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Managing Wildlands for Biodiversity: Paradigms and Spatial Tools

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Abstract

The increasing concern for the conservation of biodiversity arises from a fundamental and ongoing shift in the perception of natural resource systems and the role of humans within nature. The new management paradigm emerging from this shift emphasizes intergenerational time scales, nonequilibrium dynamics, and the information content of nature. The information content of nature manifests itself in variation in patterns at multiple spatial scales. Conservation of the information content of nature requires consideration of the entire landscape, rather than just small fragments, and must specify how anthropogenic disturbances can maintain patterns at multiple spatial scales. New geographic information system tools provide a vocabulary for analysis of pattern and specification of desired future conditions. Lacking a profound functional understanding of ecosystems, managers can use the range of variation in pattern over recent evolutionary time as an interim guide for the development of desired future conditions.

INTRODUCTION

The conservation of biodiversity has become a major concern for both public and private land managers. As with many issues, the definition, scope, and implications of biodiversity remain unclear. Various actors in the play—scientists, advocates for industry and environmental groups, land owners and managers, court justices, legislators—struggle to define the issue in terms at least comprehensible and frequently beneficial to their interests. The very complexity of the intellectual and political stew—the Endangered Species Act, Gap Analysis, the Agreement on Biodiversity, environmental mapping analysis program, among others—indicates that the issue of biodiversity is just one tip of a multi-tipped iceberg. This conceptual iceberg embodies a fundamental and continuing shift in our perception of natural resource systems and of the role of humans within nature.

The success of managers, which is measured as much in social and political as in biological terms, will depend largely on how well they appreciate the nature of this change. This paper explores the nature of this shift and formulates the resource-management problem in terms of the heterogeneity of ecological systems. It then illustrates the relationship among heterogeneity, scale, and management and follows with an examination of the types of strategies that might be used to conserve heterogeneity. Finally, I demonstrate through several case studies a range of geographic information system (GIS) tools that can be used to assess management strategies.

THE CHANGING RESOURCE-MANAGEMENT PARADIGM

What is the shift in resource-management paradigms? Simply put, we are now called upon to manage complex and still poorly understood systems in the light of an unknown future in ways that do not reduce the ability of future generations to do the same thing. Biodiversity may be used as a measure of the options open to future generations.

Many other policy concerns that apparently compete with biodiversity for attention are complementary and can be reconciled under this new paradigm. The issue of global climate change emphasizes the uncertain future. Ecosystem management expresses the notion that nature is not a static collection of commodities but rather a system whose function perpetuates its components and, therefore, provides multiple byproducts—not just to our generation but to all generations to come.

To understand this emerging imperative, we can compare it to our historical mode of management (Table 1). Under historical management, the governing time frame has been short term: we satisfy the desires of this generation and discount the desires of future generations. Perhaps because of this discounting of the future, we viewed natural resource systems in coarse-grained terms: we perceive only those aspects of the system that are important to us now. Histori-

TABLE 1. A COMPARISON OF HISTORIC TO EMERGING MANAGEMENT MODE IN TERMS OF SELECTED CHARACTERISTICS.

CHARACTERISTIC	HISTORIC	EMERGING
Time frame	1–10 years	1–200 years
Categorical grain	coarse: “biomass”	fine: “information”
Dynamics	equilibrium-centered: noise irrelevant to system trajectory	non-linear, directional, chaotic: small differences are important
Imperative	maximize production of biomass subject to constraint set	ensure at a given probability the persistence of all system components
Tool	linear programming	dynamic stochastic programming

cally, biomass—forage, timber—or just mass—minerals, water—has been the principal interest. The discounting of the future may also have implied a perception of the system as equilibrium centered, wherein noise did not affect the dynamics of the system, at least not at the time scale we used. Within this set of perceptions, the management imperative has been to maximize the production of the major product subject to a host of constraints. Resource management looked to industrial management and developed its preferred tool: linear programming.

In the emerging mode of management, the governing time frame is far longer because it begins to value the desires of the future. The expanding time frame forces us to consider the structure of the system in far more detail because no one generation can tell what aspect of nature future generations may value. Three centuries ago, the inhabitants of California placed enormous value on acorns. Given our current resource-inventory technology, they might have classified their ecosystems with respect to that particular resource. They may have considered the oozy tar pits of the Los Angeles basin as an interesting but economically trivial phenomenon. Had we used only their perspective in labeling nature, we would have missed the preeminent resource of the industrial world—petroleum—and been left with maps of acorn production, now an interesting but economically trivial phenomenon.

We cannot know now what people three centuries hence will value. What we can recognize now is the underlying heterogeneity within nature that supports the shifting desires of generations. The vocabulary of mass is simply incapable of expressing this heterogeneity. It will be supplanted by other vocabularies that stress the information content of nature, from the DNA that governs individuals to the structure of landscapes that provide habitat to individuals. This information content of nature is succinctly captured in the concept of biodiversity: “the variety and variability among living organisms and the ecological complexes in which they occur” (Office of Technology Assessment 1992). Biomass will certainly remain important—livestock do eat grass and houses are built of wood—but it will become more what it really is: residue left as living systems perpetuate themselves.

Just as our simple perceptions of resource systems give way to ones of increasing complexity, our equilibrium-centered perception of their dynamics is quickly yielding to one that accepts directional change, multiple states, and perhaps even chaos. This expanding understanding of dynamics increases our uncertainty in two ways.

First, we know that small differences, what we used to consider noise, can be extremely important to long-term dynamics. When seeds of exotic annuals sprouted in California in the late 1700s (Burcham 1981), not even modern plant-community-inventory methods would have noticed the weed patch. Yet that virtually undetectable original blip on California’s vegetational history led to a nearly complete replacement of native grassland species (Burcham 1981). Over time, small differences and individual species can be very important (Vitousek 1990).

Even if we could detect all the differences that might be important, our uncertainty regarding the values of future-driving variables, such as climate, fire, disease, and their interaction with ecological systems, makes prediction of the future very difficult.

As our perception of the environment has changed, so has the management imperative. In this new world of dizzying biological diversity and unpredictable dynamics, resource managers are now called upon to manage in ways that increase the probability that the system will persist into the future. No new tool has yet emerged that quantifies this risk-aversion problem. However, just as the description of the problem resembles that of fitness, resource management may look to ecology, particularly foraging theory and dynamic stochastic programming (Mangel and Clark 1988), to find new quantitative methods. In the context of dynamic stochastic programming, the resource-management question will become, “Given an uncertain future, what actions can I take in the next time period that will not reduce below some minimum the probability of maintaining the biological diversity of the system many time periods into the future?”

An important aspect of foraging theory and by extension natural resource management is learning and the incorporation of knowledge gained in the current time period into decisions in succeeding time periods. Monitoring and ex-

explicit protocols for updating management decisions based on new knowledge are essential elements of any serious response to uncertainty.

FALLING INTO CALIFORNIA: THE PATTERNS OF LIFE AT MANY SCALES

If the general resource-management problem deals with biological diversity, we need a means to analyze biological diversity. The definition of biological diversity given by the Office of Technology Assessment starts in the middle of life ("organisms") but then looks both up ("ecological complexes") and down ("variability among") the spatial scale. This paper proposes no new definition but simply a single trajectory through the same conceptual space—from the larger to the smaller spatial scale. This way of approaching biodiversity derives its power in part from hierarchy theory, i.e., larger processes set the stage for smaller processes (O'Neill et al. 1986), and in part from landscape ecology (Urban et al. 1987), in which those hierarchical patterns play out in space.

The great virtue of this approach for managers resides in the assumption that by conserving the system at one scale one has a high probability of conserving the smaller component parts as well, even though the manager may never know the true extent or nature of those parts. This approach allows managers to move ahead in promising directions without waiting for those ultimate systematic inventory and ecological studies that, while desirable, may never happen.

Figure 1 portrays how northern California appears from high in space. Much of the spectral and textural variety in the scene derives from the response of life to climate and geology. By means that remain obscure, our eyes and brains can classify the scene into a pattern of subregions. Figure 1 shows one way of drawing this pattern, a way that corresponds to landscapes Californians identify as the Sierra, the Central Valley, the North Interior Coast Range, the Delta, and so on.

Does this classification capture all the diversity and information within the scene? Put another way, is it possible to distinguish other patterns at a smaller scale within each polygon outlined in Figure 1, or are the components within each polygon randomly distributed? To answer this question, we zoom in to the box outlined in Figure 1, the contents of which are portrayed in more detail in Figure 2.

At this lower altitude, we see not only the pattern distinguished at the higher altitude but a great deal more detail as well. Patterns emerge within those larger polygons, with some of these drawn as additional polygons in Figure 2. Once again, these patterns correspond to landscape elements Californians recognize on the ground. Some of these landscape elements relate to human use of the environment. For instance, the metropolitan area of Sacramento clearly differs from less developed adjacent areas. Thus, certain types of disturbance—urban and irrigated agriculture—are detectable at this scale. Questions regarding such development may be most economically answered with data from this scale alone.

Again we may ask if this yet finer characterization of life has captured all the important information. Are there issues that require yet finer-grained perception? We must once again zoom in further, this time into the area near Lake Berryessa shown in Figure 2 and reproduced in more detail in Figure 3. New patterns emerge—east-facing slopes emerge from the mass of the Coast Ranges—but these new patterns do not clearly relate to a particular process or issue. They may exemplify the notion of a measured heterogeneity that has little evident relationship to our current understanding of how the system operates (Kolasa and Rollo 1991).

The iterative nature of this analysis should now be clear. As we examine more closely in Figure 4 the outlined area in Figure 3, we find again patterns that relate to our understanding of the landscape. At this scale, we can see particular habitat types, such as oak woodland, annual grassland, and riparian areas. Thus, at this scale we detect conversion of oak woodland to grassland or riparian habitat to agriculture. While coarser-grained changes (wildland to urban areas) could be analyzed with coarser-grained data, conversions within wildland require finer categorical and spatial grain.

In Figure 5 we see the area outlined in blue in Figure 4. Now we see variation within the habitat types: areas with different canopy closure in oak woodland and areas of bare soil within the grassland. Because we can detect these changes, this scale would be appropriate for monitoring management of the oak woodland and the grassland.

This trajectory could, of course, continue. In Figure 6 we see vertical variation in the structure of oak woodland patches with the consequent creation of special habitat elements—perching branches and cavities in oak trees, seasonal wet spots, and so on. This scale is appropriate for monitoring management activities that operate within habitat stages but nonetheless affect habitat suitability, e.g., water spreading, pruning, hazard-tree removal.

Closer to the ground in Figure 7, we see patterns of species distribution within the grassland. This scale is a favorite for plant demographers and by extension for foraging ecologists and range-livestock scientists interested in how grassland floristics and structure alter feeding behavior.

We will halt our trajectory in Figure 8 at a scale appropriate to anatomy. The patterns apparent at this scale derive from development processes operating on genetic material. Few human activities consciously operate at this scale. Many management activities have inadvertent and unexpected repercussions at this level.

This trajectory across spatial scales is of course an incomplete portrayal of the heterogeneity of life. Nature changes over time as well as over space. Different temporal patterns emerge at different temporal scales: vegetation types shift in response to long-term climatic changes, seral stages succeed each other after disturbances such as fire or floods, nutrient reserves are translocated within plants in response to seasonal changes. To display accurately the heterogeneity of life at different spatial and temporal scales simultaneously requires a medium more like video than photography.

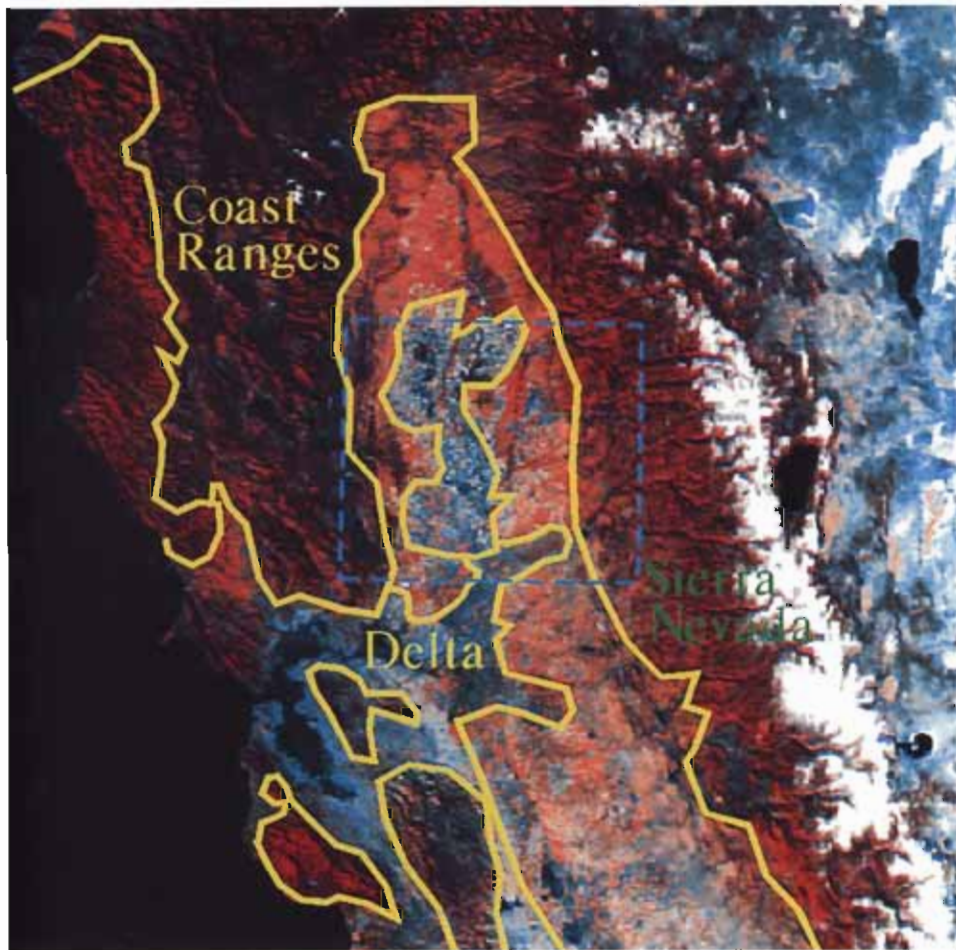


Figure 1. AVHRR scene of northern California on November 1, 1989, with selected regions outlined in yellow. Area in Figure 2 outlined in green. (Imagery: NASA Ames Aircraft Data Facility.)

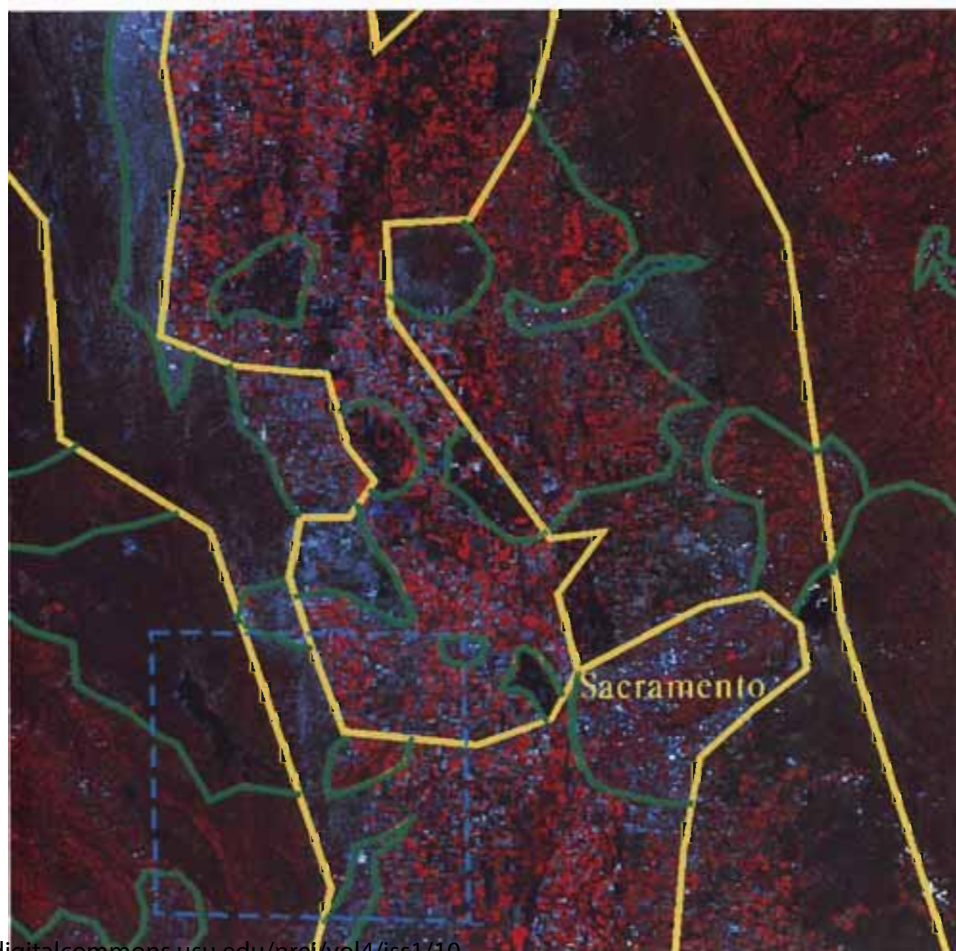


Figure 2. TM scene (bands 4, 3, and 2) of Lower Sacramento Valley on June 20, 1990, with previously selected regions in yellow, newly distinguished regions in magenta. Metropolitan Sacramento denoted by "SAC." Area covered in Figure 3 outlined in green. (Imagery: NASA Ames Aircraft Data Facility.)



Figure 3. NS001 Airborne Thematic Mapper Simulator scene of western Yolo and Solano Counties on May 31, 1991, with previously selected regions in yellow, newly distinguished regions in magenta. Area covered in Figure 4 outlined in green. (Imagery: NASA Ames Aircraft Data Facility.)

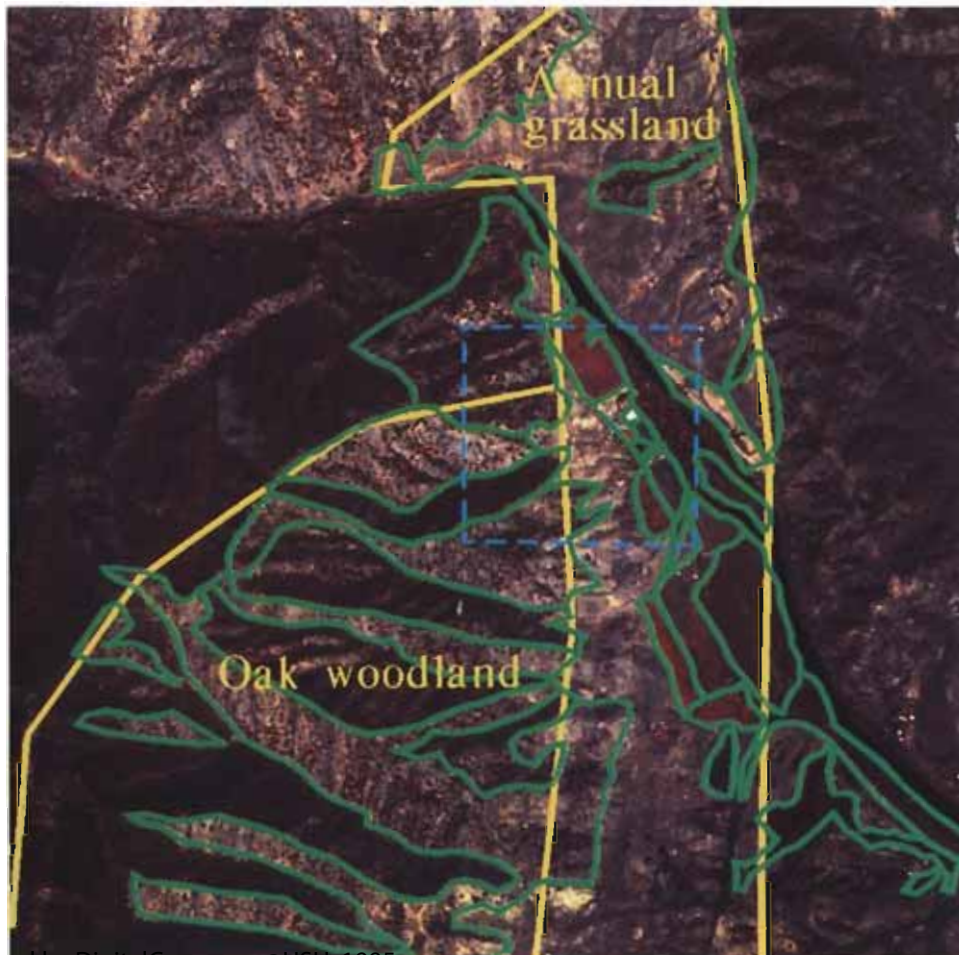


Figure 4. Scanned high-resolution IR photograph of lower Putah Creek Canyon on May 31, 1991, with previously selected regions in yellow, newly distinguished regions in magenta. Area covered in Figure 5 outlined in green. Different habitat types are readily distinguishable: oak woodland, annual grassland, irrigated agriculture. (Imagery: NASA Ames Aircraft Data Facility.)

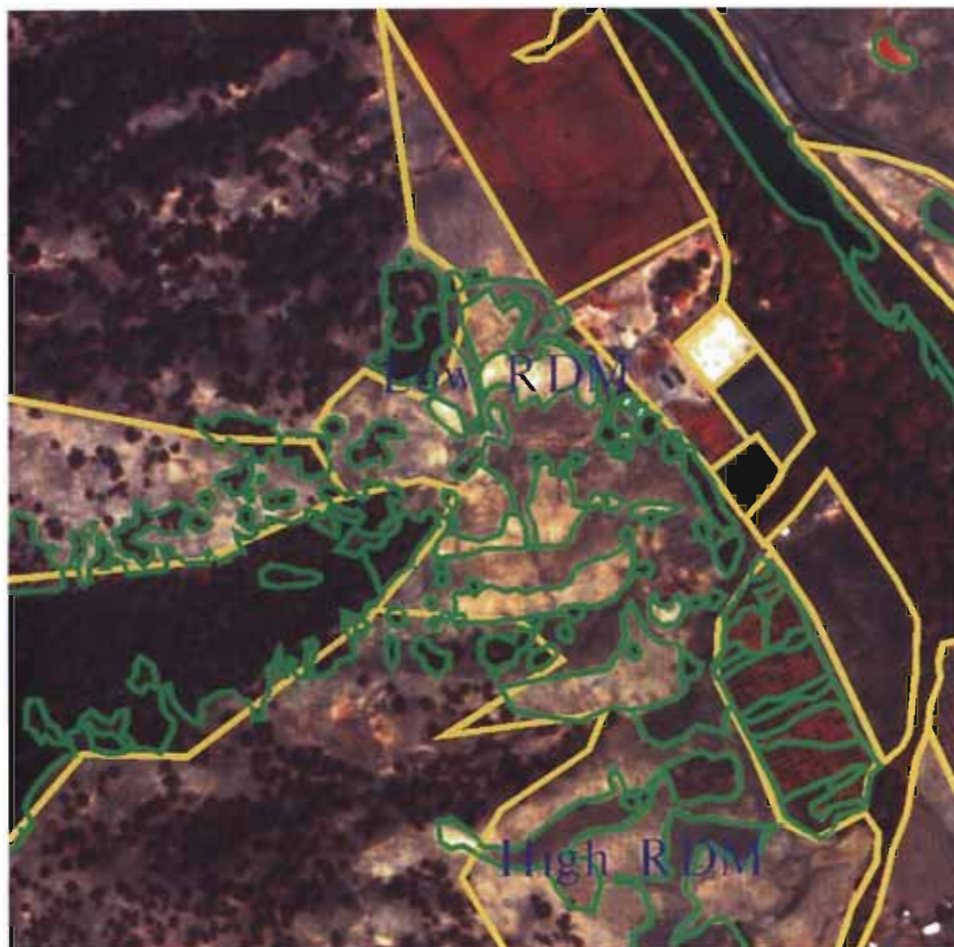


Figure 5. Scanned high-resolution IR photography of ranchlands adjacent to Putah Creek with previously selected regions in yellow, newly distinguished regions in magenta. Different habitat conditions are readily distinguishable: open vs. dense oak woodland, low residue vs. high residue annual grassland. (Imagery: NASA Ames Aircraft Data Facility.)



Figure 6. Typical valley-foothill oak woodland showing different microhabitats and special habitat elements. Photo by author.



Figure 7. Herbaceous layer within valley-foothill oak woodland showing variable species composition. Photo by author.



Figure 8. Anatomical features of a single organism within the herbaceous layer. Photo: Endangered Plant Program, California Department of Fish and Game.



Figure 9.

Captions for Figures 9-18 follow the illustration section.



Figure 10.



Figure 11.

Captions for Figures 9-18 follow the illustration section.



Figure 12.

Figure 13.



Captions for Figures 9-18 follow the illustration section.

Figure 14.



Figure 15.



Captions for Figures 9-18 follow the illustration section.

Figure 16.

WHR HABITATS: HUMBOLDT COUNTY PILOT SITE

1990



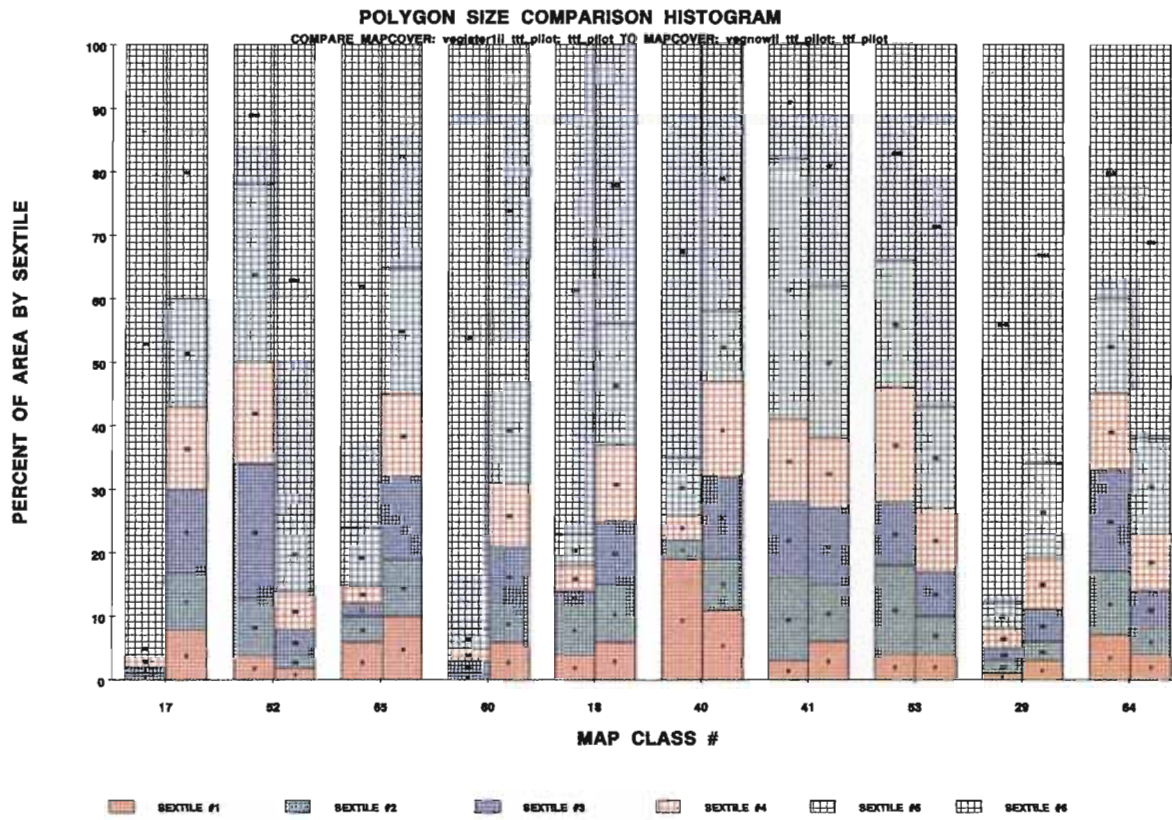
2040: EXISTING RULES

0 MILES 10



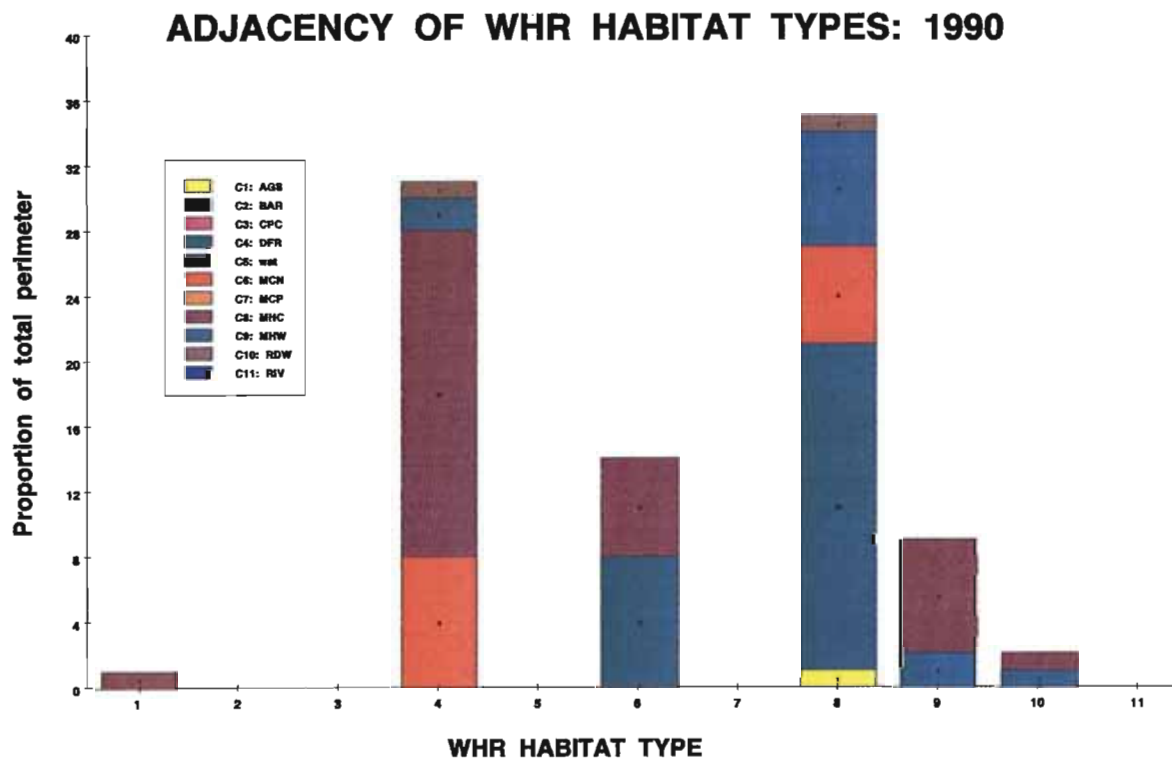
	GRASSLAND		CPC4P		DFR4D		MCN3D		MCH8P		MHC3S		MHW2D		MHW4P
	BARREN		CPC4S		DFR4M		MCN3M		MCH8S		MHC4D		MHW2M		MHW4S
	CPC2P		CPC3D		DFR4P		MCN3P		MCH6		MHC4M		MHW2P		RDW4D
	CPC2S		CPC3M		DFR4S		MCN3S		MCP3SD		MHC4P		MHW2S		RDW4M
	CPC3D		DFR2D		DFR8D		MCN4D		MHC2M		MHC4S		MHW3D		RDW4P
	CPC3M		DFR2M		DFR8M		MCN4M		MHC2P		MHC4S		MHW3M		RDW4S
	CPC3S		DFR3D		DFR8P		MCN4P		MHC2S		MHC6M		MHW3P		RDW5M
	CPC4D		DFR3M		DFR8S		MCN4S		MHC3D		MHC6P		MHW3S		RDW5P
	CPC4M		DFR3P		DFR6		MCN5D		MHC3M		MHC6S		MHW4D		RDW6
	CPC4S		DFR3S		AQUATIC		MCN5M		MHC3P		MHC6		MHW4M		

Figure 17.



Captions for Figures 9-18 follow the illustration section.

Figure 18.



Captions for Figures 9–18, shown on previous pages.

- Figure 9. *Starry Night* by Vincent van Gogh, a visual metaphor for the environment.
- Figure 10. Red and orange pixels are analogous to rare species and are located through inventory.
- Figure 11. The rare pixels, now shown as magenta, can be placed within a landscape context.
- Figure 12. The overall result of creating a conservation strategy that relies entirely on reserves for rare species: the species may be temporarily saved but the environment as a system is lost.
- Figure 13. Removing a single color everywhere throughout the image is analogous to intense single-use management.
- Figure 14. Removing some of every color everywhere throughout the image dims the image but conserves most of the information within it.
- Figure 15. Reserve, light use, and intense use can be combined over the entire image to conserve the image while using it.
- Figure 16. Current habitat and that projected for 2040 under current forest practice rules for a 170,000-acre pilot site in northern Humboldt County, California.
- Figure 17. Comparisons of patch size histograms in 1990 and 2040 for selected habitats in the pilot site. Each pair of stacked bar graphs refers to a particular habitat stage, with the right bar referring to current conditions, the left to projected conditions. Segments within each bar contain the same number of polygons. Only those habitats with the greatest shifts in patch size are shown. Map class 17 = Douglas fir, pole size, dense canopy closure (DFR3D), map class 52 = montane hardwood conifer, small tree, dense canopy closure (MHC4D).
- Figure 18. Adjacency histogram for habitat types within the pilot site in 1990. Each stacked bar represents the proportion of total edge within the map constituted by the total perimeter of a given habitat; the segments within each bar represent the proportion of the total edge that a particular habitat type shared within another habitat type.

The principal lessons of this descent into California are these:

1. The variation at all spatial scales is indeed biodiversity. Single measures of biodiversity, such as species richness (Figure 7) are only indices abstracted from this continuum after one decides on a specific grain and a single scale of observation.
2. The patterns are the structural evidence of processes and disturbances that characterize a place. Human use of the environment—urbanization, conversion, management—is just another, albeit important, class of disturbance, operating at many spatial scales as well and altering the pattern of life at those scales.

STARRY NIGHT: THE CONSERVATION OF PATTERN AT ALL SCALES

If the management imperative is to maintain biodiversity over the long term, and if biodiversity is manifested in a hierarchy of patterns, what sorts of management strategies are needed to conserve these patterns?

The painting *Starry Night* by Vincent van Gogh provides a metaphor (Figure 9). It is similar to life as described in the previous section: it consists of millions of entities (brush strokes) that, when taken together, form patterns at several scales. Metaphors are always tricky coding devices, and this one deserves some examination.

The ecological analogue to the brush stroke is an individual organism. Of course, any brush stroke contains smaller elements of color and, therefore, the classification of a brush stroke is not unambiguous. It is convenient to classify organisms into species or demes. Since there are many species or demes, these classifications might be characterized as using “16-bit color.” The larger elements of the painting—the trees, the village, the sky—are characteristic aggregations of species communities or habitats.

The classification of brush strokes into species is, however, not the only possible way of coping with variation at that level. Ecologists might perceive not species but guilds or functional groups. Since these constructs reduce the amount of variation, the functional ecology perspective might be using “8-bit color.” Philosophers and ethicists might perceive each individual, each brush stroke, as unique (24- or 32-bit color), while molecular biologists might see not brush strokes but individual pigment molecules within each stroke (by using a higher-resolution screen). Since there is as yet no “general theory of life,” we must be content with a certain open-endedness to the biological correlate of a brush stroke. Nonetheless a painting clearly emerges and exists, even if its ultimate building block remains unclear.

The painting is also not dynamic and, therefore, falls short of accurately portraying life. However, one can imagine a painting that wavers and flickers over time but that nonetheless remains identifiable as *Starry Night*.

Our metaphorical problem, as resource managers, is to use the painting while at the same time maintaining the painting’s integrity. In the light of the previous sections, integrity is maintained if the painting remains identifiable as *Starry Night*. Like the metaphor itself, this imperative requires closer examination.

First, maintaining integrity does not mean maintaining some transcendental quality such as “beauty” in the landscape. It means maintaining the patterns at many scales that make a landscape identifiable as a place. Patterns at many scales provide a structural vocabulary for defining desired future conditions of the ecological system.

Second, maintaining integrity does not mean “freezing” the landscape. The patterns that give a place identity are frequently the result of disturbance and other ecological processes. Therefore, the continued existence of those patterns—realization of the desired future condition—can be assured only through the maintenance of the processes—natural or human—that generate those patterns.

Third, the target level of integrity is as open-ended as is the meaning of the brush stroke. For the functional ecologist who sees life as the transfer of energy and nutrients over a short time horizon, the integrity of the painting is carried by coarse patterns of guilds or trophic levels within habitats. The nature of individual brush strokes can vary a great deal before

the coarse-grained picture loses its identity (Johnson and Mayeux 1992). However, for the evolutionary biologist who perceives life as the transfer of genetic information through time (with the transfer of energy and nutrients as supporting acts), even slight changes in species composition are noticeable. Many system configurations that would still be identifiable as *Starry Night* to the functional ecologist would not be identifiable to the evolutionary biologist.

In a fundamental sense, neither of these perspectives is more "correct" than the other. The relevance of each species to ecological function remains an open question,¹ depending largely on the temporal scale of the analysis and the fineness with which one defines ecological function (Chapin et al. 1992, Solbrig 1992). The use of ecological function as a surrogate for human welfare may itself be a generationally centered perception that understates the value of genetic diversity to future generations.

None of these considerations drastically changes the metaphorical challenge: to determine strategies that we might employ to "have our painting and use it too."

Many of our current conservation strategies are oriented around rare and endangered species (e.g., Thomas et al. 1990). *Starry Night* is generally bluish, with red and orange being relatively rare colors and, therefore, candidates for our metaphorical rare species. With a good inventory we can locate sites with high densities of these rare colors (Figure 10).

We can then locate these rare colors, now shaded magenta, within a landscape context (Figure 11). We can then design a reserve system that encloses high densities ("viable populations") of rare colors throughout the range of their occurrence. However, if we do not concern ourselves with the land between the reserves, we may save the colors/species but lose the painting/wildland (Figure 12). This scenario corresponds to a California that consists of either urban sprawl, irrigated agriculture, or national park. While such a scenario may seem far-fetched now, a simple glance at a map of Western Europe should convince one that over the long term such a scenario is quite possible.

The main point of Figure 12 is that reserves alone do not constitute a sufficient strategy to maintain the integrity of the painting. To conserve the diversity within *Starry Night*, we must also consider the fate of the nonreserved areas that we now see, since they contain most of the information within the painting (the biological analogue—that considerable biodiversity is maintained within managed ecosystems—is discussed by Pimental et al. 1992). Simply enlarging the size of reserves would be technically effective; but in any populated region, putting more land in nature reserves is very difficult and in any event is not likely to encompass more than a small fraction of the land surface.

What strategies might we employ on nonreserved areas? Historically, we have frequently managed landscapes for particular resource values, such as water, large saw logs, or particular forage plants. Within our metaphor, such single-use management appears as the complete extraction of a single color, such as green, from throughout the painting (Figure 13). When we do this, we get a cartoon of the original

painting—something that reminds us of what once was but is really quite different from the original.

Another alternative is to take out some of all colors throughout the scene (Figure 14). This strategy corresponds to a selective harvest scheme that removes a small proportion of all species and age classes. This strategy certainly dims the painting but results in a scene that when compared to those left by other strategies is closest to the original.

These strategies could be combined over the entire landscape (Figure 15). Reserves would maintain all the information in nature as clearly as possible, while management of most of the remaining landscape maintains enough information to assure the integrity of the entire system. Finally, certain areas are reserved for intensive culture and urban development. While virtually no information remains in those areas, the information they formerly contained appears in other areas and is not lost to the entire system. The resulting scene is not identical to the original; but the strategy allows the current generation to use the scene, as it must for its survival, while maintaining the integrity of the scene, as must be done for the survival of future generations.

The metaphoric strategy works—the painting remains apparent—principally because the strategy maintains the pattern of color over the whole scene. The take-home lessons are two:

1. If management is to succeed, it must consider the entire landscape, not simply small pieces of it.
2. In addition, the management prescriptions related to biodiversity must get beyond the no-use recommendation and must begin to describe how use can be tailored to maintain the patterns characteristic of the place at all scales.

LANDSCAPE EVALUATION: THE DESCRIPTION OF PATTERNS AT MANY SCALES

Assessing how well a strategy maintains the pattern of life at many scales requires a means to quantify those patterns. The California Department of Forestry and Fire Protection has developed a vocabulary of pattern analysis and implemented that vocabulary in its Landscape Evaluation Module or LEM.

Figures 1 through 8 illustrate the problem. In each figure, different units each have a distinct gestalt. Areas within each unit are not identical, yet the image analyst sees them as similar enough to lump together as different from another area. How can this gestalt be quantified?

For a given landscape mapped to a given level of detail, LEM calculates three classes of measures that taken together portray the gestalt of the landscape mosaic:

1. How much of each map class we have (e.g., aggregate acres within each habitat type).
2. How total area in each map class is broken into pieces (e.g., the proportion of each habitat type in six different class sizes).
3. What map classes are next to what other map classes (e.g., edge between two habitat types as a proportion of the total edge within the map).

¹See West and Whitford, this volume.

The premise that underlies these measures is that two different areas that are similar in all three of these dimensions are ecologically equivalent at least for organisms and processes that correspond to the grain of the data.

This software has been used for a variety of issues at a variety of scales but generally within forested landscapes. Its use to analyze changes in forested habitats resulting from silvicultural prescriptions comes closest to how the software might be used in rangeland.

Problem definition establishes certain perceptual parameters that differ from those appropriate to other problems. Table 2 compares these parameters to those involving urbanization impacts in a six-county area of the Central Sierra Nevada (Greenwood and Marose 1993). It also contains some guesses regarding the parameter values that might be obtained in rangelands for certain management issues.

In the silvicultural case, the management disturbance alters habitat characteristics. To detect those changes, the analysis requires data of fine categorical and spatial grains. Specifically the analysis uses a map of WHR habitat stages (Mayer and Laudenslayer 1988) that portrays habitat in terms of species mix, mean diameter breast height of trees, and average canopy closure. The spatial grain, or minimum mapping unit, is five acres. To date, the study has been limited to 170,000 acres (Barrett et al. 1993).

In contrast, the management disturbance of development eliminates rather than alters habitat characteristics. The categorical grain of the data need not be very fine to capture these changes. In the case of the Central Sierra, the analysis used a map of WHR habitat types, i.e., habitats defined by species mix alone. The problem definition also establishes an upper and lower limit on what we can see, with the entire region covering 10^5 acres and the minimum mapping unit 100 to 1,000 acres.

Table 2 also includes some estimates of parameters relevant to more traditional rangeland management issues. If prescribed fire generally renews shrublands, then a finer-grained description, perhaps using seral stages or maturity classes, is necessary to understand impacts. If, however, prescribed fire results in type conversions, a coarser-grained description utilizing life-form classes may be sufficient. The spatial scale will depend on the spatial scale of factors that drives fire intensity and the resulting effects of fire. The extent of analysis might be defined by management concerns or by larger ecological factors that set the nature of the fire regime.

The categorical and spatial grains associated with grazing management depend, as do those associated with prescribed fire, on how grazing affects the entire system. If the effects must be characterized in terms of species composition, a very fine categorical grain may be necessary. The corresponding spatial grain will depend on the scale of factors that interacts with grazing intensity to determine species composition and may not be fine at all. Similar arguments can be engaged where soil erosion rather than species composition is the primary characteristic affected by grazing.

Figure 16 shows fine-grained habitat data for a 170,000-acre swath through northern Humboldt County, California. The habitat data for 1990 were obtained under contract as part of the Timberland Taskforce established by the California Legislature in 1990 (California Timberland Taskforce, in press). The habitat data for the year 2040 represent a projection based on existing California Board of Forestry timber harvest rules (Barrett et al. 1993)

LEM provides a means of quantifying the differences between the current and future scenarios in Figure 16. The first output of LEM captures changes in the aggregate acres of habitat stages (Table 3). The future scenarios affect differ-

TABLE 2. PERCEPTUAL PARAMETERS OF DIFFERENT MANAGEMENT PROBLEMS, (WHR HABITAT TYPES, AND STAGES DESCRIBED BY MAYER AND LAUDENSLAYER 1988)

DISTURBANCE	CATEGORICAL GRAIN	SPATIAL GRAIN	EXTENT
Silvicultural treatments in commercial timberland	fine (WHR habitat stages)	$10^0 - 10^2$ acres	10^5 acres
Residential and commercial development in wildlands	coarse (WHR habitat types)	$10^2 - 10^3$ acres	$10^6 - 10^7$ acres
Prescribed fire in shrublands	fine (seral stages if shrubs remain)	?scale of factors driving fire intensity	?
	coarse (life-forms if type conversion occurs)		
Grazing management in grasslands	very fine (in areas where grazing shifts competitive advantage among plant species)	?scale of factors driving species mix	?
	fine (in areas where grazing changes erosional processes)	?scale of topography	

TABLE 3. EXTENT OF DOUGLAS FIR (DFR) AND MONTANE HARDWOOD CONIFER (MHC) HABITAT STAGES IN 1990 AND PROJECTED FOR 2040 UNDER CURRENT RULES, IN TERMS OF ACRES AND PERCENT OF STUDY AREA, WITH PERCENT CHANGE (COMPARATOR ACRES * 100/REFERENCE ACRES). [AVERAGE TREE SIZE: 1=SEEDLING, 2=SAPLING, 3=POLE, 4=SMALL TREE, 5=LARGE TREE, 6= MULTI-LAYER; CANOPY CLOSURE: S= SPARSE, P= PARTIAL, M= MODERATE, D= DENSE]. CHANGES IN OTHER HABITATS NOT SHOWN.

	COMPARATOR ACRES	REFERENCE ACRES	COMPARATOR %	REFERENCE %	PERCENT CHANGE(%)
DFR1	2406	0	1	0	999999
DFR2D	1715	15	1	0	11433
DFR2M	3217	22	2	0	14623
DFR2P	320	0	0	0	999999
DFR2S	3303	0	2	0	999999
DFR3D	7694	356	5	0	2161
DFR3M	939	1284	1	1	73
DFR3P	6	139	0	0	4
DFR3S	9	74	0	0	12
DFR4D	17997	24636	11	15	73
DFR4M	2767	5634	2	3	49
DFR4P	74	932	0	1	8
DFR4S	152	404	0	0	38
DFR5D	4777	9776	3	6	49
DFR5M	22	162	0	0	14
DFR5P	171	13	0	0	1315
DFR5S	601	47	0	0	1279
DFR6	46411	24934	28	15	186
MHC2M	0	15	0	0	0
MHC2P	0	112	0	0	0
MHC2S	0	185	0	0	0
MHC3D	152	1865	0	1	8
MHC3M	64	2955	0	2	2
MHC3P	0	1023	0	1	0
MHC3S	0	1365	0	1	0
MHC4D	3951	36712	2	22	11
MHC4M	1470	5105	1	3	29
MHC4P	1252	1226	1	1	102
MHC4S	869	866	1	1	100
MHC5D	2788	5801	2	3	48
MHC5M	138	108	0	0	128
MHC5P	691	74	0	0	934
MHC5S	3	49	0	0	6
MHC6	7511	770	4	0	975

ent habitat types in different ways. In Douglas fir habitats, the area in both early and late seral stages increases, while intermediate habitat stages decline. In montane hardwood-conifer habitats, only late seral stages increase as all other habitat stages decrease. The origin of these changes can be understood in terms of the aging of all habitat types on national parkland, harvesting of dense intermediate habitat types, and replanting of montane hardwood-conifer as Douglas fir plantations. One might expect, therefore, that different watersheds within this swath might vary considerably from this average change over the whole area.

The second type of output (Figure 17) refers to change in patch-size distribution within a habitat type. Each pair of columns refers to a habitat stage, with the right column

capturing its patch-size distribution in 1990 and the left the distribution expected in 2040. To create each column, LEM ranks all polygons within each habitat type according to their area and then divides that list into six groups with equal numbers of polygons. Each segment of a column shows the area encompassed by polygons in each sextile.

The proportion of each habitat in larger blocks shifts in different directions. Figure 17 shows that the proportion of Douglas fir, pole-size dense canopy habitat in polygons greater than 15 acres increases greatly (from 40 percent to 96 percent) while the proportion of montane hardwood conifer, 12 to 24 inches dbh, dense canopy closure habitat in polygons greater than 61 acres declines precipitously from 73 percent to 21 percent.

The third type of output captures the spatial relationships between habitat stages. The spatial relationships in any given map are expressed in an adjacency histogram (Figure 18). LEM sets the total length of "edge" within the map to 100 percent. Each column in the histogram corresponds to a habitat type. The total length of each bar represents its perimeter as a proportion of the total edge, while each segment portrays the edge that habitat shares with other habitats.

Table 4 portrays the change in adjacency. Certain pairings of habitats are greatly diminished or eliminated entirely;

others are greatly increased and some new adjacencies are created.

LANDSCAPE STANDARDS

LEM provides GIS tools that quantify patterns of life at any scale. Given different management alternatives, it can quantify differences in resulting landscapes. It stops short, however, of providing standards or criteria by which to judge landscapes; it provides only a vocabulary with which such standards can be expressed.

TABLE 4. PERCENT OF CURRENT TOTAL PERIMETER AND CHANGE IN ADJACENCY OF SELECTED PAIRS OF WHR HABITAT STAGES BETWEEN 1990 MOSAIC AND MOSAIC PROJECTED FOR 2040 UNDER EXISTING RULES. HABITAT TYPES: MHC = MONTANE HARDWOOD CONIFER, DFR = DOUGLAS FIR, MCN = MIXED CONIFER, MHW = MONTANE HARDWOOD, RDW = REDWOOD. AVERAGE TREE SIZE AND CANOPY CLOSURE CODES AS IN TABLE 3.

HABITAT TYPE	HABITAT TYPE	REFERENCE%	%CHANGE
ADJACENCY ELIMINATED			
GRASSLAND	MHC3M	0.13	0
DFR3M	MCN5D	0.10	0
DFR4D	MHC3M	0.12	0
DFR4M	MHC3M	0.25	0
DFR4M	MHC3P	0.11	0
DFR4P	MHC4D	0.15	0
MHC3D	MHW4D	0.47	0
MHC3M	MHC4M	0.12	0
MHC3S	MHC4D	0.16	0
MHC4D	MHW3D	0.80	0
MHC4M	MHC5D	0.10	0
MHC5D	MHW4D	0.27	0
MHW3D	MHW4D	0.27	0
ADJACENCY DECREASED AT LEAST 50%			
GRASSLAND	MHC4M	0.16	6
DFR4D	MHC4D	3.91	10
DFR5D	MHC4D	1.18	2
MCN4D	MHC4D	0.45	2
MCN5D	MHC4D	1.73	1
MCN6	MHC4D	0.39	5
MHC3D	MHC4D	0.52	6
MHC3M	MHC4D	0.46	2
MHC3M	MHW4D	0.24	4
MHC4D	MHC4M	0.69	10
MHC4D	MHC4S	0.11	9
MHC4D	MHC5D	0.54	2
MHC4D	MHW4D	2.37	7
MHC4D	RDW6	0.24	4
ADJACENCY INCREASED MORE THAN 150%			
DFR3M	DFR6	0.10	150
DFR4D	MCN4D	0.18	333
DFR4D	MCN5D	0.60	365
DFR4D	RDW6	0.11	218
DFR5D	RDW6	0.12	242
DFR6	MHC6	0.13	1100
DFR6	RDW6	0.52	502

How might standards be developed? Recall that the goal is to maintain the patterns of life at many scales, with the assumption that patterns at scales smaller than those used will be maintained as well. Since all the species present today survived the recent evolutionary past, an initial working hypothesis is that the highest probability of maintaining all parts to the system is achieved by keeping the system within the parameter space of aggregate area, patch-size distribution, and adjacency of that past. As the managed system diverges from the parameter space, the probability of losing some species or processes increases. Defining the trade-offs between system state and probability of loss is a task for scientists. Deciding the acceptable risk of loss is a task for policy makers.

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