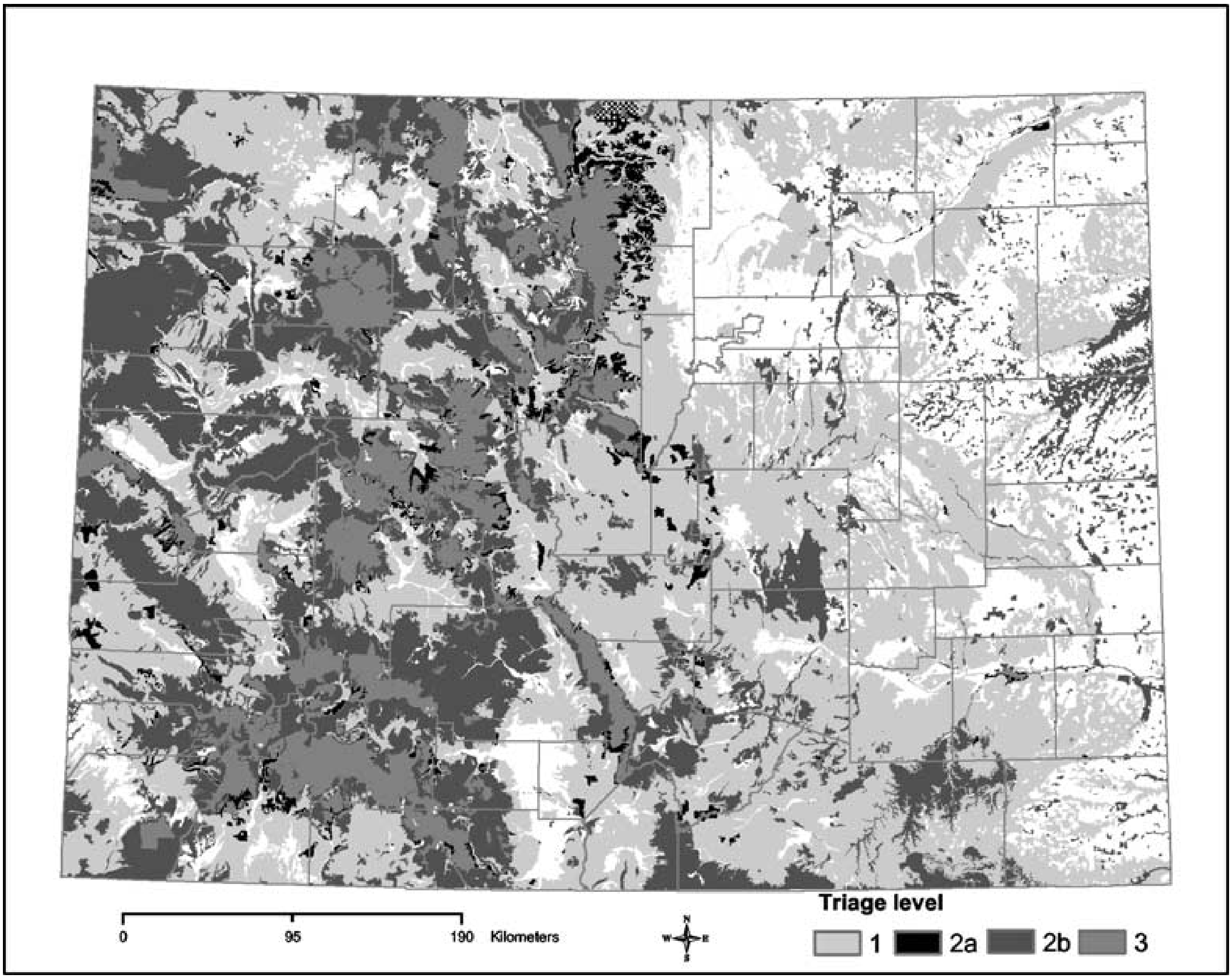

Figure 4. Conservation triage levels in Colorado (white areas within the state are "non-natural" land-cover types). Protected areas are comprised of land status 1 and 2 (see Fig. 3). Areas are threatened (at risk) if a land cover-patch has >20% roaded area, >15% developed area, or <30% conservation potential. Triage levels: 1, areas not protected and at risk; 2a, areas protected and at risk; 2b, areas protected but not at risk; 3, areas protected and not at risk.

A next step to assessing threats to biodiversity is to group species based on their sensitivity to human land uses. For example, Cassidy et al. (2001) distinguished species as "at risk," "well-adapted," and "neutral." One of the challenges in characterizing sensitivity is that much of this information is not well known or has not been compiled adequately. One of the benefits of identifying distributions of species that are at risk is that it will likely reduce the number of species for which information will need to be collected and may provide a way to better target the geographic location where conservation action should be focused.

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