Emulating Natural Forest Landscape Disturbances

Concepts and Applications

Edited by

AJITH H. PERERA,
LISA J. BUSE, AND
MICHAEL G. WEBER

COLUMBIA UNIVERSITY PRESS
NEW YORK

DISCLAIMER
The opinions expressed in this text are those of the individual authors and do not necessarily reflect official views or policies of the funding agencies or the institutions with which the authors are affiliated.

Columbia University Press
Publishers since I893
New York   Chichester, West Sussex

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA

Emulating natural forest landscape disturbances: concepts
and applications /edited by Ajith H. Perera, Lisa J. Buse,
and Michael G. Weber.
p. cm.
Includes bibliographical references (p.).
lSBN 0-231-12916-5 (cloth: alk. paper)
1. Forest management—United States. 2. Forest ecology—United States. 3. Ecological disturbances—United States. 4. Forest management—Canada. 5. Forest ecology—Canada. 6. Ecological disturbances—Canada. I. Perera, Ajith H. II. Buse, Lisa J. III. Weber, Michael G.

SD143.E5 2004
634.9′2—dc22   2003068813

Columbia University Press books are printed on durable and acid-free paper.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

CHAPTER 13

Using a Decision Support System to Estimate Departures of Present Forest Landscape Patterns from Historical Reference Condition

An Example from the Inland Northwest Region of the United States

PAUL F. HESSBURG, KEiTH M. REYNOLDS,
R. BRION SALTER, and MERRICK B. RICHMOND

Human settlement and management activities have altered the patterns and processes of forest landscapes across the inland northwest region of the United States (Hessburg et al. 2000C; Hessburg and Agee in press). As a consequence, many attributes of current disturbance regimes (e.g., the frequency, duration, severity, and extent of fires) differ markedly from those of historical regimes, and current wildlife species and habitat distributions are inconsistent with their historical distributions. Just as human-caused changes in ecological processes have led to alterations in landscape patterns, changes in patterns have produced alterations in ecosystem processes, and particularly in forest disturbance (Kimmins, chapter 2, this volume). Today's public-land managers face substantial societal and scientific pressure to restore landscape patterns of structure, composition, and habitats that will restore some semblance of natural processes and revitalize the productivity of terrestrial ecosystems. Motivations for restoration stem from genuine concerns over the functioning of ecological systems and aversion to the risks and uncertainties associated with current conditions, but our lack of knowledge of the ecosystem's former characteristics and variability limits our efforts. In this chapter, we present one approach to estimating the extent to which present forest landscape patterns have departed from the baseline conditions that existed before modern management began (around 1900). Our goal is to approximate the range and variation of these historical patterns and use that knowledge to evaluate present forest conditions and assess the ecological importance of departures.

Background

For a long time, ecologists asserted that ecosystem dynamics could be explained by theories of stable equilibria and "the balance of nature" hypothesis (e.g., Milne and Milne 1960; Lovelock 1987), but these explanations are no longer considered valid. Wu and Loucks (1995) proposed an alternative framework they termed the *hierarchical patch dynamics* paradigm, which comprises five elements. We briefly paraphrase these elements here, because our approach is based on their framework:

1. Ecological systems can be viewed as nested, *discontinuous hierarchies of patch mosaics* (Allen and Starr 1982; Ahl and Allen 1996). The clearly divisible scales associated with this hierarchical organization have been referred to as loose *vertical coupling* between levels. This loose coupling makes it possible to disassemble complex systems into their constituent levels for study without significant loss of information.
2. *The dynamics of ecosystems are an emergent property of the patch dynamics that occur at each level in the hierarchy*. However, most of the energy and material exchange occurs within individual levels of a hierarchy.
3. Across a broad range of spatial and temporal scales, *patterns enable and constrain ecological processes, and ecological processes create, maintain, modify, and destroy patterns*. Patterns and processes are tightly linked, and particular patterns and processes are linked to certain spatial and temporal scales.

4. At all spatial scales, *ecosystems exhibit transient patch dynamics and nonequilibrium behavior* because of the stochastic properties of the geological and climatic processes that support ecosystems.
5. *Lower level processes are incorporated into higher level structures and processes in the hierarchy of patch dynamics*. This incorporation integrates the effects of lower level (e.g., site) processes and higher level constraints imposed by the geological and climatic systems to generate quasi-equilibrium patch dynamics at all levels. These dynamics become manifest as a finite range of conditions that is somewhat predictable, as long as the underlying processes and higher-level constraints remain substantially unchanged.

Objectives

In our case study, we have developed an approach to estimating the quasi-equilibrium conditions associated with one level in a forest's hierarchy of patch dynamics. For simplicity, we have called these conditions the *reference conditions* and have called the typical variation in these conditions the *reference variation*. We chose the range on either side of the median that contained 80% of the historical values (hereafter, the *median range*) of metrics of spatial patterns as our estimate of reference variation because most historical observations typically clustered in this range.

Our study focused on forest landscapes and the spatial patterns of their structural classes (i.e, successional stages or stand development phases), cover types, and related conditions. We focused on these patterns because important changes in the dynamics of altered forest ecosystems are often reflected in the structures of the living and dead elements of the landscape (Spies 1998). The processes that underlie this focus are forest disturbances, including fires, forest diseases and insect outbreaks, unusual weather, and herbivory. Geological and climatic inputs constrain the forest patterns and related disturbances. We determined that environmental constraints occur at a subregional scale. (See the *Methods* section for the basis of these assertions.)

We describe a repeatable, quantitative method (outlined in table 13.1) for estimating the range and variation in historical forest vegetation patterns and in vulnerability to disturbance. Our objective is to estimate a reference variation that allows us to evaluate the direction, magnitude, and potential ecological importance of some of the changes we have observed in present-day forest landscape patterns. To automate our approach, we programmed estimates of reference variation for one ecological subregion into the Ecosystem Management Decision-Support (EMDS) system (Reynolds 1999a, 2001a). To illustrate this approach, we compared the current patterns for an example watershed from the same subregion with the estimates of reference variation, which allowed us to identify vegetation changes that lay beyond the range of the estimates. Changes that fell in the range of the estimates were assumed to lie within the natural variation of the interacting ecosystem's geological disturbance and climatic processes. Changes that lay beyond the range of the estimates were termed *departures* that could be explored in more detail to determine their potential ecological implications.

Methods

Stratifying Inland Northwest Watersheds

To identify sample landscapes constrained by similar environmental contexts, we used the ecological subregions of Hessburg et al. (2000a) to stratify subwatersheds (about 5000-10,000 ha) of the eastern Washington Cascades into geologic and climatic zones (figure 13.1 Subwatersheds (figure 13.2) were used as the basic sampling units because they provided a rationale for subdividing land areas that share similar climate, geology, topography, and hydrology, and enabled future use of our study data and results in integrated terrestrial and hydrologic evaluations of the landscape. Subwatersheds compose the sixth level in the established hierarchy of U.S. watersheds (Seaber et al. 1987) Lehmkuhl and Raphael (1993) showed that some spatial pattern attributes are influenced by the size of the area being analyzed when analysis areas are too small. We used subwatersheds or logical subwatershed pairs larger than 4000 ha to avoid this bias.

We selected the ecological subregion (ESR) 4, the Eastern Cascades, Warm/Wet/Low Solar Moist and Cold Forest subregion (hereafter, the Moist & Cold Forests subregion) as the geoclimatic zone in which we sampled and estimated reference conditions. Landscapes of this subregion are dominated by Moist (67% of the area) and Cold (21% of the area) forest potential vegetation types, with total annual precipitation of 1100-3000 mm (wet), generally warm growing season temperatures (mean annual daytime temperature,

TABLE 13.1. Approach for Estimating the Departure of Present Forest Landscape Patterns from Historical Reference Conditions[1]

Step	Action	References
1	Stratify the inland Northwest United States subwatersheds (5000-10,000 ha) into ecological subregions by using a published hierarchy	Hessburg et al. (2000a)
2	Map the historical vegetation of a large random sample of the subwatersheds of one subregion (the Moist and Cold Forests ESR4 subregion) from 1930s-1940s aerial photography	Hessburg et al. (1999b)
3	Statistically reconstruct the vegetation attributes of all patches of sampled historical subwatersheds that showed any evidence of timber harvesting	Moeur and Stage (1995)
4	Analyze spatial patterns for each reconstructed historical subwatershed by calculating a finite, descriptive set of class and landscape metrics in a spatial analysis program (FRAGSTATS)	McGarigal and Marks (1995); Hessburg et al. (1999b)
5	Observe the data distributions from the analysis of spatial patterns for the historical subwatersheds and define reference conditions, based on the typical range of the clustered data	Hessburg et al. (1999a,b)
6	Define reference variation as the range on either side of the median that contains 80% of the historical values of the class and landscape metrics for the sample of historical subwatersheds	Hessburg et al. (1999a,b)
7	Estimate reference variation for spatial patterns of ESR4 forest composition (cover types) and structure (stand development phases); model the accumulation of ground fuel (loading) and several attributes of fire behavior	Hessburg et al. (1999a,b); Huff et al. (1995); O'Hara et al. (1996); Ottmar et al. (in press)
8	Program the ESR4 reference conditions into a decision-support model (EMDS)	Reynolds (1999a,b, 2001a,b) Hessburg et al. (1999b)
9	Map the current vegetation patterns of an example watershed (Wenatchee_13, from the Wenatchee River basin, also from ESR4)	
10	Objectively compare a multiscale set of vegetation maps of the example watershed with corresponding reference variation estimates in the decision-support model	Hessburg et al. (1999a,b)

[1]The historical reference conditions are from around 1900.

5-9°C), and relatively low levels of solar radiation (frequently overcast skies, 200-250 W·m^{-2} Hessburg et al. 2000a). The subregion contains 93 subwatersheds. To map historical and current vegetation, we randomly selected18 subwatersheds to represent about 20% (194%) of the total number of subwatersheds and about 20% (22.3%) Of the subregion's area (figure 13.3).

One test of the validity and scaling of an ecological stratification is to evaluate how well the stratification reduces the variance of some of the ecological patterns and processes that it constrains. To evaluate the effectiveness of our subregion map at reducing variation in the area of fire regimes, we used GIS software to combine the subregion map with a predicted historical (about 1800) map of fire severity for the same areas (Hann et al. 1997). We then calculated the mean subwatershed area (percentage of total) and the variance of each severity class for the subwatersheds of six subregions of the eastern Cascades. The results showed that our subregions reduced the subwatershed variation in fire severiry in all but a single instance (table 13.2). In that

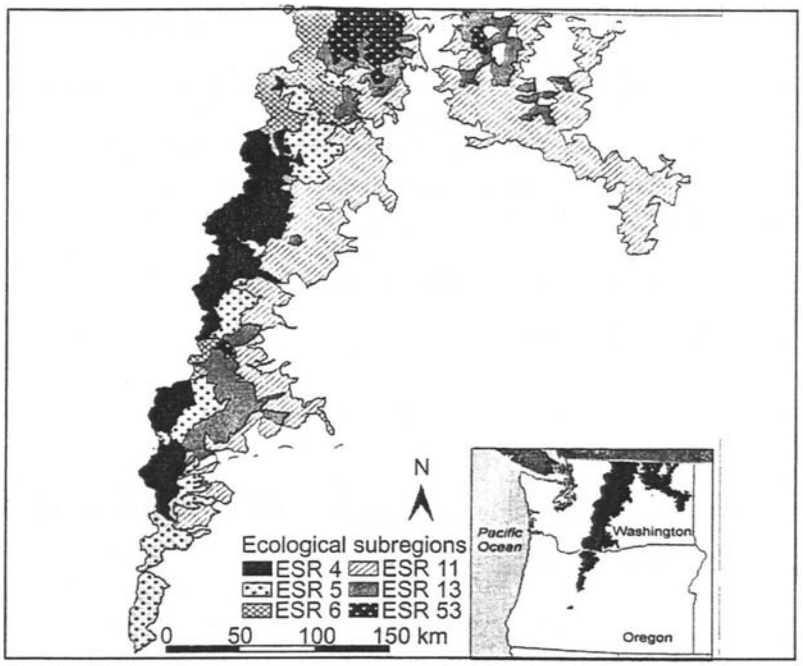

FIGURE 13.1. Map of the ecological subregions of the eastern Washington Cascades in the western United States. The ecological subregions (ESR) are: 4, Warm/Wet/Low Solar Moist and Cold Forests; 5, Warm/Moist/Moderate Solar Moist and Cold Forests; 6, Cold/Wet/Low and Moderate Solar Cold Forests; 11, Warm/Dry and Moist/Moderate Solar Dry and Moist Forests; 13, Warm and Cold/Moist/Moderate Solar Moist Forests; 53, Cold/Moist/Moderate Solar Cold Forests. Adapted from Hessburg et al. (2000c).

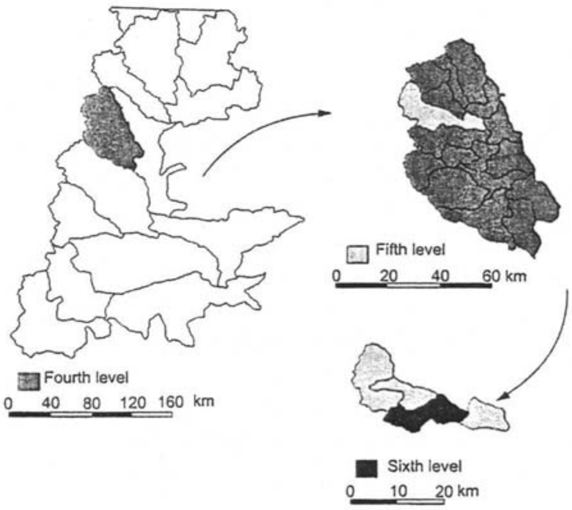

FIGURE 13.2. Hierarchical organization of subbasins (fourth level), watersheds (fifth level), and subwatersheds (sixth level) in the eastern Washington Cascades of the western United States (see also Seaber et al. 1987). The example shows the Wenatchee River subbasin at the fourth level, the Little Wenatchee River watershed at the fifth level, and our case study subwatershed (Wenatchee_13) at the sixth level (see also figure 13.4).

case (ESR11, the Dry & Moist Forests subregion), the variance of high severity fires exceeded the overall variance among subregions. This can be explained by the broad variation in topography and climatic gradients among subwatersheds; some had little or no high elevation terrain, whereas others had a considerable area of this terrain. For example, in subregion ESR11, dry and moist forests potential vegetation types either dominated the area of a subwatershed or were associated with high elevation cold forest types or low elevation dry shrublands and, grasslands, both of which were historically areas with high severity fires.

Mapping Historical, Current, and Potential Vegetation

For each selected subwatershed, we mapped historical (1930s-1940s) and current (1990s) vegetation by interpreting aerial photographs. The resulting vegetation attributes let us derive forest cover types (sensu Eyre 1980), structural classes (sensu O'Hara et al. 1996; Oliver and Larson 1996), and potential vegetation for individual patches using the methods of Hessburg et al. (1999b, 2000b). The potential vegetation represented the most shade tolerant tree species that would provide the dominant cover in the absence of disturbance (e.g., Arno et al. 1983). Vegetation types were assigned to patches at least 4 ha in size by means of stereoscopic examination of color (current) or black and white (historical) aerial photographs. The scales of these photographs were 1:12,000 (current) and 1:20,000 (historical). Photointerpreters used available field inventory plot data to inform and correct errors in their visual interpretations. The attributes of the interpreted vegetation were the same as those reported

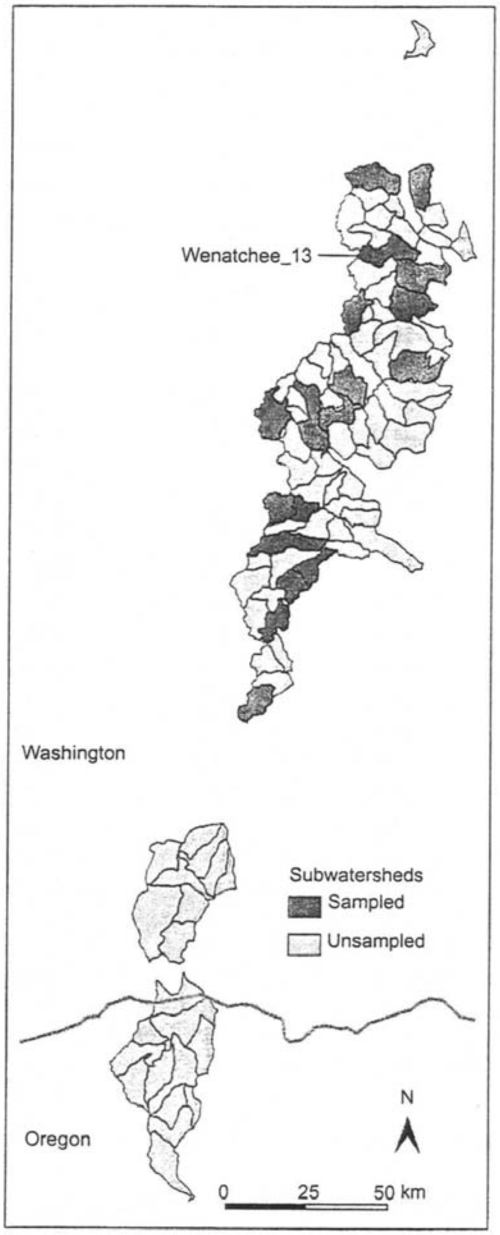

FIGURE 13.3. The subwatersheds sampled in the ESR4 (Moist and Cold Forests) ecological subregion. Note the location of Wenatchee_13, the subwatershed used in our case study.

by Hessburg et al. (1999b). Patches were delineated on clear overlays, and were georeferenced. Overlay maps were then scanned, edited, edge matched, and imported into GIS software to produce vector coverages with patch attributes.

Reconstructing the Attributes of Partially Harvested Historical Patches

Nine of the 18 historical subwatersheds (about 77% of the total area) showed evidence of timber harvesting, and nearly all this harvesting was light-to-moderate selection cutting. To reconstruct the preharvest vegetation attributes, we used Moeur and Stage's (1995) *most similar neighbor inference* procedure. Their algorithm is a multivariate procedure that identifies the patch that comes closest to matching a set of detailed design attributes and a set of broad-scale global attributes. This *stand-in* patch is chosen based on a measure of similarity that summarizes the multivariate relationships between the global and design attributes. Canonical correlation analysis is used to derive the similarity function. This analysis lets us define the historical values for each harvested patch as equal to the values for the design attributes of the corresponding stand-in patch.

The attributes of the reconstructed harvested patches comprised the total crown cover, overstory crown cover, canopy layers, and the overstory and understory size classes (seedlings/saplings, <27 cm dbh; poles, 12.7-22.6 Cm dbh; small trees, 22.7-40.4 Cm dbh; medium trees, 405-635 cm dbh; large trees, >635 cm dbh). The global attributes comprised the total annual precipitation (mm), mean annual daytime flux of shortwave solar radiation ($W \cdot m^{-2}$), and mean annual daytime temperature (°C) for 1989, which was considered a "normal" weather year (Thornton et al. 1997); the slope, aspect, and elevation; the potential vegetation group; and the landform feature (e.g., dissected glaciated slope, alpine glacial outwash, scoured glaciated slope, meltwater canyon or coulee). Modal values for each global attribute were assigned to individual patches in the maps in the GIS software. We obtained 2-km raster maps for the I989 temperature, precipitation, and solar radiation from the University of Montana (Thornton et al. 1997) and a 1-km raster map of the potential vegetation groups developed by Hann et al. (1997) from the Interior Columbia Basin Ecosystem Management Project (www.icbemp.gov). Maps of slope, aspect, and elevation were derived from a 90-m-resolution digital elevation model by using standard methods. Landform features were photointerpreted from 1:12,000 scale color resource aerial photography by Wenatchee National Forest geology and soils personnel (Carl Davis, Wenatchee National Forest, Wenatchee, Washington, pers. comm.) and verified by sampling in the field.

Associating Fuel and Fire Behavior Attributes with Patches Based on Vegetation Characteristics

By using established classification rules (Ottmar et al. 1996; Schaaf 1996), we assigned vegetation patches to one of 192 fuel condition classes ac-

TABLE 13.2. Variance in the Percentage of Total Area (S)[1] for Historical Fire Severity Classes in Subwatersheds in and among Ecological Subregions of the Eastern Washington Cascades in the Western United States

Ecological Subregion	Fire Severity Class	Mean Subwatershed Area (%)	S[1]	Quotient[2] ($S_{subregion}$ / $S_{all\ subregions}$)
ESR4: Warm/Wet/Low Solar Moist and Cold Forests (*n* = 93 subwatersheds)	Low	28.5	502	0.55
	Moderate	55.1	488	0.63
	High	16.4	240	0.40
ESR5: Warm/Moist/Moderate Solar Moist and Cold Forests (*n* = 80 subwatersheds)	Low	55.7	671	0.74
	Moderate	32.7	548	0.71
	High	11.6	172	0.28
ESR6: Cold/Wet/Low and Moderate Solar Cold Forests (*n* = 43 subwatersheds)	Low	18.2	302	0.33
	Moderate	66.8	339	0.44
	High	14.9	210	0.35
ESR11: Warm/Dry and Moist/Moderate Solar Dry and Moist Forests (*n* = 293 subwatersheds)	Low	58.8	756	0.83
	Moderate	7.4	139	0.18
	High	33.8	888	1.47
ESR13: Warm and Cold/Moist/Moderate Solar Moist Forests (*n* = 78 subwatersheds)	Low	68.1	590	0.65
	Moderate	15.0	202	0.26
	High	16.8	357	0.59
ESR53: Cold/Moist/Moderate Solar Cold Forests (*n* = 27 subwatersheds)	Low	29.4	784	0.87
	Moderate	51.9	666	0.86
	High	18.8	185	0.31

Source: Historical fire severity classes are from Hann et al. (1997)

[1] S = the population variance associated with the mean area occupied by a fire severity class. $S_{subregion}$ = *S* for the subwatersheds of the indicated subregion. $S_{all\ subregion}$ = *S* for the subwatersheds of all six subregions.

[2] A quotient of 1 indicates that the variance associated with the mean area occupied by a fire severity class in subwatersheds of a subregion equals that of all subregions combined; a value <1 indicates that the variance in a subregion is less than the composite value; a value >1 indicates that the variance in a subregion is greater than the composite value.

cording to their cover type, structural class, and type (or absence) of prior logging. Fuel classes were used to compute the patch's fuel consumption, energy release component, particulate emissions (particulate matter [PM]2.5 and PM10 μ), crown fire potential, and fire behavior attributes for average prescribed burns and wildfires based on published procedures (Huff et al. 1995; Hessburg et al. 2000c). Equations for estimating fuel consumption for both burn scenarios were taken from the CONSUME 2.0 model (Ottmar et al. 1993, www.fs.fed. us/pnw/fera/ products) and the First Order Fire Effects model (Reinhardt et al. 1996, www.frames. gov/tools/ FOFEM). The attributes of fire behavior associated with each vegetation patch were the rate of spread, flame length, and Byram's fireline intensity (Rothermel 1983) We computed these attributes for an average wildfire scenario by using the equations of the National Fire Danger Rating System (Rothermel 1972; Deeming et al. 1977; Cohen and Deeming 1985).

Estimating the Reference Conditions

We used the FRAGSTATS software (McGarigal and Marks 1995) to characterize spatial patterns in 18 different maps of the historical subwatersheds of the Moist Sr Cold Forests subregion: (1) physiognomic conditions; (2) cover types; (3) structural classes; (4) cover types combined with structural classes; (5) potential vegetation types combined with cover types and structural classes; (6) canopy layers; (7) total crown cover; (8) patches of late-successional, old, and other forest; (g) patches with and without large remnant trees after wildfires; (10) fuel loading; (11-14) crown fire potential, fireline intensity, rate of spread, and flame Length in an average wildfire; and (15-18) crown fire potential, fireline intensity, rate of spread, and flame length under prescribed burning.

We chose five class metrics to display the area and connectivity of the classes in each map: the percentage of the total area, patch density per 10,000 ha, mean patch size (ha), mean nearest-neighbor distance (m), and edge density (m.ha^{-1}). These metrics characterized the spatial patterns of individual classes in a landscape mosaic, such as the ponderosa pine (*Pinus ponderosa* Laws.) cover type in a landscape map of all cover types. Mean, median, full range, and reference variation statistics were computed for the 18 subwatersheds sampled for the subregion by using the S-PLUS software (Statistical Sciences 1993).

We characterized the features of each mapped landscape mosaic by using nine metrics. Landscape metrics characterized the spatial pattern relationships among the classes that composed the landscape mosaics (all cover types). Of the nine metrics for which we chose to display landscape patterns, six were already available in FRAGSTATS and three were added to the FRAGSTATS source code. We evaluated map patterns using the following parameters:

- *Patch richness:* patch richness (PR) and relative patch richness (RPR) (McGarigal and Marks 1995);
- *Diversity:* Shannon's diversity index (SHDI) (McGarigal and Marks 1995) and Hill's transformation of Shannon's index, N1 (Hill 1973) which is less sensitive to the occurrence of rare patch types than SHDI;
- *Dominance:* Hill's inverse of Simpson's lambda, N2 (Simpson 1949; Hill (1973), which combines measures of diversity and dominance and is the least sensitive of the three diversity measures to the occurrence of rare patch types;
- *Evenness:* a modified Simpson's evenness index (MSIEI) (McGarigal and Marks 1995), which measures relative to maximum evenness, the evenness of patch types, including rare ones, and Alatalo's evenness index (R21) (Alatalo 1981), which measures the evenness among the dominant patch types;
- *Interspersion and juxtaposition:* an index of interspersion and juxtaposition (IJI) (McGarigal and Marks 1995); and
- *Contagion:* an index of contagion (CONTAG) (McGarigal and Marks 1995), which measures dispersion and interspersion of patch types.

We also evaluated the influence of rare and dominant classes on our measures of diversity and evenness. We supplemented the FRAGSTATS source code with the equations for computing the N1, N2, and R21 metrics. The mean, median, full range, and reference variation were again computed for the above mentioned landscape metrics for the subregion by using the S-PLUS software.

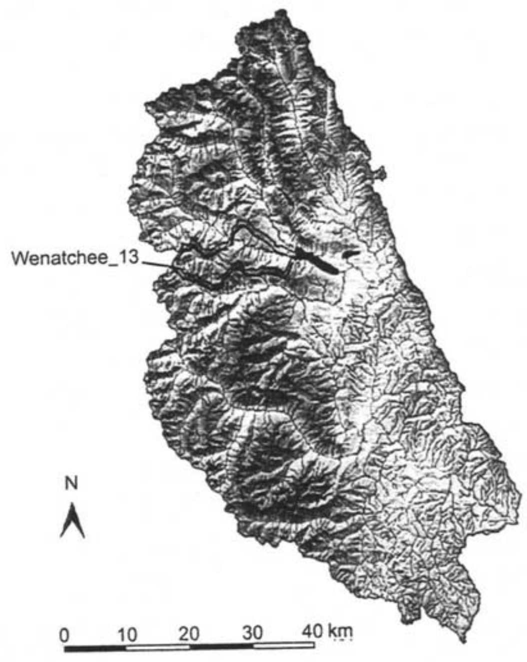

FIGURE 13.4. Map of the Wenatchee_13 subwatershed, a sixth-level drainage (hydrological unit designation: 170200111102) of the Wenatchee River subbasin of eastern Washington State in the western United States. (Refer to figure 13.2 for the geographical context for this figure.)

In the *Results and Discussion* section of this chapter, we use the estimates of reference variation to quantify spatial patterns in the departures of 18 different maps of an example subwatershed (Wenatchee_13) in its current condition. The 95537-ha Little Wenatchee River and Rainy Creek subwatershed, Wenatchee_13, lies in the Wenatchee River subbasin of the eastern Cascades of Washington (figure 13.4) The western edge of Wenatchee_13 abuts the crest of the Cascades, and the eastern edge abuts the dry and mesic forests of the lower Wenatchee drainage. We evaluated the current conditions in Wenatchee_13 against the estimates of reference variation by using a decision-support model. Our goal was to identify the subset of all vegetation changes that may have important ecological implications (departures). Finally, we conducted a transition analysis on the historical and current maps of cover type and structural class to discover the path of each change (tables 13.3 and 13.4)To conduct the transition analysis, we rasterized the maps of historical and current cover type (or structural class) to a pixel size of 30 m. These 30-m raster versions were combined in a

TABLE 13.3. Transitions from Historical to Current Cover Type Conditions for Wenatchee_13

Historical Patch Type[1]	Current Patch Type											
	ABAM	ABGR	ABLA2	Herb	LAOC	Other	PIPO	PSME	Shrub	TSHE	TSME	Total[2]
ABAM	1.3		1.7	0.1		0.2		0.6	0.8	1.1	0.2	6.2
ABGR	0.1					0.1		0.3		0.5	0.1	0.9
ABLA2	1.3		8.3	0.9		0.7		0.3	0.2	0.6		12.4
Herb			0.6	1.0		0.4		0.7	0.1	0.1		2.8
LAOC	0.2							0.2				0.5
Other	0.4	0.1	1.5	0.2		4.0		1.9	0.2	0.6		8.9
PIPO						0.4	5.6	4.6				10.6
PSME	3.6	0.5	2.4	0.3	0.4	0.7	1.1	16.0	0.5	5.2	0.3	30.8
Shrub	0.2		0.5	0.2		0.2		0.4	2.5	0.4		4.4
TSHE	4.6	0.1	0.7	0.1		0.3	0.2	4.5	0.2	8.5		19.1
TSME			0.2					1.1		1.8	0.3	3.3
Total[2]	11.8	0.7	15.9	2.6	0.4	6.9	6.9	30.4	4.5	18.8	0.9	100.0

Notes: Wenatchee_13 is a subwatershed of ecological subregion ESR4 (Moist and Cold Forests). Values represent the percentage of the subwatershed area that transforms from one cover type in its historical condition to another cover type in the current condition, with values rounded to one decimal place.

[1] Cover types: ABAM, amabilis fir (*Abies amabilis* [Dougl.] Forbes); ABGR, grand fir (*Abies grandis* [Dougl.] Lindl.); ABLA2, alpine fir (*Abies lasiocarpa* [Hook.] Nutt.) and Engelmann spruce (*Picea engelmannii* Parry); Herb, all herbland cover types and structural classes combined; Other, all nonforest and nonrangeland and anthropogenic types combined; PIPO, ponderosa pine (*Pinus ponderosa* Laws.); PSME, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco); Shrub, all shrubland cover types and structural classes combined; TSHE, western hemlock (*Tsuga heterophylla* [Raf.] Sarg.); TSME, mountain hemlock (*Tsuga mertensiana* [Bong.j Carr.).

[2] Totals may not add to 100% because of rounding errors.

single coverage, so that each pixel had a historical and current cover type (or structural class). We computed the number of pixels for each unique type of historical-to-current transition, divided this number by the total number of pixels, and multiplied that result by 100 to derive a percentage of the subwatershed area.

Evaluating the Wenatchee_13 Landscape

We used the EMDS software (Reynolds 1999a, 2001b) to compare current spatial patterns in Wenatchee_13 with the reference conditions for the subregion. The current conditions were depicted by using 18 maps that represented a multiscale cross section of the conditions with respect to vegetation, fuel, and potential fire behavior. Each map was evaluated in EMDS against a corresponding set of estimates of reference variation.

Programming estimates of reference variation for the subregion

EMDS (version 3.0) is a decision-support system for integrated landscape evaluation and planning. The application provides support for landscape evaluation through logic and decision engines integrated with the ArcGIS 8.1 GIS software (Environmental Systems Research Institute, Redlands, California). In our application, the Net Weaver logic engine (Reynolds 1999b) evaluated data representing the current conditions of the landscape (which can be represented by data distributions, ranges of conditions, states, or mathematical functions) against a knowledge base we designed using the NetWeaver Developer System to derive interpretations of ecosystem conditions.

We had two main reasons for using EMDS in the present application. First, logic-based models accommodate large, multiscale analytical problems. In this study, for example, the class and landscape metrics that defined the reference conditions for the 18 evaluations were coded in NetWeaver using more than 2700 parameters. Second, although the knowledge bases evaluated by EMDS can be large and complex, the logic engine lets users trace the results using a browser interface that conveys the basis for each conclusion. Due to space limitations, we refer

TABLE 13.4. Transitions from Historical to Current Structural Class for Wenatchee_13

Historical Patch Type[1]	Current Patch Type										
	si	seoc	secc	ur	yfms	ofms	ofss	Herb	Shrub	Other	Total[2]
si	0.3	0.8		0.6	0.6		0.1	0.1	0.1	0.1	2.8
seoc	0.6	3.2	0.5	2.1	3.0	2.7	1.0	0.4	0.7	0.7	15.1
secc		0.1	0.2	0.3		0.7					1.4
ur	0.6	1.6	1.8	6.3	1.9	1.3	0.3		0.1	0.3	14.4
yfms	0.4	1.3		2.6	2.7	0.2	0.6	0.5	0.4	0.3	9.0
ofms	6.9	3.9	2.2	4.9	3.0	14.1	1.6	0.2	0.3	0.9	38.0
ofss	0.2	0.3	0.4	0.5	0.9	0.3	0.4		0.1	0.1	3.2
Herb	0.2	0.1		0.2	0.2	0.1	0.7	1.0	0.1	0.4	2.8
Shrub	0.1	0.3		0.4	0.1	0.4	0.2	0.2	2.5	0.2	4.4
Other	0.7	0.6		0.4	1.7	0.1	1.0	0.2	0.2	4.0	8.9
Total[2]	10.2	12.1	5.2	18.5	14.1	20.0	5.9	2.6	4.5	6.9	100.0

Notes: Wenatchee_13 is a subwatershed of ecological subregion ESR4 (Moist and Cold Forests). Values represent the percentage of the subwatershed area that converts from a structural class in the historical condition to another class in the current condition, rounded to one decimal place.

[1] Structural classes: Herb, all herbland cover types and structural classes combined; ofms, "old forest, multistory"; ofss, "old forest, single story"; Other, all nonforest and nonrangeland and anthropogenic types combined; secc, "stem exclusion, closed-canopy" seoc, "stem exclusion, open-canopy" Shrub, all shrubland cover types and structural classes combined; si, stand initiation; ur, understory reinitiation; yfms, "young forest, multistory."

[2] Totals may not add to 100% because of rounding errors.

readers to Reynolds (2001a,b) for detailed discussions of decision-support systems and the advantages of performing landscape evaluations in EMDS.

Results and Discussion

In our evaluation of patterns in the forest landscape, we examined the characteristics of the 18 landscape mosaics, as well as the spatial patterns of the component classes. Before we examined the products of the EMDS-based evaluations of Wenatchee_13, we first compared several different historical and current maps to assess obvious changes. We hoped to determine whether the most visible changes represented departures or were within the bounds of reference variation. We examined the following maps:

- Historical (1949, prior to reconstruction with most-similar-neighbor analysis) and current (1992) visible logging extent (color plates 18a and b, respectively);
- Historical (after reconstruction with most similar-neighbor analysis) and current cover types (color plates 18c and d, respectively);
- Historical and current structural classes (color plates 18e and f, respectively);
- Potential vegetation types (color plate 18g);
- Topography (color plate 18h);
- Historical (after reconstruction with most-similar-neighbor analysis) and current (1992) fuel loading (color plates 19a and b, respectively; and
- Historical and current crown fire potential (color plates 19c and d, respectively), flame length (color plates 19e and f, respectively), and fireline intensity (color plates 19g and h, respectively) under an average wildfire scenario.

In the map of visible logging extent, selection cutting had affected about 7.7% of the area. Selection cutting had a relatively minor influence on structural conditions in the harvested areas, as fewer than half of the harvested "old forest, multistory" patches were sufficiently influenced to change their structural designation, and those that were affected were converted to "stem exclusion, open-canopy" or "old forest, single-story" structures. However, early selection cutting significantly modified cover types. Selection cutting apparently targeted large overstory ponderosa pine growing in the warm-dry and cool-moist

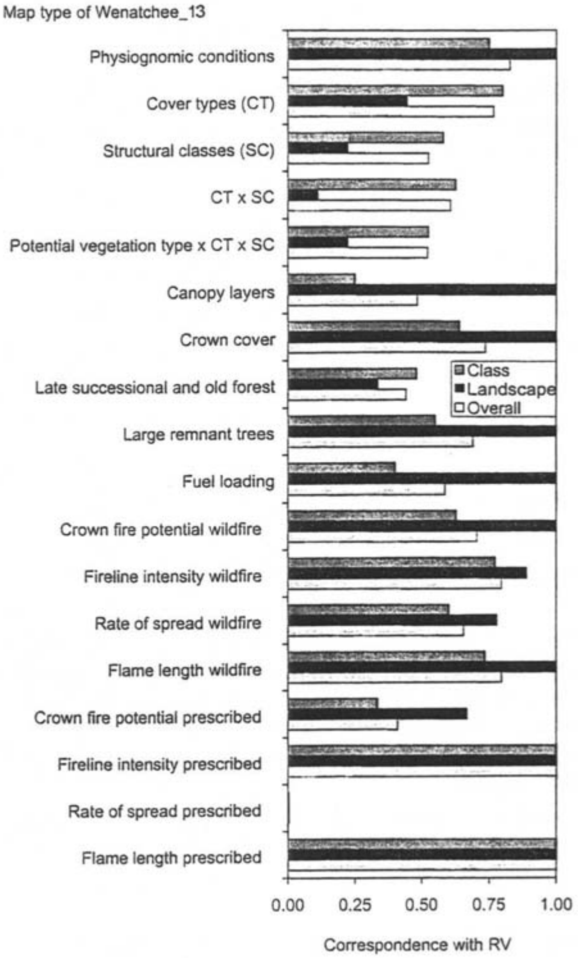

FIGURE 13.5. Summary graph of the results of using the EMDS system to analyze 18 maps representing the current conditions in the Wenatchee 13 subwatershed. Evaluations using five class metrics, nine landscape metrics, and the class + landscape metrics (overall comparison) compared with a map of current conditions with the corresponding reference variation (RV) estimates for the Moist and Cold Forests ecological subregion (ESR4).

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco)/ grand fir (*Abies grandis* [Dougl.] Lindl.) potential vegetation types and converted much of the harvested area to a Douglas-fir cover type. An additional 23.7% of the current subwatershed area has been influenced by timber harvesting, and the most recent cutting has been patch clearcutting to promote regeneration in the same potential vegetation types.

The historical cover type and structural class maps (color plates 18c,e) show simple, contagious patterns of land cover and forest structure reflecting the relatively simple patterns of potential vegetation types (color plate 18g) and topography (color plate 18h). Both the simple patterns and the high historical area of "old forest, multistory" patches (38%, table 13.4) suggest that fires have been infrequent in Wenatchee_13. The current logging extent, cover type, and structural class maps (color plates 18b,d, and f, respectively) show a landscape fragmented into 49 regeneration units based on the type of harvesting (minimum, 2.25 ha; maximum, 302 ha; median, 11.8 ha). A significant area of the ponderosa pine cover type has been converted to Douglas-fir (4.6%), and 18% of the "old forest, multistory" area has been lost to the western hemlock (*Tsuga heterophylla* [Raf.] Sarg.)-western red cedar (*Thuja plicata* Donn), Douglas-fir, and ponderosa pine cover types (see table 13.3).

Historical maps of fuel loading (color plate 19a), crown fire potential (color plate 19c), flame length (color plate 19e), and fireline intensity (color plate 19g) depict a landscape that displayed large contiguous areas with a very high (>30 Mg·ha^{-1}) fuel loading and the potential for crown fires under an average wildfire scenario, high to extreme flame lengths >6 m), and high to extreme fireline intensities (>1038 kW·m^{-1}). It is evident from looking at the historical fuel (color plate 19a), fire behavior (color plate 19c), and structural class (color plate 19e) maps that fires seldom burned in the Wenatchee_13 watershed, but when they did, they were probably significant: moderate severity fires with a large stand-replacement component (see table 13.2, ESRLF). Current conditions suggest that past management activities in Wenatchee_13 have reduced the likelihood of stand-replacing fires, their attendant ecological effects, and the scales of those effects.

EMDS Evaluation of Wenatchee_13

For simplicity, the results of the complete EMDS analysis are summarized in graphical form (figure 13-5). The x-axis shows the degree of correspondence between current Wenatchee_13 spatial patterns for a given map and the estimated reference variation. Intervals along the [0, 1] scale represent the following levels of correspondence between the two: 0 = no correspondence; [0.01, 0.25] = very weak; [0.26, 050] = weak; [0.51, 0.75] = moderate; [0.76, 0.99] = strong; and 100 = full correspondence. For example, in an evaluation of current physiognomic conditions, there is moderate correspondence when 75% of the values of each class metric for each physiognomic type fall within their respective ranges of reference variation, but full correspondence when 100% of the values for the landscape metrics fall within these ranges.

Evaluations of cover types

Evaluations of the current cover type conditions show strong overall correspondence; the correspondence is strong when the five class metrics are evaluated against estimates of reference variation for all cover types, and weak when the nine landscape metrics are evaluated (figure 13.5). Chief among the departures for the class metrics are the elevated patch densities for the Douglas-fir, grand fir, western hemlock-western red cedar, shrubland, and nonforest cover types. Weak correspondence between the current cover type mosaic and estimates of reference variation is a result of elevated cover type richness, which is indicated by departures in patch richness and diversity (table 13.5).

Physiognomic conditions

Physiognomic conditions show strong overall correspondence; correspondence was full when landscape metrics are evaluated, and moderate when class metrics are evaluated (figure 135) When we traced the basis of the latter conclusion in EMDS, we learned that the patch densities of shrubland and nonforest and the edge density of forest (increased by the increased number of cutting units and their boundaries) are well above the limits of reference variation. Fragmentation of forest cover types is so widespread

TABLE 13.5. Comparison of Nine Metrics Representing the Current Combined Cover Type–Structural Class Landscape Conditions in the Subwatershed Wenatchee_13

	Range Estimate		Wenatchee_13	
Landscape Metrics[1]	Min	Max	Current Conditions	Historical Conditions
Richness and diversity				
RPR full range	20.48	61.45		
RPR 80% range (RV)	24.10	41.93	**55.42**	**46.99**
PR full range	17.00	51.00		
PR 80% range (RV)	20.00	34.80	**46.00**	**39.00**
SHDI full range	2.22	3.26		
SHDI 80% range (RV)	2.34	2.87	**3.32**	**2.96**
N1 full range	9.21	26.05		
N1 80% range(RV)	10.40	17.66	**27.66**	**19.30**
N2 full range	6.25	20.00		
N2 80% range (RV)	7.97	13.04	**25.00**	**14.29**
Evenness				
MSIEI full range	0.56	0.79		
MSIEI 80% range (RV)	0.62	0.76	**0.82**	0.71
R21 full range	0.59	0.81		
R21 80% range (RV)	0.63	0.77	**0.90**	0.73
Contagion and interspersion				
CONTAG full range	50.59	61.02		
CONTAG 80% range (RV)	50.91	59.35	**48.60**	53.25
IJI full range	64.37	77.12		
IJI 80% range (RV)	67.72	74.76	74.58	74.03

Notes: Corresponding reference variation (RV) and full range estimates developed for ESR4 B the Moist and Cold Forests subregion are also shown. Values in **bold** lie outside RV.

[1] CONTAG, contagion index; UI, interspersion and juxtaposition index (see also McGarigal and Marks 1995); MSIEI, modified Simpson's evenness index; N1, Hill's N1 index = e^{SHDI}; N2, Hill's N2 index = 1/SIDI; PR, patch richness; R21, Alatalo's evenness index = (N2 - 1)/(N1 - 1); RPR, relative patch richness; SHDI, Shannon diversity index.

that it affected the edge density of the forest physiognomy.

Structural Glass Conditions

Structural class conditions show only moderate overall correspondence between current conditions and estimates of reference variation, moderate correspondence when class metrics are evaluated, and very weak correspondence when the landscape metrics are evaluated. Key departures for the class metrics are the elevated patch density and reduced mean patch size. Weak correspondence between the current structural class mosaic and the estimates of reference variation is a result of elevated diversity, dominance, evenness, interspersion, and juxtaposition of structural classes, and of dramatically reduced contagion.

Combined cover type-structural class conditions

The combined map of cover type and structural class shows moderate overall correspondence between current conditions and estimates of reference variation; correspondence is moderate when class metrics are evaluated, and very weak when the landscape metrics are evaluated. Key departures for the class metrics are elevated patch densities and reduced mean patch sizes for most cover type-structural class combinations, but the mean nearest-neighbor distance is also reduced for most classes. In addition, there are departures in the percentage of total area in the ponderosa pine, western larch (*Larix occidentaIis* Nutt.), grand fir, and amabilis fir (*Abies amnbilis* [Dougl.] Forbes) stand-initiation structures, representing an expanded area of new forest, and in intermediate forest structures ("stem exclusion, open-canopy," "stem exclusion, closed canopy," and "young forest, multistory") associated with the ponderosa pine, grand fir, and western hemlock-western red cedar cover types.

Weak correspondence between the current combined cover type-structural class mosaic and the estimates of reference variation is a result of increased richness, diversity, dominance, evenness, interspersion, and juxtaposition of structural class patches and of reduced contagion. The combined potential vegetation type-cover type-structural class mosaic shows nearly identical results (figure 13.5).

Fragmented landscapes

The common finding among each of the 18 map evaluations is that the landscape had become highly fragmented, an observation that is consistently indicated by reduced contagion, elevated patch densities and mean nearest-neighbor distances, and reduced mean patch sizes. Nowhere is this better indicated than in the evaluations of fuel loading, crown fire potential, and fire behavior patterns. For example, fuel loading shows moderate overall correspondence between current conditions and estimates of reference variation; correspondence is full when landscape metrics are evaluated, and weak when class metrics are evaluated. When we traced the basis of the conclusions in EMDS, we learned that patch density and mean patch size in all fuel loading classes are well outside of the reference variation (color plate 19b).

Departures in Landscape Patterns for Wenatchee_13

Reduced area of old forest

Tables 13.3 and 13.4 display all cover type and structural class transitions from the historical to the current conditions. Early selection cutting apparently targeted large, easily accessed overstory ponderosa pine growing in warm-dry and cool-moist Douglas-fir-grand fir potential vegetation types, and large overstory Douglas-fir growing in cool-moist western hemlock-western red cedar and amabilis fir potential vegetation types. Most of the recent regeneration cutting has been in the same environments. Analysis of the transitions from historical to current structural classes (see table 13.4) shows a net IS% reduction in "old forest, multistory" structures and corresponding increases in stand initiation (6.9%), "stem exclusion, open-canopy" (3.9%), "stem exclusion, closed-canopy" (2.2%), understory reinitiation (4.9%), and "young forest, multistory" (3.0%) structures.

Reduced cover of large, early seral overstory trees

Similarly, analysis of the transitions from historical to current cover types (see table 13.3) shows a net 3.7% reduction in the ponderosa pine cover type and an increase (4.6%) in the Douglas-fir cover type. A combined cover type-structural class transition analysis showed a total transition of large, early seral overstory Douglas-fir cover equal to 11.7% of the subwatershed area to late seral cover comprising amabilis fir (3.6%), grand fir (0.5%), alpine fir (*Abies lasiocarpa* [Hook.] Nutt.)-Engelmann spruce (*Picea engelmannii* Parry) (2.4%), and western hemlock-western red cedar (5.2%) understory cover types. This transition can also be seen in table 13.3, and it reflects

TABLE 13.6. Comparison of Three Class Metrics Representing the Current Cover Type–Structural Class Combinations in the Subwatershed Wenatchee_13

	Percentage Area						Patch Density (10,000 ha)						Mean Patch Size (ha)					
			RV		Full Range				RV		Full Range				RV		Full Range	
SC[1]	C[2]	H	Min	Max	Min	Max	C	H	Min	Max	Min	Max	C	H	Min	Max	Min	Max
Ponderosa pine (PIPO)																		
si	**1.4**	0.2	0.0	1.1	0.0	3.0	**4.0**	1.0	0.0	2.0	0.0	12.0	34.4	19.4	0.0	38.1	0.0	74.9
seoc	0.5	0.6	0.0	2.1	0.0	4.8	3.0	**6.0**	0.0	5.0	0.0	24.0	15.3	9.3	0.0	38.6	0.0	129.2
secc	**0.7**	0.0	0.0	0.0	0.0	4.4	**4.0**	0.0	0.0	0.0	0.0	7.0	**16.1**	0.0	0.0	0.0	0.0	66.4
ur	0.4	0.0	0.0	2.1	0.0	6.2	2.0	0.0	0.0	2.0	0.0	11.0	20.7	0.0	0.0	45.7	0.0	327.7
yfms	0.6	0.2	0.0	1.9	0.0	2.4	**5.0**	2.0	0.0	3.0	0.0	10.0	11.1	10.8	0.0	87.8	0.0	139.9
ofms	**3.0**	**8.5**	0.0	2.3	0.0	8.5	**2.0**	**2.0**	0.0	1.0	0.0	15.0	**144.8**	**405.9**	0.0	34.3	0.0	405.9
ofss	0.3	1.1	0.0	1.3	0.0	3.0	1.0	2.0	0.0	3.0	0.0	7.0	26.6	**52.3**	0.0	33.3	0.0	56.8
Douglas-fir (PSME)																		
si	4.1	1.6	0.0	8.4	0.0	10.0	**44.0**	5.0	0.0	14.0	0.0	21.0	9.3	30.0	0.0	57.1	0.0	92.1
seoc	4.1	5.0	0.0	9.2	0.0	17.2	**23.0**	**18.0**	0.0	15.0	0.0	28.0	18.0	28.3	0.0	128.8	0.0	475.7
secc	3.6	0.1	0.0	14.9	0.0	20.5	**21.0**	1.0	0.0	13.0	0.0	18.0	17.1	7.8	0.0	195.7	0.0	425.3
ur	4.0	4.0	0.4	19.5	0.0	27.5	20.0	9.0	0.1	24.0	0.0	32.0	20.3	42.2	17.0	175.6	5.8	327.9
yfms	3.0	1.4	0.6	9.3	0.0	21.7	17.0	8.0	0.3	23.0	0.0	33.0	18.0	16.5	10.6	74.8	0.0	91.9
ofms	7.5	**16.9**	0.0	12.5	0.0	16.9	**17.0**	**17.0**	0.0	15.0	0.0	17.0	44.5	101.0	0.0	271.0	0.0	878.7
ofss	4.1	1.9	0.0	4.6	0.0	7.3	**4.0**	6.0	0.0	7.0	0.0	11.0	98.8	30.1	0.0	128.9	0.0	142.5
Western larch (LAOC)																		
si	**0.3**	0.0	0.0	0.2	0.0	1.3	1.0	0.0	0.0	1.0	0.0	2.0	**25.4**	0.0	0.0	17.6	0.0	74.3
ur	0.0	0.3	0.0	11.6	0.0	21.0	0.0	2.0	0.0	21.0	0.0	47.0	0.0	13.3	0.0	54.8	0.0	132.0
yfms	0.2	0.0	0.0	0.3	0.0	2.4	1.0	0.0	0.0	1.0	0.0	2.0	14.6	0.0	0.0	15.1	0.0	96.2
ofms	0.0	0.2	0.0	3.5	0.0	7.8	0.0	1.0	0.0	22.0	0.0	34.0	0.0	**20.5**	0.0	15.1	0.0	26.3
Grand fir (ABGR)																		
si	**0.1**	0.0	0.0	0.0	0.0	0.2	**1.0**	0.0	0.0	0.0	0.0	1.0	**4.6**	0.0	0.0	0.0	0.0	15.6
seoc	0.1	**0.8**	0.0	0.3	0.0	0.8	1.0	1.0	0.0	1.0	0.0	3.0	7.6	**73.2**	0.0	13.5	0.0	73.2
yfms	**0.3**	0.0	0.0	0.1	0.0	1.4	**2.0**	0.0	0.0	0.0	0.0	1.0	**15.4**	0.0	0.0	8.6	0.0	146.2

ofms	**0.3**	0.0	0.0	0.0	0.0	0.0	**4.0**	0.0	0.0	0.0	0.0	0.0	**6.4**	0.0	0.0	0.0	0.0	0.0
Amabilis fir (ABAM)																	
si	**3.0**	0.3	0.0	2.6	0.0	6.2	**12.0**	2.0	0.0	8.0	0.0	10.0	26.4	12.8	0.0	43.5	0.0	62.1
seoc	1.1	1.7	0.0	4.5	0.0	6.1	8.0	13.0	0.0	14.0	0.0	23.0	13.6	13.6	0.0	84.6	0.0	173.9
secc	0.5	0.2	0.0	13.1	0.0	14.6	3.0	1.0	0.0	14.0	0.0	17.0	14.2	16.9	0.0	118.1	0.0	188.4
ur	3.4	2.2	0.0	10.0	0.0	13.9	12.0	9.0	0.0	18.0	0.0	22.0	29.4	23.8	0.0	91.4	0.0	173.8
yfms	1.7	1.0	0.0	6.1	0.0	12.5	10.0	7.0	0.0	14.0	0.0	30.0	15.9	13.0	0.0	73.4	0.0	100.4
ofms	1.9	0.8	0.0	2.4	0.0	10.6	2.0	4.0	0.0	4.0	0.0	7.0	**92.2**	19.4	0.0	57.2	0.0	281.4
ofss	0.2	0.0	0.0	2.5	0.0	21.8	2.0	0.0	0.0	4.0	0.0	6.0	10.8	0.0	0.0	90.0	0.0	461.5
Alpine fir–Engelmann spruce (ABLA2)																	
si	1.3	0.8	0.0	12.8	0.0	15.9	**15.0**	2.0	0.0	14.0	0.0	18.0	9.2	36.9	0.0	87.3	0.0	109.9
seoc	3.3	2.4	0.3	3.3	0.0	4.0	**16.0**	**16.0**	1.0	13.0	0.0	19.0	20.8	15.1	10.4	54.4	0.0	72.1
secc	0.2	0.2	0.0	2.5	0.0	3.1	**3.0**	4.0	0.0	4.0	0.0	5.0	6.8	3.6	0.0	75.1	0.0	248.9
ur	4.4	2.7	0.0	11.0	0.0	25.3	**20.0**	9.0	0.0	13.0	0.0	17.0	22.3	29.1	0.0	163.1	0.0	267.6
yfms	6.7	6.2	0.2	12.7	0.0	19.7	**30.0**	**26.0**	1.0	24.0	0.0	32.0	22.0	23.6	19.2	69.7	0.0	85.4
Western hemlock–western red cedar (TSHE/THPL)																	
seoc	**3.0**	**4.6**	0.0	1.1	0.0	4.6	**5.0**	**6.0**	0.0	4.0	0.0	6.0	**57.0**	**73.3**	0.0	47.9	0.0	73.3
secc	0.2	0.9	0.0	6.6	0.0	8.0	1.0	2.0	0.0	6.0	0.0	12.0	15.8	41.5	0.0	100.3	0.0	279.3
ur	5.9	1.8	0.0	8.7	0.0	31.4	**13.0**	**7.0**	0.0	6.0	0.0	13.0	46.6	24.3	0.0	288.8	0.0	660.3
yfms	**1.5**	0.3	0.0	1.2	0.0	3.4	**4.0**	2.0	0.0	3.0	0.0	11.0	36.2	13.9	0.0	40.5	0.0	94.5
ofms	**7.1**	**11.4**	0.0	1.8	0.0	11.4	**16.0**	**7.0**	0.0	5.0	0.0	7.0	44.9	**155.6**	0.0	74.1	0.0	155.6
ofss	1.2	0.2	0.0	4.7	0.0	7.2	**8.0**	1.0	0.0	3.0	0.0	8.0	14.7	18.3	0.0	143.5	0.0	259.7
Mountain hemlock (TSME)																	
secc	0.1	0.1	0.0	0.8	0.0	3.8	1.0	1.0	0.0	1.0	0.0	3.0	8.4	8.6	0.0	52.8	0.0	225.1
ur	0.4	**3.2**	0.0	2.3	0.0	3.2	2.0	2.0	0.0	3.0	0.0	9.0	16.6	**154.9**	0.0	83.7	0.0	238.7
yfms	0.2	0.0	0.0	2.5	0.0	7.3	1.0	0.0	0.0	5.0	0.0	13.0	17.5	0.0	0.0	31.3	0.0	74.4
ofms	0.3	0.0	0.0	0.4	0.0	2.1	1.0	0.0	0.0	0.0	0.0	2.0	**25.7**	0.0	0.0	12.9	0.0	111.9

Notes: Corresponding reference variation (RV) and full range estimates developed for the ESR4 Moist and Cold Forests subregion are also shown. Values in **bold** lie outside RV.

[1] SC (structural classes): ofms, "old forest, multistory"; ofss, "old forest, single story"; secc, "stem exclusion, closed-canopy"; seoc, "stem exclusion, open-canopy"; si, stand initiation; ur, understory reinitiation; yfms, "young forest, multistory." Species names are as defined in table 12.3.

[2] C, current; H, historical; RV, reference variation.

the removal of large Douglas-fir overstories from "old forest, multistory" patches.

In table 13.6, we compare current and historical values of three class metrics (percentage of total area, patch density, and mean patch size) for a partial list of cover type-structural class combinations with corresponding estimates of reference variation. For example, the estimated percentage area of the ponderosa pine stand-initiation class is 0.0-1.1% of the total area. In the current condition, this class occupies 1.4% of the area, and the current area is above the estimates for reference variation. This increased dominance of ponderosa pine stand-initiation structures resulted from regeneration harvests.

Also in table 13.6, we display historical values of the class metrics and the full range of historical values for each class and metric. Significant historical and current departures from reference variation are highlighted in bold. Class metrics for several current and historical cover type-structural class combinations lie outside the estimated reference variation. Structural classes of the ponderosa pine, Douglas-fir, and western hemlock-red cedar cover types exhibit the greatest departures, because these classes contain the greatest area of "old forest, multistory" structures, and old forests were targeted for early selection cutting, and more recently, for regeneration harvests (Hessburg et al. 1999b; Hessburg and Agee in press) (see tables 13.3, 13.4) In the historical condition, there was no area of "stem exclusion, closed canopy" or understory reinitiation patches in the ponderosa pine cover type, and the area in "young forest, multistory" patches was small (0.2%). A likely explanation is that historical surface fires and dry site conditions on sites with southern aspects maintained open-canopy rather than closed-canopy stem-exclusion structures (Agee 1993). The net effect was a simplified landscape mosaic on lower montane sites with southern aspects; ponderosa pine land cover was historically dominated by "old forest, multistory" and "old forest, single story" structures, and trace amounts of stand initiation, "stem exclusion, open canopy," and "young forest, multistory" structural classes (see tables 13.4, 13.6).

Working with unique or borderline watersheds of a subregion

The estimates of reference variation for areas of ponderosa pine, Douglas-fir, and western hemlock-western red cedar "old forest, multistory" patch types ranged, respectively, from 0% to 2.3, 12.5, and 1.8%, but the historical areas of these structures were 8.5, 16.9, and 11.41 respectively; these values lie well above the estimated range of reference variation. Wenatchee_13 is somewhat unusual among the historical subwatersheds we sampled because 38% of the watershed comprised "old forest, multistory" structures (see table 13.4) and this area was aggregated in a few large patches (table 13.6). This observation suggests that it may be appropriate to consider the full range of values for the class and landscape metrics when evaluating opportunities to restore the area, connectivity, and pattern of old forests and perhaps other attributes of some Moist and Cold Forest subregion landscapes. Unique fire ecology, landform features, or environments may make some landscapes of a subregion appear atypical. We discuss some reasons for this in our *Conclusions* section.

Relevance of Departures in Landscape Patterns

At relatively fine to broad spatial and temporal scales, the response of terrestrial species to landscapes and their patterns indicates whether these environments are more or less suitable to their particular needs. Changes in the patterns of vegetation at certain spatial and temporal scales may have a direct bearing on species migration, colonization, the availability of habitats and food, and the persistence of a species in a landscape (Wisdom et al. 2000). As patterns change significantly, different suites of species may be favored. Such changes also influence the spatial and temporal scales and parameters of disturbance regimes. As tables 13.5 and 13.6 show, variability in the spatial patterns of historical landscapes was commonplace. Variable landscape patterns at subwatershed, watershed, subregional, and regional scales probably provide alternating periods and patterns of plenty and need that may help native species to develop broad genetic and phenotypic diversity and necessary adaptations as long as habitats do not become overly fragmented or isolated in space or time (Swanson et al. 1994). Natural variability in vegetation patterns, climate, and geological systems is also linked to natural variation in disturbance regimes.

After evaluating the classes in the 18 maps with respect to reference variation, we characterized departures in spatial patterns for each landscape mosaic. For example, we compared the overall current cover type-structural class mosaic of Wenatchee_13 with corresponding estimates of reference variation (table 13.5). Current values of eight of the nine landscape metrics lie beyond these limits; historical values of five metrics also show evidence of departures. In the Wenatchee_13 historical condition, all richness and diversity metrics are above the estimates of reference variation for the subregion. Thus Wenatchee_13, at least in this temporal snapshot, displayed a richer and more diverse array of cover type-structural class patches than ordinarily occurred in similar subwatersheds of the subregion in the period for which we characterized reference variation. This was probably true of other watersheds and landscape attributes at other times. In the historical condition, Wenatchee_13 displayed nearly 47% of the total possible number of cover type-structural class combinations that were present in the entire subregion (relative patch richness$_{\text{historical}}$; table 13.5); in the current condition, more than 55% of those possibilities are displayed. The historical value of absolute patch richness exceeds the estimated reference variation by more than four cover type-structural class patch combinations, and seven cover type-structural class combinations developed in the landscape as a consequence of management activities.

In the historical Wenatchee_13, three indices registered as lying above the reference variation: Shannon's diversity index, which measures the proportional abundance of classes and the equitable distribution of area; N1, a transformation of Shannon's diversity index; and N2, the inverse of Simpson's lambda, a metric that represents dominance and diversity. Current values for the three metrics also lie above the limits of the full range of variation. Timber harvesting coupled with fire exclusion has created many new cover type-structural class combinations. For example, a comparison of historical and current values of N2 indicates that the number of dominant cover type-structural class combinations increased from about 14 to 25 (table 13.5).

A comparison of the historical and current values of the evenness metrics (modified Simpson's evenness index and Alatalo's R21 evenness index) shows significantly elevated evenness among the cover type-structural class combinations. The modified Simpson's index is sensitive to changes in the evenness of all classes, including rare ones; Alatalo's index is sensitive to changes in the evenness of the dominant classes. Harvesting activities increased the complexity and evenness of patterns in the cover type-structural class mosaic. Considering only the dominant 25 cover type-structural class combinations (N2$_{\text{current}}$), the current mosaic displays 90% of the maximum possible evenness for the number of classes in the subregion (R2$_{\text{current}}$). The historical mosaic displays 73% of the maximum possible evenness (table 13.5).

The current value of the contagion metric also lies outside the range of the estimates of reference variation, but unlike other landscape metrics, contagion decreased when compared with its historical value. Contagion was apparently reduced by timber harvesting (color plate 18b) and perhaps by fire exclusion, which fragmented the historical areas of "old forest, multistory" structures. Timber harvests had homogenized the simple, contagious patterns of forest structure in the historical landscape.

Conclusions

A scientific and social consensus is emerging that land managers must restore more natural conditions to forests. One approach focuses management and restoration efforts on emulating natural disturbance, but restoring the role of disturbance requires to some extent emulation of the range and variation in the vegetation conditions that support it. Before settlement of the region, fire played a dominant role in sculpting vegetation patterns and the associated processes. Before restoring the natural role of disturbance, managers must restore more natural variation in the spatial and temporal patterns of vegetation.

We estimated reference variation conservatively so as to define an approximate range of ecologically justifiable conditions (e.g., Landres et al. 1999; Parsons et al. 1999; Swetnam et al. 1999) and to identify ecologically important changes in pattern features (e.g., extents and patterns of old forest or early seral species). When preparing restoration prescriptions,. reference conditions should be used as a general rather than a rigid guide, and restored landscapes should reflect broad variation in patterns rather than the modal conditions.

Our selection of a range statistic was arbitrary; other variance measures could be used. We used the median because the right-skewed distributions of reference variation required a measure of central tendency that defined a representative range of conditions. We excluded extremes by not using the full range of variation.

The sampling method used to define the reference conditions substitutes space for time. Broad sampling of spatial patterns of vegetation from similar environments with similar disturbance and climatic regimes should reveal a representative cross section of temporal variation in these patterns (Pickett 1989). In effect, variation observed over broad spaces and narrow times may be as effective as observing variation over broad times and narrow spaces; both let us infer variations in spatial pattern at a single location or across a single landscape over time. Particularly when we try to explain the influence of processes, sampling locations must have comparable biophysical and climatic conditions (Pickett 1989). We addressed this concern by stratifying our reconstructed historical subwatersheds into subregions with similar climate, geology, biology, and disturbance regimes. The remaining potential pitfalls include an inadequate time depth, locally incompatible disturbance and climate histories, convergent environmental histories, and nonhomogeneous environments.

Comparing current values of spatial pattern metrics with estimates of reference variation reveals ecologically important departures. Comparing historical values with these estimates reveals unique landscapes or landscape conditions that lie outside the typical reference conditions. Atypical cases should be frequent, because regionalizations define homogeneous ecoregions; in reality, these overlap somewhat, and each resembles neighboring ecoregions to some extent (e.g., see Hessburg et al. 2000a). It is difficult to map intergradations between the cores of ecoregions, where atypical landscapes and patterns often appear. To minimize this problem, we analyzed reference variation, but the full range of conditions could be used to evaluate apparently atypical conditions.

Regionally synchronous weather or disturbance (convergent environmental histories), which are often related, would simplify estimates of a region's reference variation. For this reason, estimates should ultimately include variations resulting from stochastic features and rare events. This can be done by temporally and spatially broadening samples where data are available and by process modeling (e.g., Keane et al. 2002b, chapter 5, this volume), in which simulated vegetation conditions contribute to computing reference variation. We simulated vegetation and disturbance conditions in a few ecoregions and found that estimates such as those presented in this chapter correspond reasonably well with the simulated results. However, the possibility for errors or uncertainties in the spatial data remains, and can lead to estimation and prediction errors.

Managers can use our approach to perform similar evaluations elsewhere. To do so, it is essential to associate estimates of reference variation with specific potential vegetation types, because distributions of cover type-structural class combinations vary significantly; fire, insect, and pathogen disturbances, which account for much of the natural variation in vegetation spatial patterns, strongly correlate with the environmental setting (Pickett and White 1985). Hessburg et al. (1999b) illustrated how reference variation can be computed for potential vegetation type-cover type-structural class combinations and how that information can identify biophysical environments and guide revisions to cover type-structural class patterns.

Empirical estimates of reference variation serve several useful functions. Managers can use them to:

- Evaluate current conditions and estimate potential consequences for native species and processes (Morgan et al. 1994; Landres et al. 1999);
- Assess scenarios that differ from reference conditions and evaluate the potential opportunities and risks for native species, processes, and ecosystem productivity; Develop and evaluate specific restoration goals (Allen et al. 2002);
- Develop strategies and conservation and restoration priorities at multiple geographic scales; and
- Monitor progress in ecosystem management at relevant geographic scales.

A decision-support system, such as EMDS, can automate landscape evaluations at several scales. At a regional scale, fully integrated knowledge bases can represent reference conditions for subregions. Landscape evaluations can reveal subregions that contain the land areas with important or extensive departures from natural ranges and thereby guide the strategic allocation of planning and restoration resources (e.g., Reynolds and Hessburg 2004). At a Subregional scale, evaluating a few critical attributes of all watersheds can identify priorities for more complete evaluation. At a subwatershed or landscape scale, evaluations, such as the one in this chapter, can help map alternative restoration scenarios and contrast them with estimates of reference variation before choosing and implementing the most suitable approach.

Acknowledgments

The Sustainable Management Systems Program of the U.S. Department of Agriculture Forest Service's Pacific Northwest Research Station provided financial support for this study. The authors thank Dave W. Peterson, Jim Agee, Ed Depuit, and three anonymous reviewers for their helpful comments and reviews of earlier drafts.

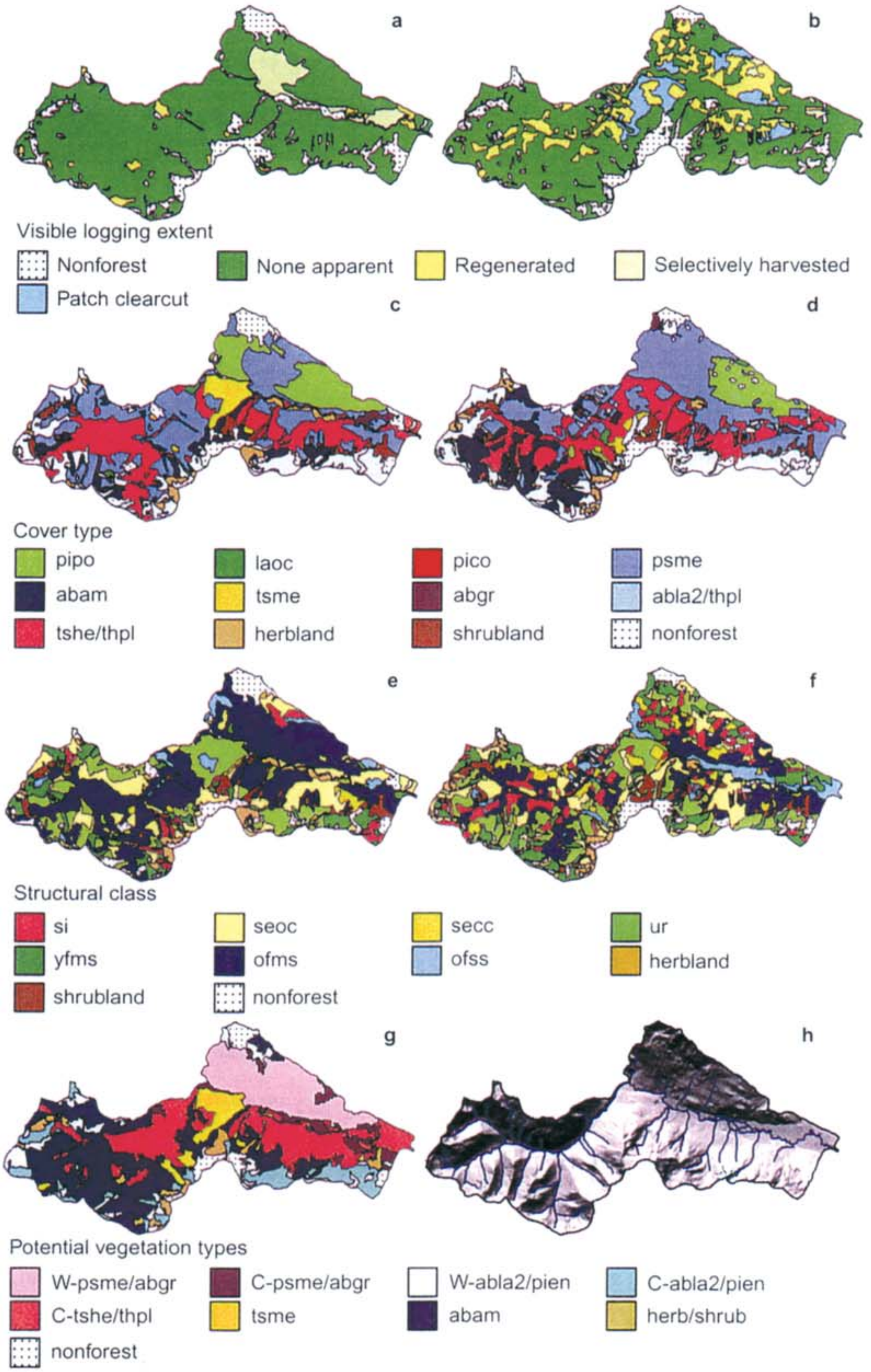

PLATE 18. Maps of Wenatchee_13, showing (a) historical (1949) and (b) current (1992) representations of visible logging extent, (c) historical (1900, after reconstruction) and (d) current (1992) cover types, (e) historical (1900, after reconstruction) and (f) current structural classes, (g) potential vegetation types, and (h) topography. Cover type classes and potential vegetation types are defined in table 13.3, and structure classes are defined in table 13.4. The letters W and C before a potential vegetation type indicate a warm-dry or cool-moist variant of the vegetation type, respectively.

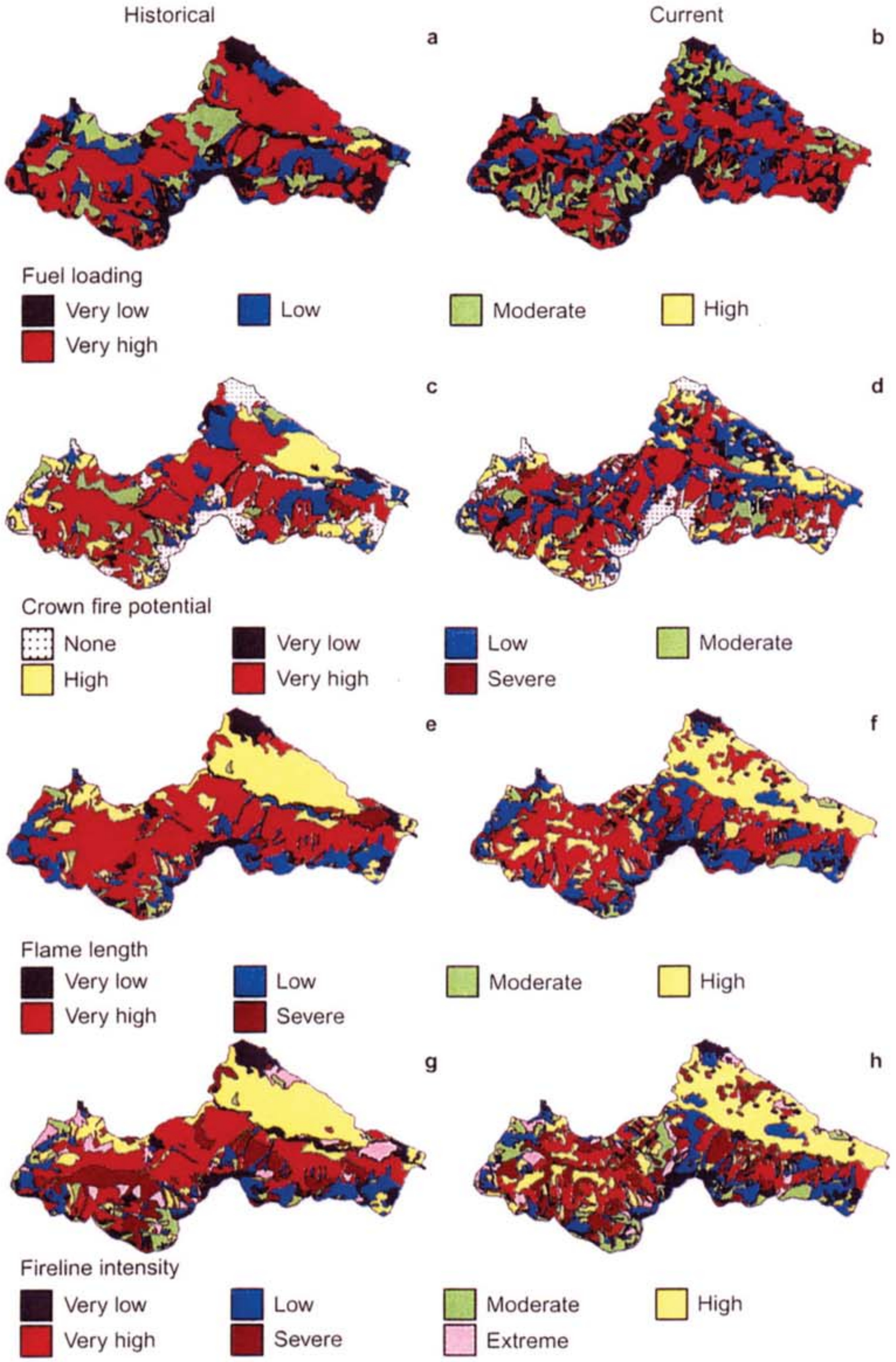

PLATE 19. Maps of Wenatchee_13, displaying historical (1900, after reconstruction) and current (1992) (a, b) fuel loading, (c, d) crown fire potential, (e, f) flame length, and (g, h) fireline intensity, respectively, under a wildfire scenario. Fuel loading (Mg·ha^{-1}) classes: very low, <22.5; low, 22.5–44.9; moderate, 45–56.1; high, 56.2–67.3; very high, >67.3. Crown fire potential classes are represented by an index. Flame-length (m) classes: very low, <0.6; low, 0.7–1.2; moderate, 1.3–1.8; high, 1.9–2.4; very high, 2.5–3.4; severe, >3.4. Fireline intensity (kW·m^{-1}) classes: very low, <173.0; low, 173.0–345.9; moderate, 346.0–1037.8; high, 1037.9–1729.6; very high, 1729.7–2594.4; severe, 2594.5–3459.2; extreme, >3459.2.