Interface Between Ecology and Land Development in California
Edited by J.E. Keeley. 1993. Southern California Academy of Sciences, Los Angeles.

GIS Tools for the Assessment of Land Use Impacts on Biodiversity

Gregory Greenwood and Robin Marose

Forest and Rangeland Resources Assessment Program
California Department of Forestry and Fire Protection
P.O. Box 944246, Sacramento, CA 94244-2460
Tel. (916) 739-2588, (916) 739-2689; Fax (916) 739-4552

Abstract. Planning for regional biodiversity requires a means of portraying simultaneously the land management activities of multiple agencies as well as assessing the cumulative impact of these activities against standards. The Forest and Rangeland Resources Assessment Program has developed software that analyzes user-defined areas in terms of proportions of different habitat stages, distributions of habitat patch size, adjacency of habitat patches, connectivity of habitats, numbers of rare species or communities, and representation of important regional gradients, and compares such areas to standards derived for the entire region. The software can be used to assess high-contrast landscapes, typical of urbanized California, as well as mosaic landscapes more typical of California's rural areas.

Keywords: Biodiversity; habitats; land management.

Conservation and Landscape Structure

A recurrent theme in recent conservation literature is the need to adopt a landscape level approach to the conservation of biodiversity (Harris 1984; Baker 1989; Grumbine 1990; Doremus 1991; WRI 1991). Entire ecosystems, rather than individual species, are increasingly seen as the units with which conservation should work. Although reserves are often the conservationist's tool of choice, cultural, political, and economic factors greatly limit the ability of society to withdraw large areas from production. While portions of habitats of marginal economic value, such as upper-elevation forest and alpine areas, have been reserved in California (Forest and Rangeland Resources Assessment 1988), the extent of reserves in economically valuable lands such as oak woodland is currently low (only 4% for oak woodland: Greenwood et al., in press). We expect that no more than 8% of the oak woodland will ever be in reserves, leaving 92% of this habitat type subject to some form of management. As Pimentel et al. (1992) suggest, most biological diversity exists within human-managed ecosystems. The challenge to those government agencies charged with ensuring the long-term sustainability of managed ecosystems is to devise strategies to sustain biodiversity within these managed systems.

The key question is what do we want the managed landscape to look like? A reasonable working hypothesis is that we would like the landscape to resemble that which nature would produce (Hansen et al. 1991). Although this hypothesis is appealing, it requires that we establish a vocabulary that describes and quantifies landscapes. While both structure and function are different facets of nature, structure provides a more quantifiable basis for discussing landscapes.

Hierarchical concepts suggest that nature produces pattern at every spatial scale (Urban et al. 1987), a feature evident to all who deal with remote sensing data. In a fundamental way, the conservation of nature entails conserving the essence of these patterns at all scales. This paper concentrates on measures of pattern at the landscape scale, but we suggest that the principles could be applied at any scale within nature.

Measures of Landscape Structure

The Forest and Rangeland Resources Assessment Program has developed geographic information system (GIS) software to facilitate the quantification and comparison of landscapes. The landscape analysis software (LAS) characterizes mosaics by

1. Calculating the proportion of the landscape covered by different mapping classes

2. Quantifying the polygon size distribution within each mapping class

3. Calculating the degree of adjacency or juxtaposition between mapping class polygons

4. Portraying the connectivity of specific habitat types over a range of scales

Furthermore, it compares mosaics according to these four measures. Finally, it performs standard GIS accounting at a landscape level: it provides totals of point features such as rare species, linear features such as stream corridors and roads, and other polygon features such as ownership or soil types.

Since LAS is a geographic tool, most of its output is graphic in nature and not easily reproduced in the black and white format of journals. The results reported here have been adapted from color output and illustrate the types of analyses accomplished by this software. They do not convey the full amount of information generated by LAS in maps, graphs, and tables.

Central Sierra Case Study

The population of the Central Sierra — a six county region from Tuolumne County in the south to Nevada County in the north — is expected to increase by more than 40% from 1990 to 2005 (California Department of Finance 1991). This demographic increase will certainly affect the State's interest in wildlife, biodiversity, wildland fire protection, and the viability of resource-based industries, largely through its impact on vegetation and habitat. To explore these effects, the software analyzed a regional vegetation coverage as it was changed by the projected build-out of the General Plans of the six counties.

The vegetation coverage (Forest and Rangeland Resources Assessment Program, unpublished data 1992) describes the vegetation using the Wildlife Habitat Relationship (WHR) habitat descriptions (Mayer and Laudenslayer 1988). The coverage shows urban areas, lower elevation grasslands and oak woodland, Sierra mixed conifer, montane hardwood forests along canyons, and other features. Figure 1 shows vegetation generalized from this coverage.

LAS produces an acreage table (Table 1) that shows the acreage and proportion of the area covered by different WHR habitat types in the region. The region has 22 different types and covers more than 5 million acres.

Figure 1. Central Sierra vegetation generalized from WHR coverage.

Table 1. Area and proportion of the central Sierra in each Wildlife Habitat Relationship type

Habitat type	Acres	Percent
Alpine dwarf shrub	7,338	0
Agriculture	450,597	9
Annual grass	81,601	2
Barren	424,143	8
Blue oak-digger pine	156,048	3
Blue oak woodland	59,488	1
Chamise-redshank chaparral	161,853	3
Interior and/or canyon live oak	485,871	9
Jeffrey pine	48,948	1
Lodgepole pine	56,336	1
Mixed chaparral	243,945	5
Mixed conifer	1,828,288	35
Montane chaparral	62,202	1
Montane hardwood	305,894	6
Nonforested wetland	2,678	0
Red fir	404,659	8
Subalpine conifer	30,558	1
Sagebrush	35,851	1
Urban-agriculture	30,536	1
Urban	104,574	2
Valley-foothill hardwood	87,971	2
Water	163,012	3
Total	5,232,391	

While the proportion of the landscape covered by different habitat types is an essential characteristic of the landscape, it does not capture all the information in the map. Many different map configurations could yield identical proportions. For instance, a map with 22 polygons, one for each habitat type, would produce a table identical to Table 1.

Consequently, the second critical characteristic of the landscape is the polygon or patch size distribution within each habitat type (Fig. 2). Each bar in the histogram corresponds to a specific habitat type. LAS sorts the polygons in each habitat type by area and then creates six groups with equal numbers of polygons in each group. These sextiles are represented by different sections within each bar in Figure 2. The length of each sextile represents the proportion of the total area of the habitat type contained in that group. The acreages used for breakpoints between sextiles are printed within each bar.

Taken together, the bars in Figure 2 present a landscape signature derived from patch size. They account for many of the degrees of freedom within the map and portray the habitat as perceived by within-habitat specialists.

Still, many radically different habitat configurations could have similar proportions of habitats and distributions of polygon size. In fact, any spatial arrangement of a fixed set of polygons will yield similar proportions and polygon size distributions.

Thus, a third dimension of the maps — spatial relationships between habitat polygons — is portrayed in the adjacency histogram (Fig. 3).

LAS calculates the total length of boundaries within the map and then calculates the proportion of that total that separates different pairs of habitat. Each bar there-

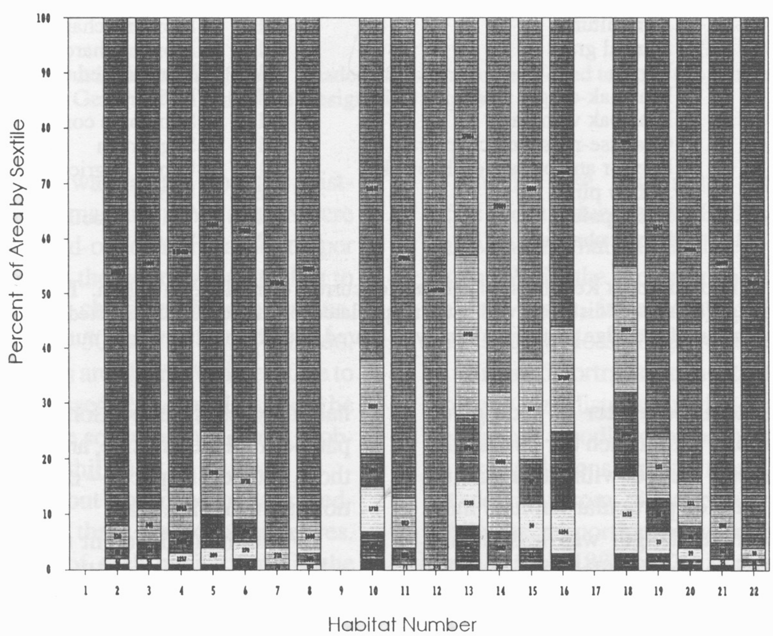
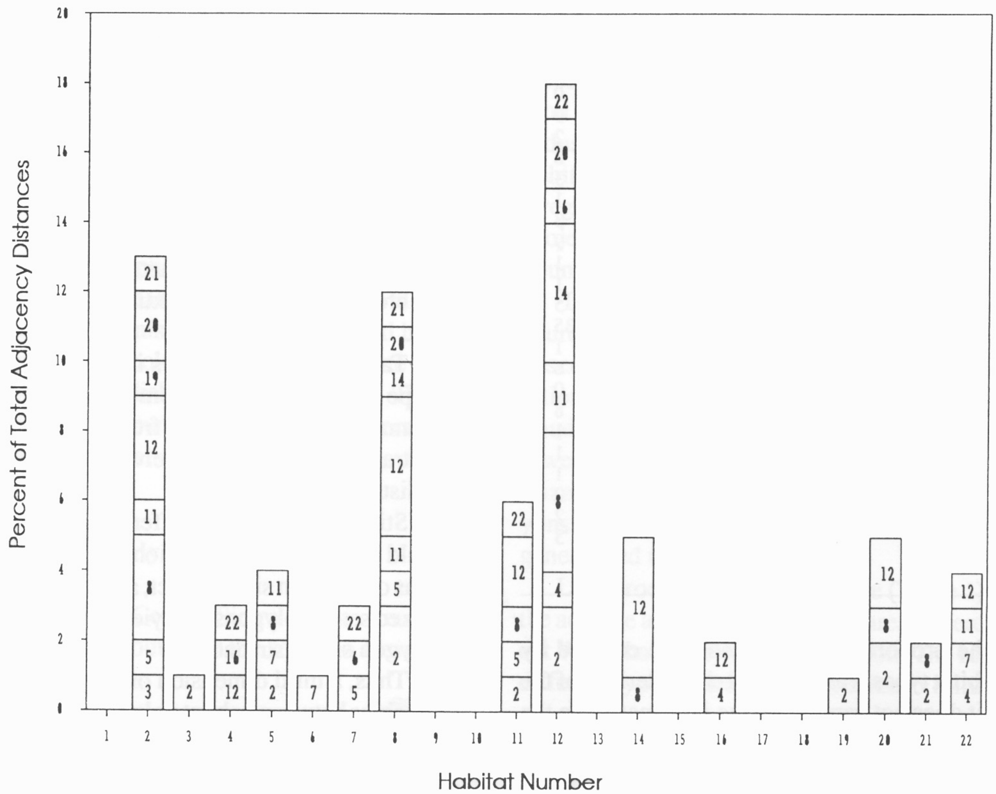


Figure 2. Current polygon size distributions for WHR habitat types in the central Sierra. Sections of each histogram bar represent the proportions of total habitat area contained in sextiles derived from size ordering of habitat polygons. The largest 16.7 percent of habitat polygon comprise the uppermost section, while the smallest 16.7 percent comprise the lowermost section. The area of the largest plygon in each sextile is printed within it. See Figure 3 for identity of habitat types.



Habitat No.	Name	Habitat No.	Name
1	Alpine dwarf shrub	12	Mixed conifer
2	Agriculture	13	Montane chaparral
3	Annual grass	14	Montane hardwood
4	Barren	15	Nonforested wetland
5	Blue oak-digger pine	16	Red fir
6	Blue oak woodland	17	Subalpine conifer
7	Chamise-redshank chaparral	18	Sagebrush
8	Interior and/or canyon live oak	19	Urban - agriculture
9	Jeffrey pine	20	Urban
10	Lodgepole	21	Valley - foothill hardwood
11	Mixed chaparral	22	Water

Figure 3. Adjacencies of Wildlife Habitat Relationship habitats for current central Sierra region. The height of each bar represents the proportions of the total edge (adjacency distance) within the map related to individual habitat listed on the abscissa. Sections within each bar represent the proportion of the edge of each habitat type shared with the habitat whose number appears within the section.

fore corresponds to the total perimeter of each given habitat type and the sections within each bar portray the proportion of the perimeter shared with other habitat types. The absence of bars for particular habitats indicates that the total perimeter length was less than 1 percent of the total and therefore rounded to zero.

As with the polygon size distribution, this histogram provides a landscape signature of the spatial relationships between habitat polygons. It summarizes the landscape as perceived by organisms that are edge, rather than interior, specialists.

These three measures — the total amount of different habitat types, the allocation of those aggregate areas into patches of different size, and finally the juxtaposition of those patches in space — capture the essential information in the habitat map.

While many different maps could yield similar results, those maps are all essentially similar. Thus, it should be possible to express landscape-level goals in terms of these three measures and compare alternative future plans to this standard to determine the ways in which the alternative landscape departs from the standard. An analysis of the General Plan build-out illustrates this capability.

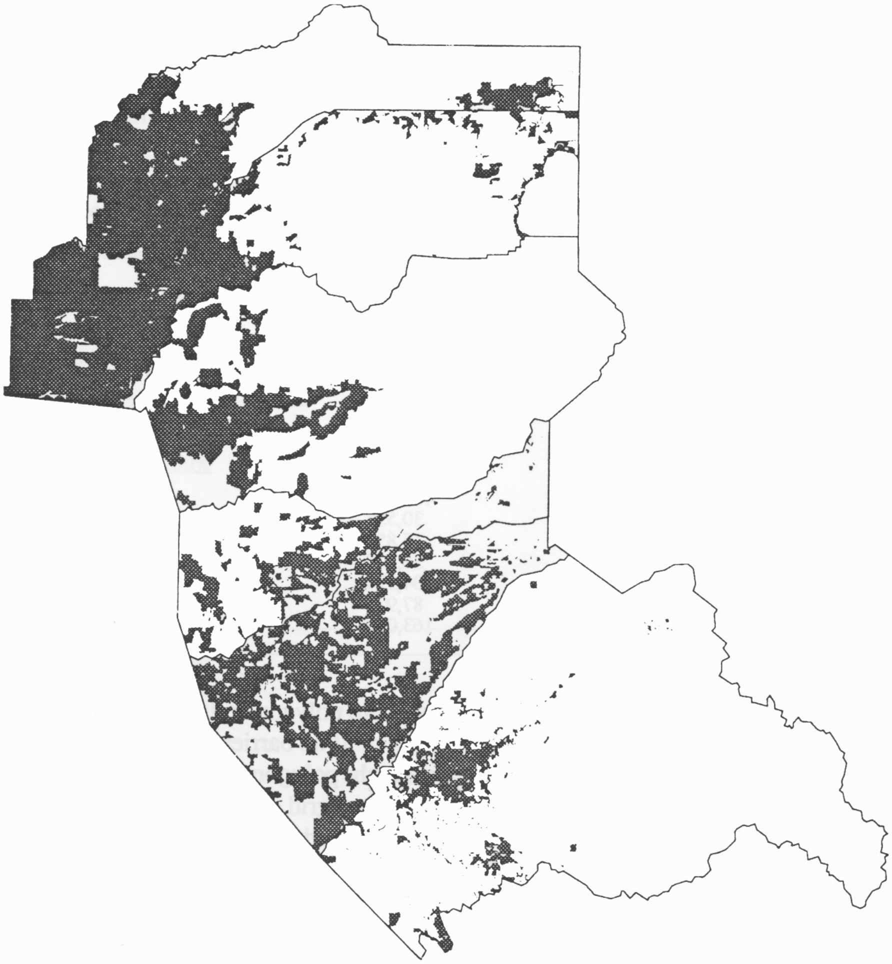


Figure 4. General Plan build-out in the central Sierra. Shaded areas can be developed to densities greater than 1 unit per 40 acres. (Preliminary data from County General Plan Land Use Designation maps.)

The build-out landscape was created from the existing vegetation coverage by masking those areas where the General Plans allow build-out denser than 1 unit per 40 acres (Fig. 4). Obviously, the extent of habitat lost to development varies with the choice of threshold value. The corridors of Highways 50 and 80 in El Dorado, Placer, and Nevada Counties are clearly visible. (Due to the number of assumptions used, these results should be considered illustrative of the software, not of the probable future of the Sierra foothills.)

LAS compares the built-out landscape to the preceding scenario in terms of the three landscape measures. Table 2 reports the extent of each habitat type in the baseline scenario and the relative change in proportion of habitat types following build-out. A value of 100% indicates no change between scenarios (i.e., the proportion in the comparator scenario is 100% of that in the reference) and values less than 100% indicate declines.

In this case, agriculture loses more than 300,000 acres and is reduced to 30% of its current extent. Several oak woodland habitats decline to 35-60% of their current extent. While the decline in mixed conifer is not great in percent terms, its absolute value (230,000 acres) is similar to the loss of agricultural land.

Figure 5 portrays the most important shifts in habitat polygon size distribution that result from the build-out. In blue oak woodland the proportion of the habitat found in large polygons (greater than 1715 acres for this habitat) declines from 78% currently to 52% with build-out, while the proportion between 270 and 1715 acres increases from 18% to 37% percent. A similar pattern of fragmentation is apparent for interior and/or canyon live oak.

Finally, Table 3 identifies some of the habitat juxtapositions that are either reduced or increased as a result of the build-out.

Table 2. Area of the central Sierra in WHR habitat types with General Plan build-out, area and proportion of total habitat types presently, and percentage change with build-out

Habitat type	Predicted Build-out (acres)	Present Build-out (acres)	Present Habitat (% total area)	Change (% current extent)
Alpine dwarf shrub	7,338	7,338	0	100
Agriculture	142,653	450,597	9	32
Annual grass	53,426	81,601	2	65
Barren	417,479	424,143	8	98
Blue oak-digger pine	95,645	156,048	3	61
Blue oak woodland	32,188	59,488	1	54
Chamise-redshank	103,012	161,853	3	64
Interior and/or canyon live oak	224,685	485,871	9	46
Jeffrey pine	45,980	48,948	1	94
Lodgepole pine	54,536	56,336	1	97
Mixed chaparral	164,975	243,945	5	68
Mixed conifer	1,598,413	1,828,288	35	87
Montane chaparral	59,366	62,202	1	95
Montane hardwood	278,106	305,894	6	91
Nonforested wetland	2,427	2,678	0	91
Red fir	399,795	404,659	8	99
Subalpine conifer	30,528	30,558	1	100
Sagebrush	31,845	35,851	1	89
Urban-agriculture	10,391	30,536	1	34
Urban	1,287,459	104,574	2	1,231
Valley-foothill hardwood	31,857	87,971	2	36
Water	160,199	163,012	3	98

First the build-out eliminates several classes of habitat adjacencies. While none of these classes are particularly prevalent currently, the loss of adjacencies between blue oak woodland and mixed conifer, and between valley foothill and montane hardwood types may interfere with organisms that exploit such juxtapositions.

Next, several important habitat adjacencies are much reduced with build-out. Juxtapositions of several habitats with agriculture are currently important and are drastically reduced with the build-out. Adjacencies among several oak woodland and chaparral habitat types are also greatly reduced with build-out.

Not surprisingly, the interface between urban areas and habitats increases with build-out. Increasing interface is particularly important with mixed conifer, interior and/or canyon live oak, and mixed chaparral.

Connectivity

The concept of connectivity requires that one relabel the landscape mosaic in terms of core areas, matrix, and barriers. Matrix allows movement of organisms, but does not provide all the prerequisites for reproduction. Barriers inhibit movement.

The scale of inquiry also affects connectivity. If the median distance between patches in a landscape is 2 km, the landscape may be very fragmented at the 1-km scale, but quite connected at the 5-km scale. Patches that are connected at a given scale are termed "linked polygons."

In order to identify linked polygons, a grid is laid over the relabelled landscape. Picking a single grid cell within a core area, LAS determines the distance to the next core polygon and the type of matrix that separates the two. If no barrier is encountered, then LAS characterizes the polygons as linked at a scale determined by the number of grid cells separating the polygons.

LAS produces maps of polygons linked at different scales along with reports on the number of linked polygon groups. The allocation of total core area to linked polygon groups at each scale is shown in histograms.

As with other landscape measures, LAS analyzes and compares the connectivity of core habitats under different scenarios. While the software produces maps, the results are summarized in Table 4.

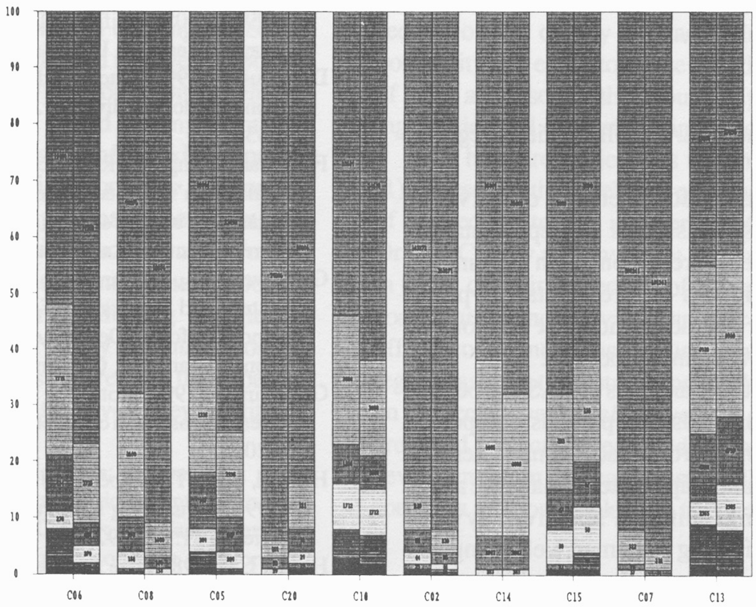
Under current conditions the nearly 800,000 acres of hardwood habitat appear relatively connected at scales of 2 km and greater. As the scale declines from 10 km to 2 km, the number of linked polygon groups increases slightly from 3 to 6. When the scale declines to 1 km the number jumps to 23. Even at this smallest scale, however, most of the hardwoods are still concentrated in three groups, all on the order of hundreds of thousands of acres.

With the build-out scenario, the acreage of hardwoods has been cut nearly in half, from nearly 800 to around 400 thousand acres. The connectivity of hardwoods is drastically affected by the build-out. Fragmentation is apparent at even the largest scale. The nearly continuous habitat at the 5- and 10-km scales under the current scenario is split into two fragments by the Highway 50 corridor.

The scale at which fragmentation accelerates has increased to over 2 km. Whereas previously only 6 groups appeared at the 2-km scale, with build-out, 31 groups are created. At the 1-km scale, the number of fragments quadruples with build-out.

Table 3. Selected changes in habitat adjacencies as a result of General Plan build-out in the central Sierra

Habitat pair	Current Build-out (% total edge)	Predicted Build-out (% of current)
Adjacency eliminated		
Barren-nonforested wetland	0.01	0
Blue oak-mixed conifer	0.01	0
Montane hardwood-valley foothill hardwood	0.04	0
Adjacency reduced by more than 50%		
Agriculture-annual grass	0.81	38
Agriculture-interior and/or canyon live oak	2.79	36
Agriculture-mixed chaparral	1.36	42
Blue oak digger pine-interior and/or canyon live oak	0.56	46
Blue oak-chamise redshank chaparral	0.78	50
Adjacency increased by more than 150%		
Urban-blue oak digger pine	0.13	892
Urban-blue oak woodland	0.03	1133
Urban-chamise redshank chaparral	0.15	693
Urban-interior and/or canyon live oak	0.90	388
Urban-mixed conifer	1.62	383



Map Class #	Habitat Type	Map Class #	Habitat Type
C02	Agriculture	C08	Interior and/or Canyon live oak woodland
C05	Blue oak/digger pine woodland	C10	Lodgepole pine
C06	Blue oak woodland	C13	Montane chaparral
C07	Chamise-redshank chaparral	C14	Montane hardwood
		C15	Nonforested wetland

Figure 5. Paired polygon size distributions for 10 habitat types in the central Sierra: right element = current distribution; left element = General Plan build-out.

Table 4. Number and size of linked hardwood polygons currently and with build-out of the Central Sierra General Plans, at different scales (median distance between patches)

	Value by Scale			
Item	1 km	2 km	5 km	10 km
Number of linked polygon groups:				
Current	23	6	3	3
Build-out	102	31	18	18
Size of largest three linked polygon groups: (thousands of acres)				
Current	467	680	786	788
	157	99	-	-
	96	-	-	-
Build-out	121	194	279	281
	75	77	83	83
	35	66	9	9

Once again, the data on the nature and extent of build-out are preliminary. No conclusions regarding actual or future situations in these counties should be drawn from these data. Once the data are verified and a consensus is reached regarding development impacts, LAS will be used to assess the regional impacts of projected development on the entire landscape of the Central Sierra.

Uses of LAS

As demonstrated here, LAS will facilitate regional habitat analyses.

LAS will also be useful for reserve or conservation strategy design because it assesses the representativeness of prospective reserve areas along with the numbers of rare species, occurrences of rare habitats, types of ownerships, and other characteristics that are counted through the landscape accounting portion.

Finally, the connectivity analysis of LAS can be used to assess the impact of landscape patterns on specific taxa. Such assessment may provide additional criteria by which to narrow in on landscape patterns that have a high probability of conserving California's biodiversity while at the same time contributing to human well-being.

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