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Recent changes (1930s–1990s) in spatial patterns of interior northwest forests, USA

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Abstract

We characterized recent historical and current vegetation composition and structure of a representative sample of subwatersheds on all ownerships within the interior Columbia River basin and portions of the Klamath and Great Basins. For each selected subwatershed, we constructed historical and current vegetation maps from 1932 to 1966 and 1981 to 1993 aerial photos, respectively. Using the raw vegetation attributes, we classified and attributed cover types, structural classes, and potential vegetation types to individual patches within subwatersheds. We characterized change in vegetation spatial patterns using a suite of class and landscape metrics, and a spatial pattern analysis program. We then translated change in vegetation patterns to change in patterns of vulnerability to wildfires, smoke production, and 21 major forest pathogen and insect disturbances. Results of change analyses were reported for province-scale ecological reporting units (ERUs). Here, we highlight significant findings and discuss management implications.

Twentieth century management activities significantly altered spatial patterns of physiognomies, cover types and structural conditions, and vulnerabilities to fire, insect, and pathogen disturbances. Forest land cover expanded in several ERUs, and woodland area expanded in most. Of all physiognomic conditions, shrubland area declined most due to cropland expansion, conversion to semi- and non-native herblands, and expansion of forests and woodlands. Shifts from early to late seral conifer species were evident in forests of most ERUs; patch sizes of forest cover types are now smaller, and current land cover is more fragmented. Landscape area in old multistory, old single story, and stand initiation forest structures declined with compensating increases in area and connectivity of dense, multilayered, intermediate forest structures. Patches with medium and large trees, regardless of their structural affiliation are currently less abundant on the landscape. Finally, basin forests are now dominated by shade-tolerant conifers, and exhibit elevated fuel loads and severe fire behavior attributes indicating expanded future roles of certain defoliators, bark beetles, root diseases, and stand replacement fires. Although well intentioned, 20th-century management practices did not account for landscape-scale patterns of living and dead vegetation that enable forest ecosystems to maintain their structure and organization through time, or for the disturbances that create and maintain them. Improved understanding of change in vegetation spatial patterns, causative factors, and links with disturbance processes will assist managers and policymakers in making informed decisions about how to address important ecosystem health issues. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Forest and rangeland ecosystems of the Interior Northwest are remarkably diverse and productive owing to great variety in climate, geology, landforms, hydrology, flora, fauna, and ecosystem processes (Franklin and Dyrness, 1988; Bailey, 1995). Recurring disturbances, such as those caused by fires, insects, pathogens, and weather are essential to maintaining this diversity (Arno, 1976, 1980; Hall, 1976; Turner, 1987, 1989; Agee, 1993, 1994; Hessburg et al., 1994). Terrestrial plant communities range from dry, short grass prairies and sagebrush shrublands, to dry ponderosa pine and Douglas-fir forests, cool and moist western hemlock and western redcedar forests, high elevation whitebark pine and subalpine larch forests, krummholz, and heath. Alpine tundras, rock barrens, and glaciers occupy many of the highest elevations.

Vegetation spatial and temporal patterns and ecological characteristics of forest-dominated landscapes are closely related to their disturbance ecology. Broad-scale landscape patterns of life forms and physiognomic conditions arise from broad differences in topography and physiography, lithology, geomorphic processes, climate regime, and large-scale disturbances. Within the general framework of coarse patterns, meso-scale patterns result from environmental gradients, patch-scale and gap disturbances, stand development, and succession processes.

Natural fire regimes of forests range from frequent, nonlethal surface fires typical in dry ponderosa pine and Douglas-fir forests to moderately infrequent, mixed-severity fires characteristic of moist grand fir, western hemlock, and western redcedar forests, and infrequent, lethal, stand-replacing fires typical in cold subalpine forests (Agee, 1993, 1994). Likewise, native insect and pathogen disturbance regimes are variable in their frequency, severity, duration, and spatial extent. Pandemic bark beetle and defoliator outbreaks occur relatively infrequently in any given geographic area, and outbreaks when occurring, often are synchronous with climatic extremes and cycles of geographically dominant vegetation structure or composition resulting from other major pattern-forming trends or events. Insect or pathogen disturbance associated with endemic populations blends seamlessly with other succession and stand-development processes.

The declining health of forest ecosystems in the Interior Northwest has been the subject of much recent study, concern, and controversy (e.g., see Wickman, 1992; O'Laughlin et al., 1993; Everett et al., 1994; Lehmkuhl et al., 1994; Harvey et al., 1995). Land-use practices of this century have altered disturbance regimes, spatial and temporal patterns of vegetation, and reduced ecosystem resilience to native and human disturbances (Covington et al., 1994). Fire suppression and fire exclusion, timber harvest, and domestic livestock grazing have contributed most to increased forest ecosystem vulnerability to insect, pathogen, and wildfire disturbance. Concern over declining 'forest health' centers on the perception that management activities have damaged forest ecosystem structure and functioning. That perception is founded on a strongly held social value that forest ecosystems should appear 'natural' and function 'naturally.'

This paper presents results of a study conducted under the aegis of the Interior Columbia Basin Ecosystem Management Project. We report on a meso-scale (map scale $= 1 : 24\,000$) scientific assessment of vegetation change in terrestrial landscapes of the interior Columbia River basin, associated change in landscape vulnerability to fire and related PM10 (particulate matter < 10 μm in diameter) smoke production, and insect and pathogen disturbances, and we discuss the management implications of those changes. Our assessment area (58 million ha) included the Columbia River basin east of the crest of the Cascade Range and portions of the Klamath and Great Basins in Oregon ('the basin', Fig. 1)

Our study had four objectives: (1) to characterize current structure and composition of a representative sample of forest (and rangeland) landscapes; (2) to compare existing conditions to the oldest historical vegetation conditions we could reconstruct at a comparable scale; (3) to link historical and current vegetation spatial patterns with patterns of vulnerability to insect and pathogen disturbances; and (4) to link historical and current landscape vegetation characteristics throughout the basin with fuel conditions, potential fire behavior, and related smoke production. Linkages in objectives 3 and 4 would enable us to better understand causal connections among historical management activities and current conditions, and assist in evaluating current air quality and human health tradeoffs associated with wild and prescribed

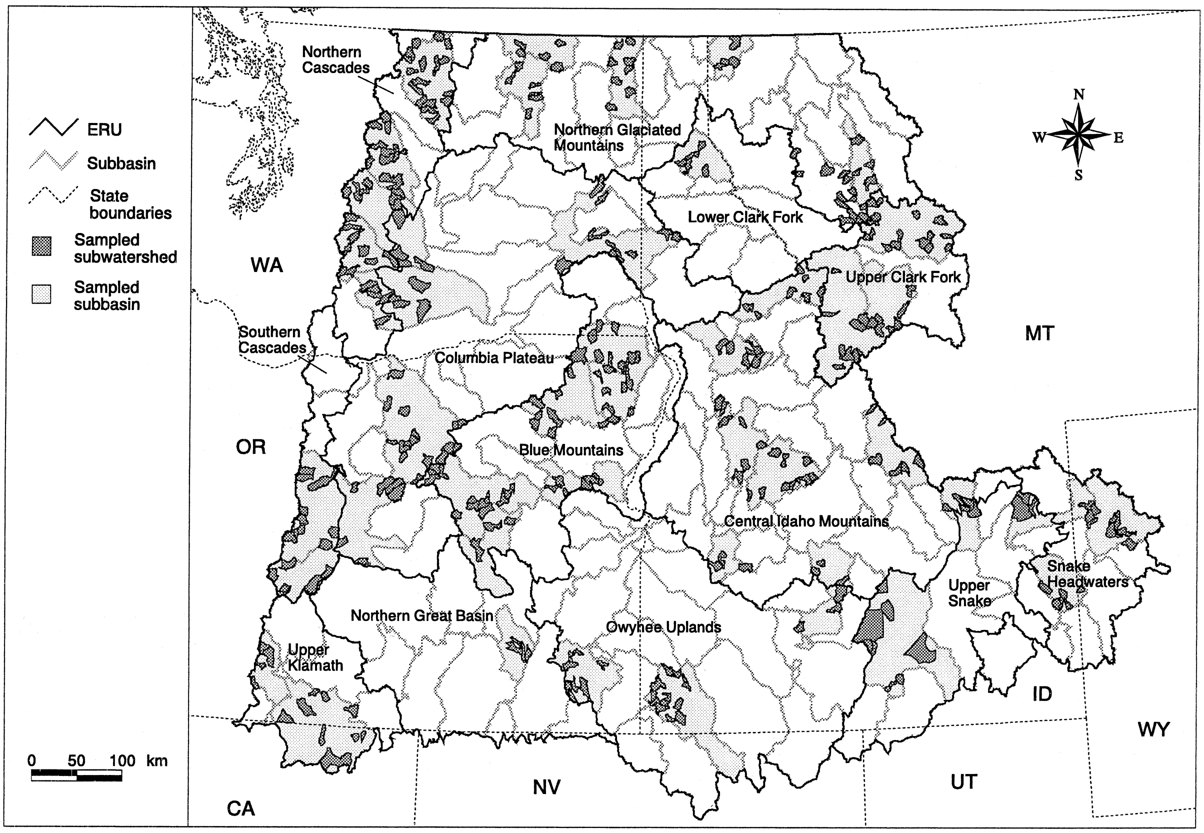

Fig. 1. Map of ecological reporting units (ERUs), and sampled subbasins and subwatersheds in the mid-scale assessment of the interior Columbia River basin.

fires, and tradeoffs associated with alternative insect and pathogen vulnerability scenarios.

2. Methods

In the mid-scale assessment, (Hessburg et al., 1999a), we quantified change in vegetation patterns and landscape vulnerability to fire, insect, and pathogen disturbances over the most recent 50–60 years. Sampling design and change analysis methods were adapted from Lehmkuhl et al. (1994). Our sample of historical conditions corresponded well with the start of the period of most intensive timber harvest, road construction, and fire suppression, and a period of declining intensity in rangeland management. We based our assessment on a stratified random sample of 337 subwatersheds (10 000 ha average area) distributed in 43 subbasins (400 000 ha average area), across all ownerships within the basin. Change analysis results were reported by ecological reporting units (ERUs, Fig. 1). Ecological reporting units were developed during the broad-scale assessment of the basin (Quigley and Arbelbide, 1997) as statistical pooling strata for generalizing results of various ecological, social, economic, and integrated assessments. The ERUs represent land areas that are broadly homogeneous in their biophysical and social ecosystem characteristics.

Forest and rangeland composition and structure were derived from raw data developed from aerial photographs taken from 1932 to 1966 (historical), and from 1981 to 1993 (current). Historical conditions of most forested settings were represented by photography from the 1930s to 1940s; while those of rangelands were represented by 1950s and 1960s aerial photography. Areas with homogeneous vegetation composition and structure were delineated as patches to a minimum size of 4 ha. Vegetation cover types, structural classes, and potential vegetation types were classified for each patch using the raw attributes, and topographic or biophysical data from other digital sources of comparable scale and image resolution.

Each patch was assigned a rating for three to seven vulnerability factors associated with each of 21 different forest insects and pathogens, including defoliator, bark beetle, dwarf mistletoe, root disease, rust, and stem decay disturbances. Vulnerability factors were unique for each host–pathogen or host–insect interaction modeled and included items such as site quality, host abundance, canopy layers, host age or host size, stand vigor, stand density, connectivity of host patches, topographic setting, and type of visible logging disturbance. Patch vulnerability factors were taken from the literature or were based on the experience of field pathologists and entomologists with expertise in specific geographic areas (Hessburg et al., 1999b). Resulting models represent substantial revisions of early versions described by Lehmkuhl et al. (1994).

Similarly, historical and current vegetation patches were matched to one of 192 fuel condition classes (Ottmar et al., 1996; Schaaf, 1996) and assigned a fuel loading. Fuel loads were used to compute fuel consumption, particulate emissions production (PM10), crown fire potential, and fire behavior attributes for an average wildfire scenario using published procedures (Huff et al., 1995; Ottmar et al., 1999). We also modeled fuel consumption and related smoke production for a current prescribed burn scenario. Algorithms for estimating fuel consumption for both burn scenarios were taken from the CONSUME (Ottmar et al., 1993) and first order fire effects model (FOFEM, Keane et al., 1994). Fire behavior attributes were rate of spread, flame length, and fireline intensity. We computed fireline intensity (Byram's, Rothermel, 1983), rate of spread, and flame length using the published equations of the National Fire Danger Rating System (Rothermel, 1972; Deeming et al., 1977; Cohen and Deeming, 1985).

2.1. Vegetation and landscape pattern analysis

This assessment was a map-based characterization of landscape patterns and ecological processes across space and time. We used the ARC/INFO (ESRI, 1995) geographical information system (GIS) to manipulate and analyze digital maps, and to develop and run spatially explicit insect and pathogen vulnerability (Hessburg et al., 1999b), and potential fuel consumption and fire behavior models (Ottmar et al., 1999).

Spatial and statistical analyses characterized change in patterns and quantified the significance of change. FRAGSTATS (McGarigal and Marks, 1995) was used to compute class and landscape pattern metrics directly from ARC/INFO data tables, and we incorporated three additional metrics (N1, N2, and R21, Table 1) into the source code. We used S-PLUS (MathSoft Inc., 1993) to summarize and analyze ARC/INFO and FRAGSTATS outputs. Vegetation maps, raw and derived patch attributes formed the basic data set for all analysis. For spatial pattern analysis, a variety of unique vegetation maps were derived in a GIS by dissolving on single or combined data items. Patch types of a map submitted to analysis could be defined by any raw attribute such as canopy layers or total crown cover class, or by any derived attribute such as cover type or structural class, either singly or in combinations.

2.2. Raster size determination

To quantify change in individual patch types and patterns of various patch types, we used raster versions of current and historical vegetation maps where patch types were physiognomic conditions, cover types, structural classes, potential vegetation types, or combinations. A raster format was chosen because several useful metrics were only available in FRAGSTATS for raster maps. The appropriate cell size was determined by calculating several class metrics in vector and raster form, with cell sizes ranging from 10 to 100 m (1 ha), in 10-m increments, and at 141 m (2.0 ha) and 224 m (5.0 ha), and plotting each raster-derived metric value against the vector value. When compared with vector values, raster bias was insignificant with 30 m and smaller cell sizes, and we used 30-m raster maps for all pattern analysis.

2.3. Sample statistics

We used percentage of area, patch density, mean patch size, edge density, and mean nearest neighbor

Table 1
FRAGSTATS indices used to quantify spatial patterns of patch types in sampled subbasins in the mid-scale ecological assessment of the interior Columbia River basin

Acronym	Scale	Index name	Description[a]
LAND (%)	class	percentage of landscape (%)	percentage of a landscape composed of the corresponding patch type
PD	class or landscape	patch density (no. per 10 000 ha)	number of patches in an area of 10 000 ha
MPS	class or landscape	mean patch size (hectare)	average patch size
AWMECI	class or landscape	area-weighted mean edge contrast index (%)	average patch edge contrast as a percentage of maximum contrast with patch edge contrasts weighted by patch area; equals 100 when all edge is maximum contrast; approaches 0 when all edge is minimum contrast
SHDI	landscape	Shannon's diversity index[b]	measures proportional abundance of patch types and the equitable distribution of patch type areas; increases with patch richness (PR) and equitability of area
RPR	landscape	relative patch richness (%)	observed number of patch types within a landscape over a realistic potential maximum number of patch types
PR	landscape	patch richness	observed number of patch types within a landscape boundary
MSIEI	landscape	modified Simpson's evenness index[c]	observed distribution of area of patch types within a landscape over evenly distributed area of patch types
IJI	class or landscape	interspersion and juxtaposition index (%)	observed interspersion of edge types over maximum possible interspersion; IJI approaches 0 when patch types are clumped, IJI approaches 100 when all patch types are equally adjacent to all other patch types
CONTAG	landscape	contagion index (%)	observed contagion over the maximum possible contagion for the given number of patch types; approaches 0 when the distribution of adjacencies among unique patch types becomes increasingly uneven; approaches 100 when all patch types are equally adjacent to all other patch types; measures patch type interspersion and patch dispersion
N1	landscape	Hill's index N1[d]	a transformation of SHDI, computed as e^{SHDI}; rare patch types are weighted less in the calculation than in pr
N2	landscape	Hill's index N2[d]	a transformation of sidi, computed as $1/(1-\mathrm{SIDI})$; rare patch types are weighted less in the calculation than in n1
R21	landscape	Alatalo's evenness index[e]	measures evenness of patch types; computed as $(\mathrm{N2}-1)/(\mathrm{N1}-1)$, where $\mathrm{PR} > 1$; values approaching 0 indicate uneven distribution of patch type areas; values approaching 1 indicate even distribution of area for the given number of patch types

[a] See McGarigal and Marks (1995) for algorithms and complete descriptions of all indices except N1, N2, and R21.

[b] Shannon and Weaver (1949).

[c] Simpson (1949).

[d] Hill (1973).

[e] Alatalo (1981).

metrics to describe change in area and connectivity of patch types in subwatersheds of an ERU. We used 10 landscape metrics to describe changes in patch type richness, evenness, diversity, dominance, contagion, interspersion, juxtaposition, and edge contrast (Tables 1 and 2). For each ERU, means, standard errors, and confidence intervals were estimated using methods for simple random samples with subwatersheds as sample units. Significant ($p \leq 0.2$) change from historical to current conditions was determined by examining the 80% confidence interval (CI) around the mean difference for the ERU. We used a moderately conservative 80% CI because we wanted to be able to detect changes in spatial patterns that were of potential ecological importance. We reasoned that with a more conservative CI, we might increase the likelihood of type II error (false positive). When we compared 90 and 95% CI estimates of mean difference with 80% estimates, we noted that important changes went undetected using the more conservative CIs. To avoid increasing the likelihood of type I error (false negative), we supplemented our significance test with

Table 2
Edge contrast weights used in calculating the FRAGSTATS metric area weighted mean edge contrast index (AWMECI) in pattern analyses of patch types of sampled subwatersheds in the mid-scale ecological assessment of the interior Columbia River basin[a]

Physiognomic type	Nonforest and nonrange	Herbland	Shrubland	Woodland	Forest (by structural class[b])				
					SI	SEOC and SECC	UR and YFMS	OFSS	OFMS
Nonforest and nonrange	0[c]	0.2	0.3	0.4	0.5	0.6	0.8	0.9	1.0
Herbland		0.0	0.2	0.3	0.4	0.6	0.7	0.8	0.9
Shrubland			0.0	0.2	0.3	0.5	0.6	0.7	0.8
Woodland				0.0	0.3	0.4	0.5	0.6	0.7
Forest SI					0.0	0.3	0.4	0.5	0.6
Forest SEOC and SECC						0.0	0.3	0.4	0.5
Forest UR and YFMS							0.0	0.3	0.4
Forest OFSS								0.0	0.3
Forest OFMS									0.0

[a] For FRAGSTATS, see McGarigal and Marks (1995).

[b] Forest structural classes are stand intiation (SI); stem exclusion open canopy (SEOC); stem exclusion closed canopy (SECC); understory re-initiation (UR); young forest multi-story (YFMS); old forest single story (OFSS); and old forest multi-story (OFMS). See also Fig. 8 for graphical illustrations of forest structural classes.

[c] Range of possible values is 0–1, with increasing values representing greater edge contrast.

two other tests. These enabled us to evaluate the potential ecological importance of change in patch area or connectivity, and the likelihood of error in rejecting the null hypothesis. First, we estimated a reference variation by calculating for each metric, the 75% range around the historical sample median, and then compared the current sample median value with this range. Second, we determined the largest changes in absolute area of a patch type within a sample using transition analysis. Transition analysis estimated the percentage of sampled area in each unique historical to current patch type transition.

We chose the median 75% range instead of the full range as a meaningful measure of reference variation to portray typical variation exclusive of extreme observations. Historical (and current) data distributions were frequently right-skewed, and the sample median value was the more accurate reflection of central tendency. Most observations were clustered within the median 75–80% range. We reasoned that more extreme variation usually results from either unique contexts or environments, or from rare events. By imposing the contrast between current median values and a typical range of historical conditions, we retained the ability to detect conditions resulting from management activities, chance events, or perhaps climate change that were unique in some aspect.

3. Results

3.1. Trends in physiognomic conditions

Significant changes in physiognomies occurred throughout the basin. Forest cover increased significantly in the Blue Mountains, Columbia Plateau, and Upper Snake ERUs (Fig. 2, Table 3) where our results suggested that effective fire prevention, suppression, and exclusion resulted in expansion of forests into areas that were previously bare ground or shrubland, or into former herbland areas previously maintained by fire or created by early logging. Connectivity (spatial aggregation) of forest increased in the Central Idaho Mountains and Upper Snake ERUs (see Hessburg et al., 1999a). Increased connectivity of forests was the result of expansion of forest cover types on former shrubland areas (Table 3). The Central Idaho Mountains contains large wild and roadless areas. Transition analysis of cover type changes indicated that increased connectivity result from effective fire suppression and fire exclusion. We note that in a few subwatersheds increased forest connectivity was associated with large scale stand replacement fires.

Area and connectivity of forest cover declined in the Upper Klamath ERU (Fig. 2). Upper Klamath forests

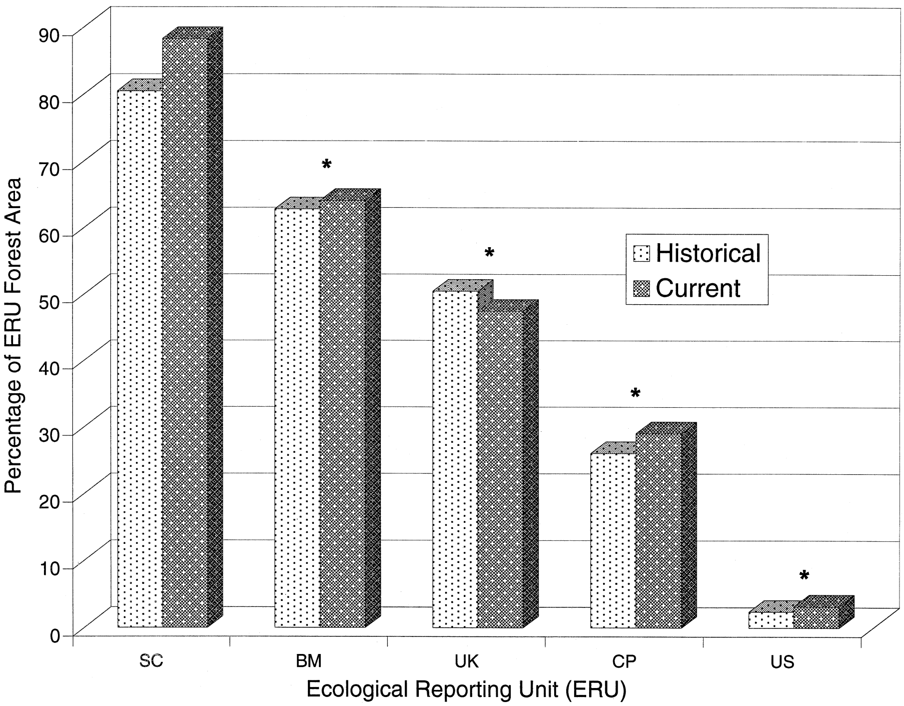

Fig. 2. Change in percentage of area in the forest physiognomy for selected ERUs. ERU abbreviations are: SC, Southern Cascades; BM, Blue Mountains; UK, Upper Klamath; CP, Columbia Plateau; US, Upper Snake. Asterisk (*) denotes significant difference at $p \leq 0.2$.

are naturally quite fragmented; forested slopes are often separated by broad grassy valley bottoms or grasslands on dry southerly aspects. Physiognomic and cover type transition analysis and trends in patch density and mean patch size indicated that timber harvest and juniper woodland expansion into the ponderosa pine cover type were partially responsible for the observed reduction; we suspect that domestic livestock grazing was involved as well. Fig. 3 illustrates altered physiognomic conditions in sampled subwatersheds of the Blue Mountains (Fig. 3A) and Upper Klamath (Fig. 3B) ERUs.

Woodland (sparsely wooded rangeland) area increased in 7 of 13 ERUs and declined in none (Fig. 4). Transition analysis suggested that fire suppression, fire exclusion, and domestic livestock grazing enabled expansion at the expense of declining herblands and shrublands. The regional decline in area of shrublands was in fact the most dramatic of all changes in physiognomic conditions (Table 3, Fig. 4). Transition analyses indicated that losses of native shrublands resulted from forest and woodland expansion (Blue Mountains and Northern Great Basin ERUs), cropland expansion (Northern Great Basin ERU), and conversion to semi-native or non-native herblands (Owyhee Uplands and Snake Headwaters ERUs). Fig. 5 illustrates reduced shrubland and increased woodland area in an Upper John Day subwatershed, Blue Mountains ERU.

Conversely, herbland increased in the Central Idaho Mountains, Northern Great Basin, Owyhee Uplands, Snake Headwaters, and Southern Cascades ERUs and declined in none. In the Northern Great Basin, herbland increased at the expense of shrubland area which fell by more than 15%. Transition analysis indicated that half of the lost shrubland area is currently occupied by juniper woodland, and the balance supports montane bunchgrasses or exotic grass and forb cover. Herblands and shrublands followed a similar pattern in the Owyhee Uplands. Across the basin, most increase in herbland resulted from expanding colline (below lower treeline) exotic grass and forb cover with shrubland conversion. Here, we note that most native herblands were converted to agricultural production prior

Table 3

Historical (H) and current (C) percentage of area[a] of physiognomic types, forest cover types, and structural classes of subwatersheds sampled in Ecological Reporting Units of the mid-scale ecological assessment of the interior Columbia River basin

Patch types	Ecological reporting units																									
	Blue Mtns		Cenral Idaho Mtns.		Columbia Plateau		Lower Clark Fork		Northern Cascades		Northern Glaciated Mtns		Northern Great Basin		Owyhee Uplands		Snake Headwtr		Southern Cascades		Upper Clark Fork		Upper Klamath		Upper Snake	
	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C
Physiognomic types																										
Forest	**62.8**	**64.1**	73.4	73.5	**26.1**	**29.1**	91.7	94.5	78.8	78.2	81.0	80.8	7.2	7.3	0.2	0.2	74.5	73.8	80.5	88.3	87.2	86.2	**50.5**	**47.5**	**2.4**	**3.2**
Woodland	**2.7**	**4.2**	0.1	0.0	**6.7**	**12.2**	–	–	**0.3**	**0.7**	–	–	**15.3**	**22.2**	**5.5**	**7.6**	**0.2**	**0.3**	0.0	0.4	–	–	**8.4**	**12.8**	3.0	2.9
Shrubland	**14.1**	**10.7**	**19.2**	**17.1**	**32.2**	**23.4**	1.9	0.6	4.8	4.1	3.1	2.5	**72.8**	**57.6**	**88.8**	**81.0**	**16.3**	**13.9**	0.5	0.5	2.5	2.1	21.4	18.8	73.8	68.5
Herbland	17.4	18.0	**3.2**	**4.5**	12.7	14.0	5.4	3.2	6.7	6.5	7.4	8.1	**3.9**	**12.2**	**1.0**	**7.4**	**6.1**	**8.7**	**0.6**	**2.7**	5.5	5.7	10.6	9.0	10.6	9.9
Other[b]	3.0	2.9	**4.2**	**4.9**	22.4	21.4	0.9	1.8	**9.4**	**10.6**	8.5	8.5	0.8	0.8	4.5	3.8	3.0	3.3	**18.4**	**8.1**	4.8	6.0	**9.1**	**12.0**	10.3	15.4
Forest cover types																										
GF/WF[c]	**15.3**	**8.4**	9.6	10.2	1.1	0.4	40.4	42.5	**1.0**	**2.2**	0.0	1.2	–	–	–	–	–	–	5.9	6.5	0.0	0.1	7.8	8.1	–	–
ES/SAF	**6.3**	**4.4**	22.7	24.1	–	–	2.5	2.2	**16.8**	**13.6**	**11.5**	**13.2**	–	–	–	–	**24.3**	**31.4**	**0.0**	**0.2**	**14.2**	**17.3**	0.1	0.1	–	–
ASP/COT	0.1	0.1	1.1	0.8	0.3	0.3	0.1	0.7	–	–	0.3	1.9	8.4	7.7	0.2	0.2	**8.8**	**5.7**	–	–	0.3	0.3	0.0	0.1	0.9	1.0
JUN	**2.7**	**4.2**	0.1	0.0	**6.5**	**12.0**	–	–	–	–	–	–	**14.1**	**21.8**	**5.5**	**7.5**	**0.2**	**0.3**	0.0	0.4	–	–	**8.4**	**12.8**	2.6	2.5
WL	2.6	2.2	**0.5**	**0.3**	**1.0**	**0.1**	0.8	2.6	1.0	1.0	**14.8**	**11.4**	–	–	–	–	–	–	–	–	2.5	3.0	0.0	0.1	–	–
WBP/SAL	**0.0**	**0.7**	5.1	2.5	–	–	–	–	**3.3**	**4.7**	0.3	0.2	–	–	–	–	6.9	5.7	0.0	0.8	**4.3**	**3.5**	–	–	–	–
LPP	2.4	2.3	9.7	9.5	1.3	0.9	2.1	1.8	5.9	5.2	8.0	8.3	–	–	–	–	**15.6**	**11.3**	19.4	20.6	20.9	19.5	1.4	1.7	0.1	0.2
LP	–	–	0.4	0.4	–	–	–	–	–	–	–	–	–	–	–	–	**0.7**	**1.1**	–	–	0.0	0.4	–	–	–	–
PP	28.4	28.9	6.0	5.9	**19.2**	**21.4**	3.0	5.1	**16.5**	**13.2**	**13.4**	**11.4**	–	–	–	–	–	–	22.7	28.1	**12.3**	**9.5**	**26.7**	**23.5**	–	–
DF	**7.7**	**17.1**	17.6	18.5	**3.0**	**3.9**	26.1	21.1	**23.8**	**25.8**	30.3	30.2	–	–	–	–	18.2	18.6	1.5	1.7	32.7	32.5	2.1	1.2	1.4	2.1
WH/WRC	–	–	0.9	1.3	**0.4**	**2.2**	14.7	17.3	**3.0**	**2.4**	**0.7**	**2.8**	–	–	–	–	–	–	–	–	–	–	–	–	–	–
MH	–	–	**0.0**	**0.0**	–	–	**1.3**	**0.6**	1.3	1.2	0.1	0.0	–	–	–	–	–	–	30.5	29.7	0.0	0.1	4.7	4.2	–	–
SP/WWP	–	–	–	–	–	–	0.3	0.6	**0.1**	**0.3**	**1.5**	**0.0**	–	–	–	–	–	–	0.3	0.3	–	–	–	–	–	–
PSF	–	–	–	–	–	–	–	–	**6.0**	**8.3**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
OWO	–	–	–	–	–	–	–	–	**0.6**	**0.9**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SRF	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.2	0.4	–	–	7.8	8.5	–	–
PJ	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.4	0.5
Forest structural classes																										
SI[d]	**3.9**	**6.5**	**9.7**	**5.9**	2.3	2.8	**32.7**	**9.5**	9.2	10.4	**16.9**	**9.4**	–	–	–	–	6.4	7.0	9.1	9.9	**15.9**	**11.1**	1.9	3.6	**0.8**	**0.3**
SEOC	**14.3**	**9.6**	18.4	17.7	6.7	7.8	**15.7**	**9.2**	13.2	13.2	11.8	11.6	6.5	6.0	0.0	0.1	**19.1**	**15.3**	12.3	14.3	18.5	18.2	11.3	10.9	**0.4**	**1.0**
SECC	5.0	5.0	7.7	8.5	3.8	3.6	**10.3**	**17.6**	7.6	7.9	**7.2**	**12.8**	0.7	1.3	–	–	**7.9**	**4.8**	**0.5**	**4.8**	**16.7**	**21.1**	1.2	1.6	0.1	0.1
UR	**13.6**	**11.2**	**16.0**	**21.4**	3.1	3.3	**16.3**	**37.7**	17.5	19.5	**18.4**	**23.3**	–	–	0.4	1.1	13.8	12.6	10.3	8.7	15.6	14.0	5.6	8.1	2.5	1.6
YFMS	**21.3**	**29.6**	18.4	17.1	**7.3**	**10.0**	14.3	17.5	21.2	22.0	**25.5**	**22.8**	–	–	0.1	0.1	**22.0**	**30.9**	46.0	45.6	19.7	21.1	**21.1**	**16.4**	0.6	1.1
OFMS	**2.2**	**1.0**	1.4	1.2	2.3	1.3	0.2	0.5	**5.8**	**2.7**	0.5	0.4	–	–	–	–	**3.2**	**1.8**	0.7	1.4	0.6	0.4	4.3	5.5	–	–
OFSS	**2.7**	**0.9**	1.8	1.7	1.1	1.0	2.2	2.5	**4.3**	**2.4**	0.7	0.6	–	–	–	–	**2.0**	**1.3**	1.6	3.7	0.2	0.3	**7.4**	**4.8**	0.1	0.0

[a] Mean values shown in bold type are significantly different at $p \leq 0.2$.

[b] ‘Other’ includes anthropogenic cover types and other nonforest and nonrange types.

[c] Forest cover types are: grand fir/white fir (GF/WF); Engelmann spruce/subalpine fir (ES/SAF); aspen/cottonwood/willow (ASP/COT); juniper (JUN); western larch (WL); whitebark pine/subalpine larch (WBP/SAL); lodgepole pine (LPP); limber pine (LP); ponderosa pine (PP); Douglas-fir (DF); western hemlock/western redcedar (WH/WRC); mountain hemlock (MH); sugar pine/western white pine (SP/WWP); Pacific silver fir (PSF); Oregon white oak (OWO); Shasta red fir (SRF); and pinyon/juniper (PJ).

[d] Forest structural classes are stand intiation (SI); stem exclusion open canopy (SEOC); stem exclusion closed canopy (SECC); understory reinitiation (UR); young forest multi-story (YFMS); old forest single story (OFSS); and old forest mult-story (OFMS).

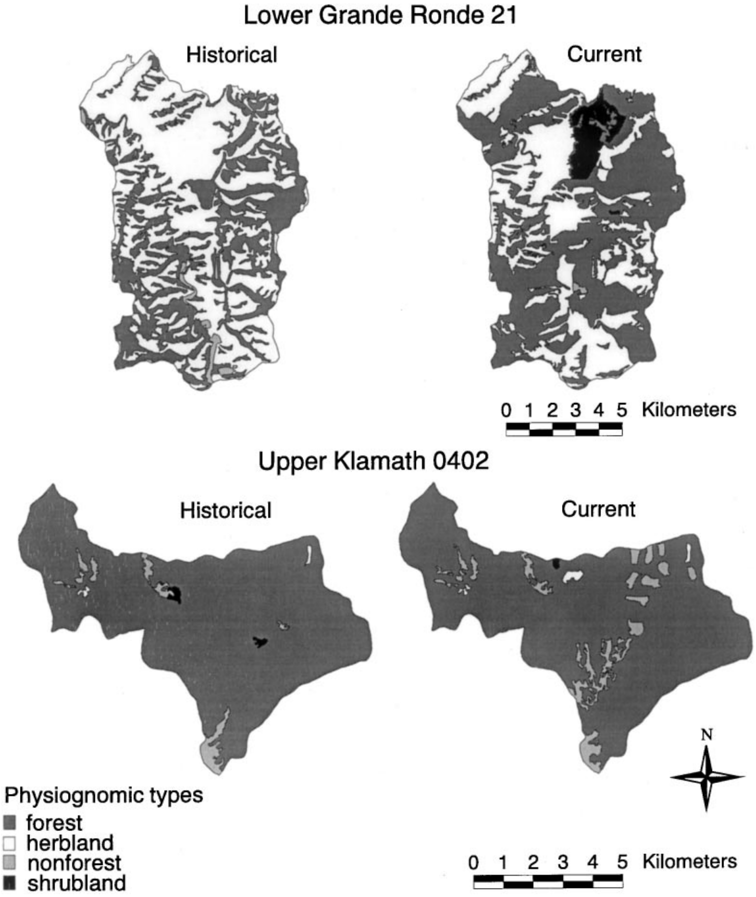

Fig. 3. Historical and current spatial patterns of physiognomic conditions: (A) subwatershed 21, Lower Grande subbasin, Blue Mountains ERU; (B) subwatershed 0402, Upper Klamath subbasin, Upper Klamath ERU.

to our historical condition. We describe changes to what are essentially relict herblands.

3.2. Forest cover type trends

Shifts from early to late seral cover species were evident in most ERUs (Table 3), but most pronounced shifts occurred in the Northern Glaciated Mountains (Fig. 6). In some ERUs, the shift was partially masked by steep climatic gradients. For example, in the Northern Cascades ERU, Douglas-fir is early seral in several mid to upper montane series (e.g., western hemlock, western redcedar), but to the east at lower elevations is climax in the Douglas-fir series. Western larch cover declined significantly in the Central Idaho Mountains, Columbia Plateau, and Northern Glaciated Mountains, and ponderosa pine cover decreased in the Northern Cascades, Northern Glaciated Mountains, Upper Clark Fork, and Upper Klamath. Ponderosa pine cover increase in the Southern Cascades resulted from regrowth of forests that were tractor-logged prior to our historical photo coverage. Lodgepole pine cover declined in the Snake Headwaters, and in six other ERUs. Western white pine cover decreased in the Northern Glaciated Mountains as a consequence of white pine blister rust, mountain pine beetle mortality, and selective harvesting, and increased slightly in the Northern Cascades as a result of recent reforestation efforts. Whitebark pine-subalpine larch cover declined in the Central Idaho Mountains, Northern Glaciated

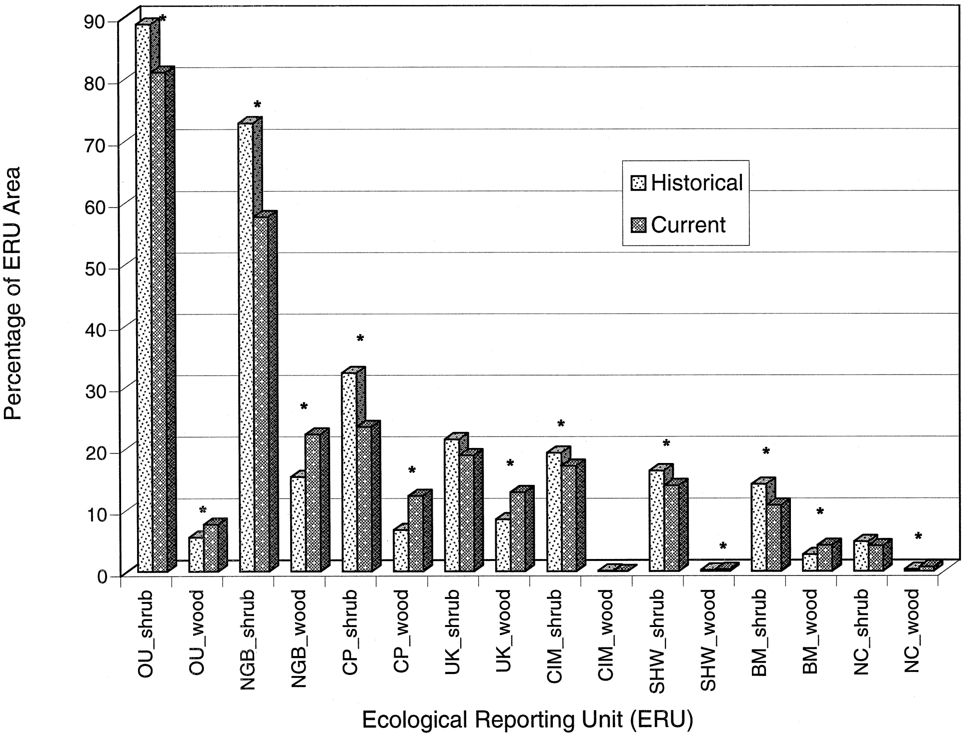

Fig. 4. Change in percentage of area in the shrubland (shrub) and woodland (wood) physiognomies for selected ERUs. ERU abbreviations are: OU, Owyhee Uplands; NGB, Northern Great Basin; CP, Columbia Plateau; UK, Upper Klamath; CIM, Central Idaho Mountains; SHW, Snake Headwaters; BM, Blue Mountains; NC, Northern Cascades. Asterisk (*) denotes significant difference at $p \leq 0.2$.

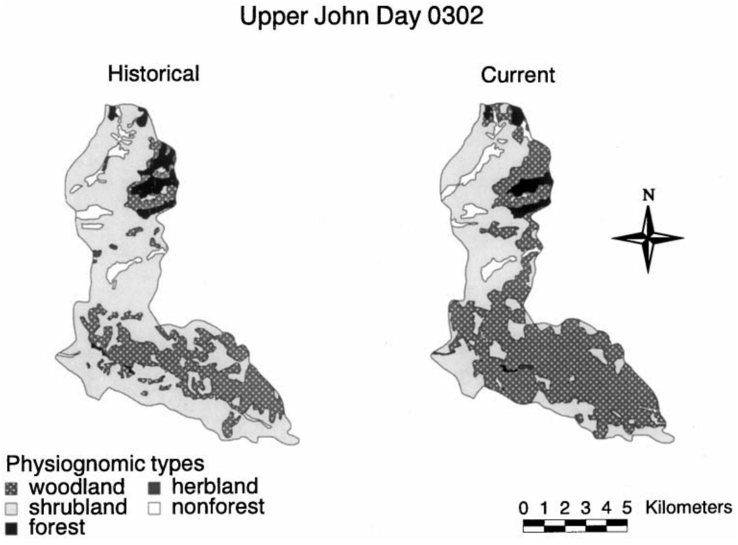

Fig. 5. Historical and current spatial patterns of physiognomic types in sampled subwatershed 0302, Upper John Day subbasin, Blue Mountains ERU.

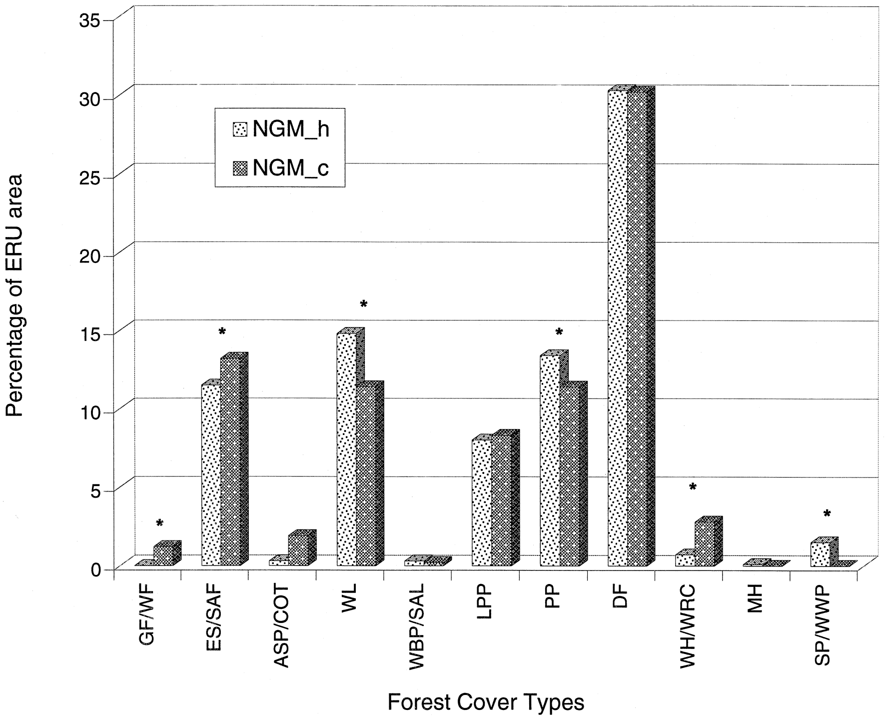

Fig. 6. Change in percentage of area in forest cover types of the Northern Glaciated Mountains ERU. Historical and current conditions are indicated by '_h' and '_c', respectively. Asterisk (*) denotes significant difference at $p \leq 0.2$.

Mountains, Snake Headwaters, and Upper Clark Fork ERUs and increased in the Blue Mountains and Northern Cascades. Decline in whitebark pine-subalpine larch cover resulted from ongoing blister rust and mountain pine beetle mortality, and expanded area of subalpine fir and Engelmann spruce.

In contrast, Douglas-fir cover increased in the Blue Mountains, Columbia Plateau, and Northern Cascades; grand fir cover increased in the Northern Cascades and Northern Glaciated Mountains; Pacific silver fir cover increased in the Northern Cascades; Engelmann spruce–subalpine fir cover increased in the Northern Glaciated Mountains, Snake Headwaters, Southern Cascades, and Upper Clark Fork; and western hemlock-western redcedar cover increased in the Columbia Plateau, and Northern Glaciated Mountains (Table 3). Engelmann spruce–subalpine fir cover declined in the Blue Mountains, and Engelmann spruce–subalpine fir and western hemlock–western redcedar cover both decreased in the Northern Cascades. Results of transition analysis suggested that noted increases in shade-tolerant cover types were best explained by fire suppression and exclusion, and selective timber harvest activities.

Added to expanded area of late seral species, average patch sizes of most forest cover species are smaller and current land cover is more fragmented (Fig. 7A and B). In the historical condition, spatial patterns of biophysical environments and disturbance regimes created patches of land cover that were large, and overall patterns were relatively simple. In the current condition, simple patterns have been replaced by highly fragmented landscape cover mosaics. In some heavily-roaded subwatersheds (Fig. 7A), patch density and mean patch size analysis, and transition analysis indicated that widely applied patterns of small cutting units are responsible for the change. In other roadless subwatersheds, fine to mid-scale disturbance processes are responsible for reduced connectivity of land cover. For example, subwatershed 55 of the Methow subbasin (Fig. 7B) resides in the Pasayten Wilderness. Prior to the era of fire suppres-

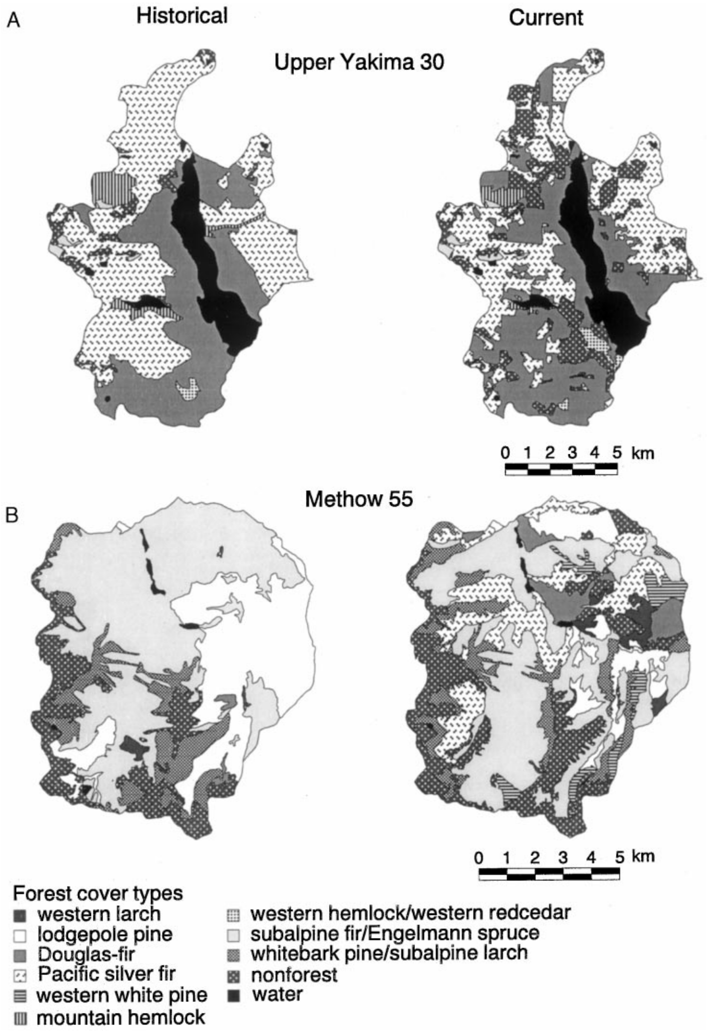

Fig. 7. Historical and current forest cover type area of (A) subwatershed 30, Upper Yakima subbasin; (B) subwatershed 55, Methow subbasin, North Cascades ERU.

sion (pre-1930s), large scale stand replacement fires would naturally occur on an infrequent basis resulting in simple landscape cover mosaics consisting of a relatively few large patches. Today, the Methow subwatershed exhibits reduced connectivity of land cover, and causative factors were small fires and bark beetle outbreaks.

In Section 3.3, we discuss changes among forest structural classes. Here, it will be important to keep in mind the scale dependence of observations. Immediately above, we reported that landscape cover mosaics exhibited increased pattern complexity in the current condition. Below, we show that patterns of structural classes have changed in a different way.

3.3. Trends among structural classes

In general, the vertical structure of individual forest patches has become more complex, but the landscape pattern of structural conditions is generally simpler when compared with historical forests. Landscape area in old forest structures (multi-story and single

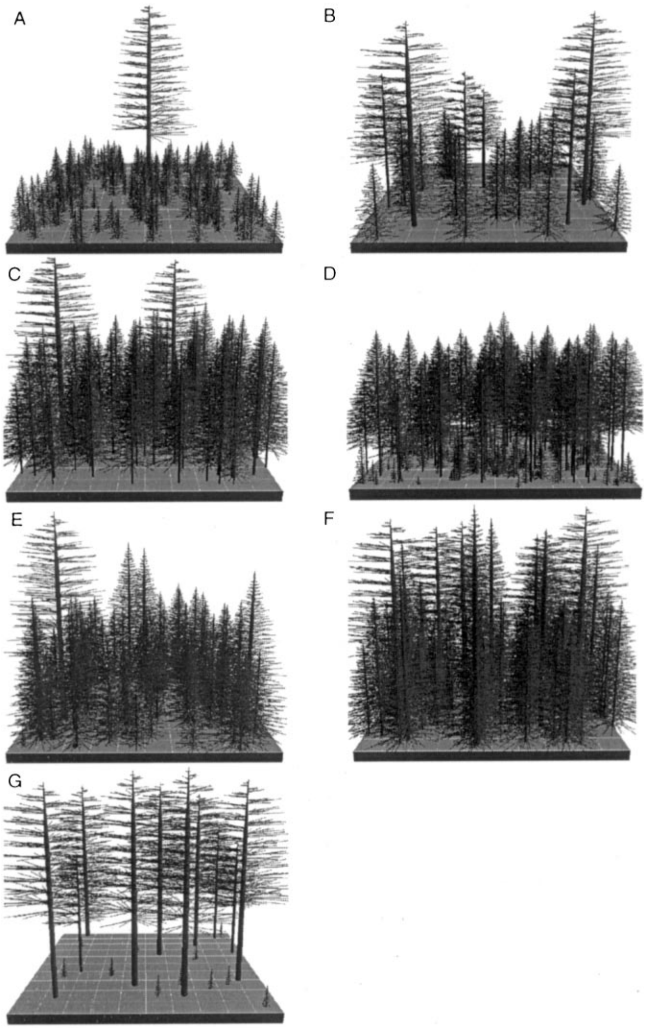

Fig. 8. Graphical representation of forest structural classes used in the mid-scale assessment of the interior Columbia River basin; (A) stand initiation, (B) open stem exclusion, (C) closed stem exclusion, (D) understory reinitiation, (E) young multi-story forest, (F) old multi-story forest, (G) old single story forest. Refer to Oliver and Larson (1996) and O'Hara et al. (1996) for expanded descriptions of forest structural classes.

story) declined in most forested ERUs (Fig. 8) , but the most significant declines occurred in the Blue Mountains, Northern Cascades, Snake Headwaters, and Upper Klamath ERUs (Fig. 9, Table 3). Landscape area in stand initiation structures (new forest) declined in five of nine forest-dominated ERUs and increased in one, the Blue Mountains. Area in stand-initiation structures declined in the Central Idaho Mountains, Lower Clark Fork, Northern Glaciated Mountains, Upper Clark Fork, and Upper Snake ERUs (Fig. 10). This stands to reason because stand replacement and mixed severity fires were historically dominant in these ERUs across space and time.

Area and connectivity of intermediate (not new and not old forest) structural classes (stem exclusion, understory reinitiation, and young multistory) increased in most forested ERUs. This change toward landscape dominance by intermediate forest structures was the general mechanism of pattern simplification. When viewed simplistically, there is currently less

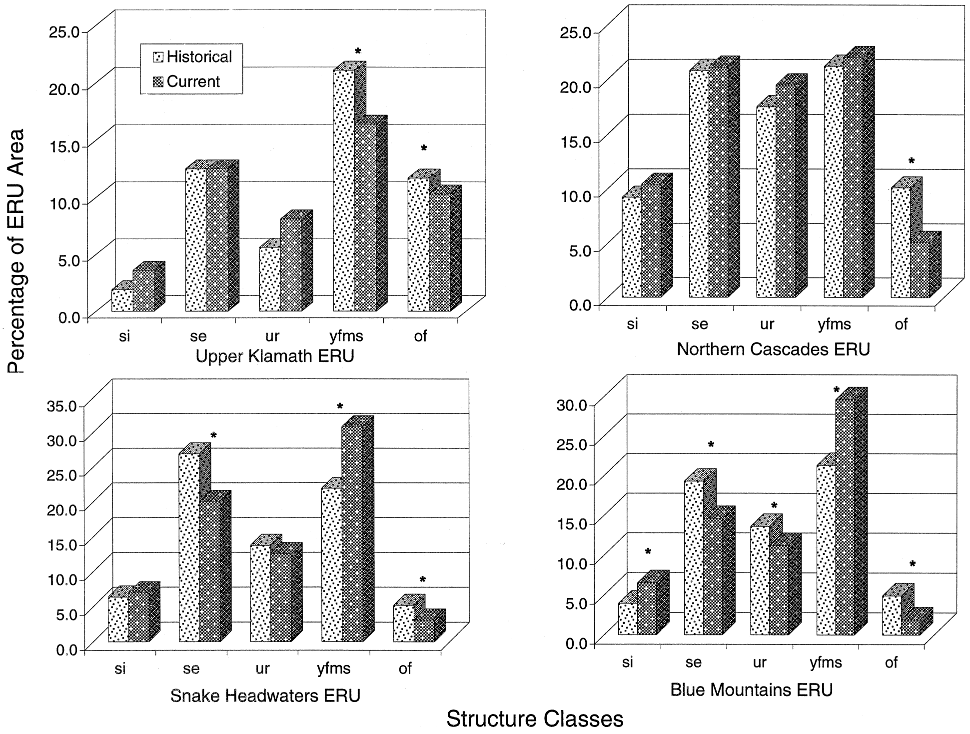

Fig. 9. Change in percentage of area in of old forest and other structures for selected ERUs. Structural class abbreviations are: SI, stand initiation, SE, stem exclusion (both open and closed canopy conditions), UR, understory reinitiation, YFMS, young multi-story forest, OF, old multi-story and single story forest. Asterisk (*) denotes significant difference at $p \leq 0.2$.

area in stand initiation and old forest structures, and considerably more area and improved connectivity of intermediate forest structures. The most notable increases in intermediate structures occurred in the Blue Mountains, Central Idaho Mountains, Columbia Plateau, Lower Clark Fork, Northern Glaciated Mountains, Snake Headwaters, Southern Cascades, and Upper Clark Fork ERUs. Area in intermediate structural classes actually declined in the Upper Klamath ERU, where transition analysis implicated extensive past harvesting.

3.4. Other structural changes

Four additional findings related to forest structural change are worthy of brief mention: (1) In the historical condition, large (>63.5 cm DBH) and medium (40.5–63.5 cm DBH) trees were once more widely distributed in structures other than old forest as a conspicuous remnant after stand-replacing wildfires. Change analysis indicated that patches with medium and large trees were targeted for timber harvest, regardless of their structural affiliation. (2) Along with other raw attributes interpreted from aerial photos, we estimated dead tree and snag abundance in each forest patch as: none, <10% , 10–39%, 40–70%, and >70% of trees dead or as snags. Change analysis with these data indicated that dead tree and snag abundance increased significantly in most forested ERUs, but primarily in the pole and small tree (12.7–40.4 cm DBH) size classes, because the medium and large trees were depleted by timber harvest. (3) Current forest patches have more canopy layers than were displayed in the historical condition, and understory layers are typically comprised of late seral species. (4) In the historical condition, forest understories were often absent or comprised of shrub and herbaceous species. Current forest understories are less often grass or

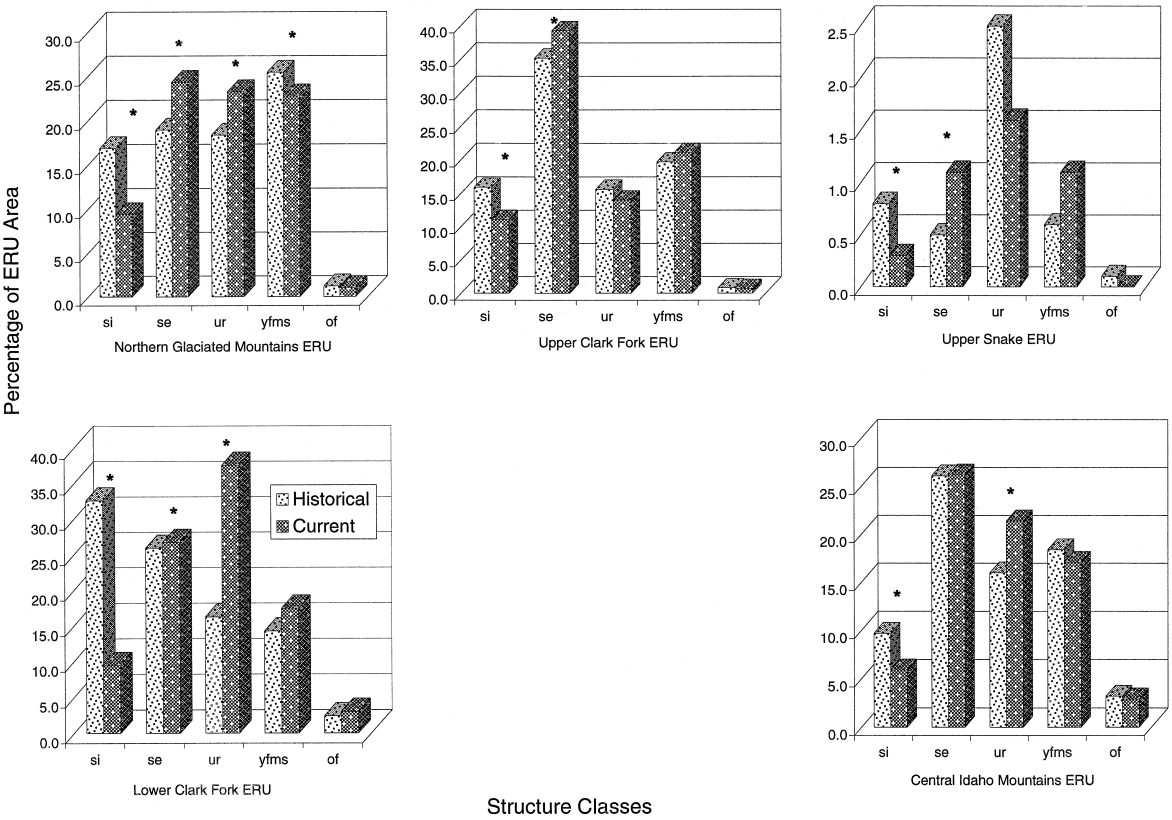

Fig. 10. Change in percentage of area in stand initiation and other forest structures for selected ERUs. Structural class abbreviations are: SI, stand initiation, SE, stem exclusion (both open and closed canopy conditions), UR, understory reinitiation, YFMS, young multi-story forest, OF, old multi-story and single story forest. Asterisk (*) denotes significant difference at $p \leq 0.2$.

shrub and mostly coniferous. With livestock grazing and the elimination of surface fires, multi-layered conifer understories developed.

3.5. Landscape spatial patterns

We conducted change analysis with cover type-structural class couplets as patch types. In the sections that follow, we discuss changes occurring across all ERUs for a given subset of metrics (Table 1).

3.5.1. Richness, diversity, and evenness

Patch richness (PR), Shannon's (1949) diversity index (SHDI), and the inverse of Simpson's λ (N2, Hill, 1973) provide different views of the diversity of patch types of a landscape. While richness tallies the number of patch types present regardless of their abundance, the SHDI and N2 indices incorporate abundance into the measurement of diversity, but N2 responds to change in the abundance of dominant patch types. Relative patch richness (RPR) relates PR to the total number of patch types (192) present in the basin. The SHDI (or its transformed equivalent N1, Hill, 1973) is intermediate in responsiveness to abundance changes between RPR and N2.

In general, for the five measures of richness and diversity (RPR and PR, SHDI and N1, and N2), all ERUs displayed a positive mean difference with two notable exceptions (Table 4): the Lower Clark Fork and Upper Klamath ERUs exhibited minor declines in PR. Using transition analysis, we attributed these declines to a history of widespread timber harvest activity. Five of 13 ERUs displayed change in PR generally on the order of a 15–30% increase, while 8 of the 13 ERUs reflected both increased dominance and diversity (N2). The PR values and transition

Table 4
Landscape metric results for 13 ecological reporting units in the mid-scale assessment of the interior Columbia River basin where patch types were cover type-structural class doublets

Landscape metrics	Ecological reporting units												
	Blue Mountains	Central Idaho Mountains	Columbia Plateau	Lower Clark Fork	Northern Cascades	Northern glaciated mountains	Northern Great Basin	Owyhee Uplands	Snake Headwaters	Southern Cascades	Upper Clark Fork	Upper Klamath	Upper Snake
Richness and diversity													
RPR_h[a,b]	11.4	11.3	7.8	15.8	13.9	11.6	4.8	2.9	11.8	7.7	11.6	9.6	5.1
RPR_c	12.1	12.5	8.2	15.5	16.0	14.3	5.3	2.9	11.9	10.6	13.5	9.5	5.2
RPR_md	0.7	1.2*	0.3	−0.3	2.0*	2.7*	0.5	0.0	0.1	3.0*	1.9*	−0.1	0.1
PR_h	22.8	22.3	15.2	30.6	27.0	22.6	9.3	5.6	22.9	14.9	22.5	18.6	9.8
PR_c	23.5	24.7	15.8	30.0	31.0	27.9	10.3	5.6	23.0	20.6	26.1	18.5	10.1
PR_md	0.7	2.4*	0.6	−0.6	4.0*	5.3*	1.0	0.0	0.0	5.8*	3.7*	−0.1	0.3
SHDI_h	2.1	2.2	1.5	2.5	2.5	2.2	1.3	0.4	2.3	1.7	2.4	1.8	1.0
SHDI_c	2.2	2.3	1.5	2.6	2.6	2.4	1.5	0.5	2.4	2.1	2.5	1.9	1.1
SHDI_md	0.0	0.1*	0.0	0.1	0.1*	0.2*	0.3*	0.1*	0.1*	0.3*	0.1*	0.0	0.0
N1_h	10.0	10.1	5.2	12.9	13.3	10.3	3.6	1.7	10.7	6.0	11.7	7.4	3.4
N1_c	9.9	10.6	5.5	14.5	15.1	12.7	4.6	2.0	11.6	9.2	12.3	8.2	3.4
N1_md	−0.1	0.4*	0.2	1.6*	1.8*	2.3*	1.1*	0.3*	0.9*	3.1*	0.6	0.8	0.0
N2_h	6.8	7.0	3.8	8.2	9.4	7.2	2.6	1.4	7.7	4.5	8.6	5.2	2.4
N2_c	6.8	7.1	3.8	10.2	10.6	8.9	3.5	1.6	8.5	6.8	8.7	6.1	2.5
N2_md	0.0	0.1	0.1	2.0*	1.3*	1.6*	0.9*	0.2*	0.8*	2.3*	0.0	0.8*	0.0
Evenness													
MSIEI_h[c]	0.58	0.60	0.46	0.61	0.66	0.61	0.44	0.15	0.62	0.55	0.67	0.51	0.34
MSIEI_c	0.58	0.58	0.46	0.67	0.68	0.63	0.54	0.20	0.65	0.60	0.65	0.54	0.35
MSIEI_md	0.00	−0.01	0.00	0.06*	0.01*	0.02	0.11*	0.05*	0.03*	0.04	−0.03*	0.04	0.00
R21_h	0.64	0.64	0.63	0.62	0.67	0.65	0.65	0.44	0.66	0.69	0.71	0.62	0.61
R21_c	0.64	0.62	0.61	0.69	0.68	0.66	0.68	0.46	0.68	0.68	0.67	0.66	0.59
R21_md	0.00	−0.02*	−0.01	0.07*	0.01	0.00	0.03*	0.01	0.02	−0.01	−0.04*	0.04*	−0.02
Contagion and interspersion													
CONTAG_h	58.2	57.3	66.3	56.6	55.8	58.1	65.8	86.1	56.2	63.3	55.1	63.3	73.3
CONTAG_c	57.9	57.6	65.8	54.2	54.9	56.4	60.6	74.0	54.8	59.7	55.8	62.1	73.6
CONTAG_md	−0.3	0.3	−0.5	−2.4*	−0.9*	−1.7*	−5.2*	−12.1*	−1.4*	−3.6*	0.7	−1.2	0.3

Table 4 (*Continued*)

Landscape metrics	Ecological reporting units												
	Blue Mountains	Central Idaho Mountains	Columbia Plateau	Lower Clark Fork	Northern Cascades	Northern glaciated mountains	Northern Great Basin	Owyhee Uplands	Snake Headwaters	Southern Cascades	Upper Clark Fork	Upper Klamath	Upper Snake
IJI_h	65.9	67.6	60.2	69.0	68.8	67.6	56.0	42.6	70.1	64.0	70.6	61.5	47.1
IJI_c	65.2	67.1	58.8	71.7	69.7	68.2	56.5	52.4	71.1	65.1	68.7	63.0	56.7
IJI_md	−0.7	−0.6	−1.4	2.7	1.0*	0.6	0.6	9.8*	1.0	1.0	−1.9*	1.5	9.6*
Edge contrast													
AWMECI_h	37.8	37.3	28.0	33.5	38.8	35.5	24.7	10.5	41.1	37.3	34.7	33.9	17.3
AWMECI_c	38.5	38.3	29.0	38.6	39.1	37.7	24.8	11.4	41.2	40.4	35.3	33.6	18.9
AWMECI_md	0.7	1.1*	1.0	5.1*	0.3	2.2*	0.1	0.9*	0.1	3.1*	0.6	−0.3	1.6*

[a] RPR values represent percentage of relative patch richness where the observed number of patch types (cover type-structural classes) in an ERU is scaled against a realistic maximum number of patch types possible across the entire basin assessment area. PR values simply represent the total number of patch types present within an ERU. N1 is a transformation of SHDI; rare patch types are weighted less than in PR. N2 also counts numbers of patch types like RPR, but N2 gives dominant patch types increased weight and can be considered a count of the average number of dominant patch types in an ERU. With N2, rare patch types are weighted less than in N1.

[b] Suffix h, average historical value among subwatersheds of an ERU; c, average current value among subwatersheds of an ERU; and md, mean difference of pairwise comparisons of sampled subwatersheds within an ERU. RPR, telative patch richness; PR, patch richness; SHDI, Shannon–Weaver diversity index; $N1 =$ Hill's index $N1 = e^{SHDI}$; $N2 =$ Hill's index $N2 = 1/(1/SIDI)$; MSIEI, modified Simpson's evenness index; $R21 =$ Alatalo's evenness index $= (N2 - 1)/(N1 - 1)$; CONTAG, contagion index; IJI, interspersion and juxtaposition index; AWMECI, area-weighted mean edge contrast index (see also Table 1, and McGarigal and Marks, 1995).

[*] Indicates statistical significance at $p \leq 0.2$.

[c] MSIEI is more sensitive to change in abundance among all patch types, whereas R21 is more sensitive to change in abundance of the dominant patch types. Increases indicate that area distributed among patch types is increasingly even. Declines indicate that some patch types are more abundant than others within an ERU. Significant figures are computed to two decimal places.

analysis indicated that cover-structure patch types not only increased in number, but new patch types occupied considerable landscape area. The ERUs displaying increased dominance and diversity are shown in Table 4.

Evenness measures assess how equitably area is distributed among patch types. Both evenness measures (MSIEI and R21) index change in the distribution of area among patch types. Many ERUs displayed increased diversity, richness, and dominance during the sample period for the diversity measures we used. Such increase typically results in a modest increase in the values of the evenness measures, if any change occurs. Our results confirmed this relation; the MSIEI and R21 indices increased in six of eight ERUs displaying increased diversity and dominance. The Upper Clark Fork and the Central Idaho Mountains were the only two ERUs to decline in evenness; the Upper Clark Fork declined in both evenness measures (Table 4). To explain changes in evenness, it is helpful to re-examine changes in the area relations of cover types and structural classes. In the Central Idaho Mountains, few cover type changes were significant, but distribution of area in forest structural classes became increasingly uneven (Table 3, Fig. 10). Area in stand-initiation structures declined from 9.7 to 5.9% of the ERU, and area in understory reinitiation structures increased from an average of 16–21.4% of the ERU. A similar pattern of change was evident in the Upper Clark Fork; few cover type changes were evident, but distribution of area in stand initiation, closed canopy stem-exclusion, and young multistory forest structures became increasingly uneven (Table 3).

Landscape metrics were averaged across sampled subwatersheds, hence, values for all metrics in the historical and current condition reflect the average per subwatershed. But an examination of data in Table 4 prompts two additional questions: (1) What is the total richness and diversity of patch types of each ERU, and (2) Have total richness and diversity values for the ERU changed during the sample period? Heltshe and Forrester (1983) describe a 'jackknife' estimator for richness that attempts to estimate total richness for a geographic area of interest. We applied this technique and a related estimator for N2 (Burnham and Overton, 1979) to the historical and current data to estimate difference in total richness and dominance for each ERU (Table 5). The jackknife technique results in estimates of the total and standard error. We used these

Table 5
Jackknife estimates of total patch-type richness and dominance (N2) for 13 ecological reporting units in the mid-scale assessment of the interior Columbia River basin where patch types were cover type-structural class doublets

Ecological reporting unit	Sampled watersheds (number)	Richness		Dominance (N2)	
		Historical (s.e.)[a]	Current (s.e.)[a]	Historical (s.e.)[b]	Current (s.e.)
Blue Mountains	44	114 (6.0)	123 (4.3)	23 (3.5)	20 (2.4)
Central Idaho Mountains	43	142 (6.4)	135 (5.7)	32 (2.9)	29 (2.7)
Columbia Plateau	38	121 (7.7)	119 (5.5)	10 (1.7)	11 (1.7)
Lower Clark Fork	5	88 (9.5)	73 (2.9)	19 (1.6)	17 (1.8)
Northern Cascade Mountains	47	135 (5.1)	133 (3.8)	36 (4.5)	36 (3.8)
Northern Glaciated Mountains	41	127 (5.1)	136 (5.4)	25 (2.4)	26 (2.7)
Northern Great Basin	4	22 (2.6)	29 (3.6)	4 (0.4)	5 (0.6)
Owyhee Uplands	22	40 (6.0)	41 (4.1)	1 (0.2)	2 (0.3)*
Snake Headwaters	15	83 (5.4)	92 (5.9)	30 (3.2)	26 (3.1)
Southern Cascades	16	69 (5.7)	80 (8.1)	15 (1.3)	15 (2.6)
Upper Clark Fork	32	113 (5.8)	120 (4.9)	25 (1.9)	23 (2.2)
Upper Klamath	13	107 (7.0)	100 (5.7)	13 (3.9)	16 (3.0)
Upper Snake	15	67 (8.3)	71 (6.5)	3 (0.4)	3 (0.9)

[a] Estimates of total richness and standard error (s.e.) were computed by using the methods of Heltshe and Forrester (1983). Estimates for total richness were rounded to the nearest integer.

[b] Estimates of total dominance (N2) and its standard error were computed by using the methods of Burnham and Overton (1979). Estimates for total dominance were rounded to the nearest integer.

* Indicates significant difference at $p \leq 0.2$.

statistics in simple two-way *t*-tests to evaluate significant change in total richness or dominance. All changes but one were insignificant, but eight ERUs displayed nonsignificant increase in richness. Jackknife estimates of richness are sensitive to differences in sample size and distribution. It is best in this instance, not to make comparisons among ERUs, but comparisons between current and historical values are appropriate. Jackknife estimates for N2 are not restricted in this way. The N2 values across ERUs range from a low of 1 in the Owyhee Uplands to 36 in the Northern Cascades. We expect forest-dominated ERUs to display much larger values of total dominance than rangeland-dominated ERUs because of their greater patch richness and diversity.

3.5.2. Contagion and interspersion

Contagion (CONTAG) and interspersion–juxtaposition (IJI) metrics quantify the extent to which pixels of differing type intermix; IJI considers length of edge between contrasting patch types, and CONTAG estimates patch dispersion and interspersion for raster maps. Seven of 13 ERUs displayed significant declines in CONTAG, and all significant mean differences values were negative (Table 4). A negative mean difference value of CONTAG indicated that across a given ERU, patches became smaller and more dispersed. Three of six ERUs with nonsignificant mean difference values of CONTAG also exhibited a negative sign. These results suggest a basinwide decrease in contagion of cover-structure patch types. With the exception of the Northern Great Basin and Owyhee Uplands ERUs, the magnitude of decrease was small relative to initial average historical values.

Only 4 of 13 ERUs displayed significant mean difference values for IJI; two were positive and two were negative (Table 4). The Owyhee Uplands and Upper Snake ERUs were noteworthy because the magnitude of the mean IJI difference for these two ERUs was especially large. Unlike CONTAG, there was no consistent pattern across ERUs for this metric, and most changes were small. We conclude that interspersion changes as measured by this metric are minimal at this scale, but that changes in interspersion and juxtaposition may be better observed at smaller pooling scales where environmental variation is controlled.

3.5.3. Edge contrast

The area-weighted mean edge contrast index (AWMECI) uses a set of user-defined values ranging from 0 to 1 to represent relative edge contrast (Table 2) between patch types, weighted by area, to evaluate change in edge contrast of a sample of landscapes. We based edge contrast weights on physiognomic and structural conditions in deference to edge-sensitive and edge-dependent terrestrial species, and their sensitivity to structural differences of edges. An increase in area-weighted mean edge contrast was indicated as the percentage of the total edge that was the equivalent of maximum contrast edge. The greater the difference in structure or physiognomic condition (e.g., an old single-story forest patch adjacent to herbland), the greater the edge contrast weight. Significant increase in AWMECI for a sample of landscapes indicated that greater contrast in structural and physiognomic condition was occurring at patch edges. Six of 13 ERUs displayed such an increase. Most increases were relatively modest except in the Lower Clark Fork where increase in maximum contrast edge averaged 5.1% of the total edge (Table 4).

3.6. Landscape vulnerability to disturbances

3.6.1. Insects and pathogens

Our analysis indicated that forest landscapes have changed significantly in their vulnerability to major insect and pathogen disturbances. Absent frequent fires, and influenced by selective harvesting and domestic livestock grazing, overstory and understory Douglas-fir cover and that of most other shade-tolerant species expanded, forest structures became more layered, and grass and shrub understories were replaced by coniferous understories. As a consequence, insect and pathogen vulnerabilities that increase with increased dominance and spatial aggregation of shade-tolerant conifers were favored by the changes in vegetation patterns. Conversely, because patches with medium and large trees of early seral species were primarily harvested, insect and pathogen vulnerabilities favored by increasing dominance and spatial aggregation of large trees of early seral species declined. A few examples follow (see also Table 6).

In many ERUs, area vulnerable to western spruce budworm increased, but most changes were not significant at the scale of an ERU. To determine whether

Table 6

Change in area (in %) highly vulnerable to insect and pathogen disturbance in 11 forested ecological reporting units in the mid-scale assessment of the interior Columbia River basin (see also Hessburg et al., 1999b)

Disturb. agent[a]	Ecological reporting units (ERU) Blue Mountains		Central Idaho Mountains		Columbia Plateau		Lower Clark Fork		Northern Cascades		Northern Glaciated Mountains		Snake Headwaters		Southern Cascades		Upper Clark Fork		Upper Klamath		Upper Snake	
	H[b]	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C
WSB	38.2	38.9	49.4	51.1	**9.3**	**12.0**	56.8	65.0	51.5	50.4	44.5	47.9	45.0	**51.8**	**10.1**	**12.3**	59.1	55.9	14.6	15.9	**1.6**	**2.1**
DFB	**5.2**[c]	**7.8**	4.4	5.0	2.9	2.6	0.2	5.9	8.7	7.4	3.6	5.0	**2.1**	**3.9**	**1.8**	**0.1**	**8.0**	**4.8**	0.0	0.0	0.5	1.0
WPB1	2.5	2.5	1.0	1.3	4.6	2.9	0.0	0.6	**3.7**	**1.8**	1.2	0.9	**34.6**	**29.2**	5.2	5.1	**2.9**	**0.5**	5.7	4.5	–	–
WPB2	17.8	19.7	3.3	3.3	**14.9**	**17.1**	1.5	3.8	**9.8**	**8.2**	7.9	7.3	–	–	20.5	24.4	**9.9**	**8.1**	19.3	21.3	–	–
MPB1	**6.7**	**5.1**	21.0	22.1	1.8	2.4	**4.0**	**12.9**	5.3	6.8	**15.4**	**18.9**	**34.6**	**29.2**	29.0	24.9	36.1	37.6	4.7	4.3	0.6	0.3
MPB2	17.8	19.7	3.3	3.3	**14.9**	**17.1**	1.5	3.8	**9.8**	**8.2**	7.9	7.3	–	–	20.5	24.4	**9.9**	**8.1**	19.3	21.3	–	–
FE	**24.6**	**15.0**	**21.3**	**26.2**	**1.8**	**2.9**	28.3	37.0	20.4	21.5	6.8	8.4	19.3	16.1	9.0	10.2	**7.8**	**9.7**	**17.1**	**18.0**	–	–
SB	**2.6**	**0.7**	3.1	3.6	–	–	0.1	0.5	6.0	5.3	**3.0**	**4.5**	**8.3**	**7.6**	0.1	0.1	6.9	5.6	–	–	–	–
DFDM	**10.1**	**16.5**	10.7	10.5	6.9	6.4	6.0	7.9	18.6	17.9	13.1	14.3	**4.1**	**6.4**	**2.3**	**0.5**	**16.2**	**13.2**	0.8	0.2	0.6	1.5
PPDM	**10.4**	**8.1**	**2.2**	**1.8**	10.8	7.8	0.0	0.9	**5.6**	**3.9**	**3.8**	**2.5**	–	–	12.9	17.9	**5.0**	**2.3**	17.8	15.5	–	–
WLDM	1.3	0.8	0.5	0.1	0.0	0.1	0.2	0.2	0.5	0.4	**6.9**	**4.2**	–	–	–	–	**2.8**	**1.3**	–	–	–	–
LPDM	1.5	1.6	13.7	15.1	0.2	0.4	0.2	2.6	2.7	3.1	9.3	9.1	**30.8**	**20.9**	10.2	11.9	22.6	22.5	0.4	0.3	0.3	0.3
AROS	40.7	41.0	37.6	39.2	9.1	10.5	55.0	65.1	**48.6**	**45.2**	**37.3**	**40.7**	**20.4**	**31.5**	**10.9**	**12.8**	34.2	31.8	13.2	13.6	1.0	1.6
PHWE	34.5	37.0	29.3	27.8	10.4	9.7	59.4	62.0	**41.7**	**39.2**	27.8	31.0	**10.9**	**12.8**	**31.1**	**35.4**	21.6	20.8	18.5	17.7	1.0	1.6
HEAN$_s$	**24.3**	**16.9**	**36.2**	**38.9**	**0.8**	**5.4**	71.4	77.0	**29.6**	**32.2**	**20.0**	**26.8**	**22.0**	**30.6**	37.1	38.3	32.2	34.6	22.8	23.3	1.0	1.7
HEAN$_p$	11.6	10.4	**2.1**	**1.7**	11.8	11.2	0.0	0.2	**7.5**	**5.9**	3.1	4.0	–	–	**13.8**	**23.4**	**5.4**	**4.0**	19.0	19.8	–	–
TRBR	**4.4**	**2.5**	**9.3**	**11.0**	–	–	1.0	1.5	**11.4**	**9.9**	**7.1**	**9.0**	13.1	15.1	0.8	0.8	9.9	10.3	–	–	–	–
SRBR	**46.7**	**52.1**	57.1	56.2	17.2	15.4	56.2	52.3	**61.2**	**57.2**	66.9	65.8	49.9	48.6	25.6	29.4	60.6	59.0	**26.4**	**17.9**	**1.5**	**2.1**
WPBR1	–	–	0.0	0.1	**1.4**	**0.1**	0.8	3.7	**0.1**	**0.2**	**1.9**	**0.3**	–	–	0.2	0.3	2.5	1.4	0.0	0.0	–	–
WPBR2	–	–	0.7	0.6	–	–	–	–	**0.4**	**0.9**	0.0	0.0	4.0	2.0	–	–	2.9	2.4	–	–	–	–
RRSR	1.1	0.8	0.1	0.3	**0.0**	**0.1**	1.0	1.7	**0.6**	**1.1**	**0.0**	**0.2**	–	–	1.1	1.7	1.2	2.3	4.8	4.1	–	–

[a] WSB, western spruce budworm; DFB, Douglas-fir beetle; WPB1, western pine beetle — type 1 attack of mature and old ponderosa pine; WPB2, western pine beetle — type 2 attack of immature and overstocked ponderosa pine; MPB1, mountain pine beetle — type 1 attack of overstocked lodgepole pine; MPB2, mountain pine beetle — type 2 attack of immature and overstocked ponderosa pine; FE, fir engraver; SB, spruce beetle; DFDM, Douglas-fir dwarf mistletoe; PPDM, ponderosa pine dwarf mistletoe; WLDM, western larch dwarf mistletoe; LPDM, lodgepole pine dwarf mistletoe; AROS, *Armillaria* root disease; PHWE, laminated root rot; HEANs, S-group annosum root disease; HEANp, P-group annosum root disease; TRBR, tomentosus root and butt rot; SRBR, Schweintizii root and butt rot; WPBR1, white pine blister rust — type 1 on western white pine/sugar pine; WPBR2, white pine blister rust — type 2 on whitebark pine; RRSR, rust-red stringy rot. See also Hessburg et al., 1999b.

[b] H, Historical condition; C, Current condition.

[c] Values shown in bold indicate significant increase or decrease ($p \leq 0.2$) from the historical to the current condition; 'na' = not applicable.

the lack of observed significant difference was scale dependent, we summarized statistical results for budworm (and other disturbances) by smaller scale pooling strata. For example, we used 4th code watersheds called ‘subbasins’ and subregional aggregations of subwatersheds based on similar climate and environments, and we were able to detect significant change. Results of these analyses suggested that ERUs were too large, and that smaller pooling strata would be more informative. In addition, we noted that the conduciveness of conditions to widespread severe budworm defoliation increased over the sample period. This was due to the increased dominance of shade-tolerant conifers, increased abundance of multi-layered host patches, and increased spatial aggregation of host patches reflected in increased average host patch size, and in some cases increased host patch density.

Throughout the basin, area vulnerable to Douglas-fir beetle and Douglas-fir dwarf mistletoe increased because forest landscapes in the existing condition exhibited increased cover and connectivity of Douglas-fir, current stand densities are elevated from historical conditions, and patches today tend to be multi-layered, often with several layers of understory Douglas-fir. Fig. 11A provides an illustration of

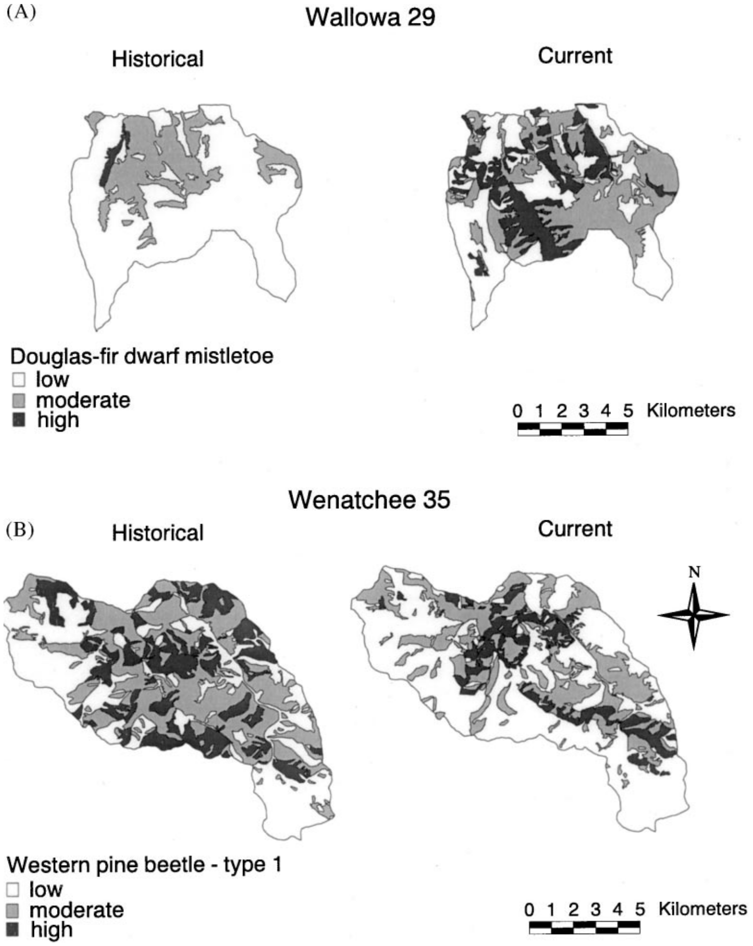

Fig. 11. Historical and current forest area: (A) vulnerable to Douglas-fir dwarf mistletoe disturbance, subwatershed 29, Wallowa subbasin, Blue Mountains ERU; (B) vulnerable to western pine beetle disturbance of medium (40.5–63.5 cm DBH) and large (>63.5 cm DBH) ponderosa pine, subwatershed 35, Wenatchee subbasin, Northern Cascades ERU.

increased forest area vulnerable to Douglas-fir dwarf mistletoe in a subwatershed of the Wallowa subbasin of the Blue Mountains ERU. Conversely, area vulnerable to western pine beetle disturbance of mature and old ponderosa pine (WPB1, Table 6) fell because medium and large ponderosa pine were selectively harvested from old forest patches and from other structures (Fig. 11B).

3.6.2. Wildfires, prescribed fires, and smoke production

Forest landscapes have been significantly altered in their vulnerability to wildfires, increasing the potential for air quality degradation, as well. In general, the risk of stand replacement fire has increased throughout the forest-dominated portion of the basin. Elevated risk is indicated by increased ground fuel loads, crown fire potential, flame length, rate of spread, fireline intensity, and smoke production (PM10), each of which are consequences of change in spatial patterns of both living and dead forest cover and structure. Changes in vegetation patterns are the result of effective fire suppression, timber harvest, and fire exclusion. Key factors responsible for fire exclusion were the widespread elimination of flashy fuels through extensive domestic livestock grazing, especially in the first half of the 20th century (Wissmar et al., 1994; Skovlin and Thomas, 1995; Hann et al., 1997, and references therein); reduced connectivity of fire-prone landscapes through placement of extensive road networks; settlement of fire-prone interior valleys and subsequent conversion to irrigated agriculture by European immigrants; and movement of American Indians, who used fire as a management tool, onto reservations (Robbins and Wolf, 1994).

A number of changes in fuel loading, PM10 smoke production (Table 7), crown fire potential, and fire behavior attributes (Table 8) were significant at the ERU scale; a few examples follow (see also Ottmar et al., 1999). In the Central Idaho Mountains, fuel loads (>45 Mg/ha), smoke production (>448 kg/ha), and flame length (>1.2 m) increased to high levels or above on more than 5% of the area. In the Lower Clark Fork ERU, fuel loads (>45 Mg/ha), PM10 smoke production (>448 kg/ha) during wildfires, and flame lengths >1.2 m during wildfires increased to moderate levels or above on approximately one-third of the ERU area. Crown fire potential increased to high levels or above on 29% of the ERU area. At present, 82% of the area of the Lower Clark Fork ERU exhibits moderate to severe crown fire potential. In the event of a wildfire today, it would be difficult to suppress expected flames on 94% of the current forest and rangeland area. At present, over 81% of the ERU would exhibit very low smoke production if prescribed fires were implemented in place of wildfires for fuels reduction. Under a wildfire burn scenario only 14% of the ERU area would exhibit very low smoke production.

Finally, in the Southern Cascades fuel loads (>45 Mg/ha) increased on nearly 5% of the ERU area, rate of spread (>2.4 m/min) during wildfires increased on more than 11% of the area, and extreme fireline intensity (>3459.2 kW/m) increased on nearly 8% of the area. At present, 56% of the ERU area exhibits moderate to extreme crown fire potential, and 82% of the forest and rangeland area would experience flame lengths in excess of 1.2 m during wildfires. In the event of a wildfire, it would be difficult to suppress flames on 8 of every 10 ha. At present, over 75% of the ERU would exhibit very low smoke production if prescribed fires were implemented in place of wildfires for fuels reduction. Under a wildfire burn scenario, 21% of the ERU area would exhibit very low smoke production.

4. Discussion

The primary utility of landscape assessment is in understanding the characteristics of ecosystems that we manage (Morgan et al., 1994). Knowledge of landscape pattern change at regional and subregional scales provides critical context for forest-level planning, watershed analysis and project-level planning, and valuable insight for ecosystem restoration, conservation, and monitoring decisions. Landscape change analysis provides an empirical basis to evaluate the historical and current rarity of landscape pattern features and aids in determining how representative current patterns are compared with recent historical conditions.

The basin assessment area is large, and we summarized many changes in vegetation condition and associated vulnerability to disturbance. Here we focus on the most important generalities lest we lose them.

Table 7

Historical and current percentage of area of fuel loading, fuel consumption, and PM10 smoke production attributes of subwatersheds sampled in Ecological Reporting Units of the mid-scale ecological assessment of the interior Columbia River basin

Attributes	Ecological reporting unt																									
	Blue Mtns		Cenral Idaho Mtns.		Columbia Plateau		Lower Clark Fork		Northern Cascades		Northern Glaciated Mtns		Northern Great Basin		Owyhee Uplands		Snake Headwtr		Southern Cascades		Upper Clark Fork		Upper Klamath		Upper Snake	
	H[a]	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C
Fuel loading																										
Very low	37.5	36.4	29.0	28.3	**74.2**	**70.8**	5.8	4.8	**23.4**	**21.7**	**21.0**	**19.4**	91.6	92.3	99.8	99.8	28.9	29.6	**22.9**	**12.8**	**19.5**	**15.6**	**51.7**	**54.9**	96.8	96.6
Low	**19.3**[b]	**16.4**	**31.5**	**26.0**	**8.9**	10.1	**46.5**	**17.3**	**22.6**	**26.3**	**28.2**	**23.3**	8.5	7.7	0.3	0.2	**37.6**	**28.2**	**17.5**	**23.4**	35.1	37.4	12.3	11.4	2.1	1.7
Moderate	12.0	13.0	8.1	8.6	8.0	10.0	9.4	14.6	10.4	10.7	**7.8**	**15.1**	–	–	–	–	11.4	12.0	**21.4**	**29.5**	16.6	17.6	3.6	7.2	0.1	0.2
High	**22.2**	**26.3**	**16.4**	**18.1**	6.4	5.8	20.4	44.1	22.9	22.7	**33.3**	**26.7**	–	–	–	–	9.5	10.8	**35.4**	**26.9**	**21.3**	**16.5**	**18.3**	**10.0**	0.9	1.3
Very high	9.0	8.0	**15.1**	**19.0**	2.5	3.3	17.8	19.3	20.7	18.7	**9.7**	**15.5**	–	–	–	–	**12.7**	**19.4**	**2.9**	**7.4**	**7.6**	**13.1**	14.2	16.5	0.2	0.2
Fuel consumption during wildfires[e]																										
Very low	**38.3**	**40.4**	**37.3**	**33.0**	**74.7**	**71.2**	**35.2**	**13.9**	30.6	31.7	**33.9**	**26.7**	91.6	92.3	99.8	99.8	36.7	36.4	**24.8**	**15.6**	**29.0**	**24.4**	**51.9**	**55.2**	96.9	90.0
Low	**20.1**	**14.4**	23.2	21.4	8.9	10.3	**17.2**	**8.2**	15.4	16.5	15.4	16.6	8.5	7.7	0.3	0.2	**29.8**	**21.5**	18.0	22.1	**25.9**	**30.3**	12.0	11.2	2.0	1.6
Moderate	20.8	21.9	10.7	10.8	13.6	14.7	9.7	19.6	**16.4**	**14.8**	**15.2**	**18.6**	–	–	–	–	11.4	11.9	24.1	30.9	**22.2**	**18.2**	13.8	11.6	0.1	0.2
High	12.0	15.4	**13.7**	**15.9**	**0.7**	**1.3**	**20.1**	**39.0**	17.3	18.5	25.8	22.7	–	–	–	–	9.5	10.8	**30.1**	**24.9**	15.3	14.1	8.7	6.4	0.9	1.3
Very high	8.8	7.8	**15.1**	**19.0**	2.2	2.7	17.8	19.3	20.4	18.5	**9.7**	**15.3**	–	–	–	–	**12.7**	**19.4**	**2.9**	**6.6**	**7.6**	**13.0**	13.6	15.6	0.2	0.2
PM10 smoke production during wildfires[e]																										
Very low	40.1	41.4	**39.4**	**35.2**	**75.4**	**72.4**	**38.5**	**13.9**	32.1	33.3	**36.2**	**27.8**	91.6	92.3	99.8	99.8	38.9	37.5	28.5	21.3	**32.5**	**27.9**	**53.1**	**56.1**	97.5	96.7
Low	**25.5**	**20.9**	24.4	22.4	**12.3**	**15.5**	**14.5**	**9.9**	18.6	20.2	**15.8**	**21.5**	8.5	7.7	0.3	0.2	**34.8**	**28.1**	**32.3**	**41.3**	**29.0**	**32.3**	13.4	16.5	1.5	1.8
Moderate	14.3	15.5	7.9	8.2	9.8	10.0	**15.0**	**24.6**	**12.4**	**11.0**	13.3	14.5	–	–	–	–	7.0	5.8	6.2	7.1	16.2	14.1	13.3	9.0	0.0	0.0
High	**17.6**	**21.5**	**26.8**	**32.5**	2.4	1.7	**30.4**	**49.5**	31.2	31.6	33.9	35.0	–	–	0.0	0.0	**18.9**	**27.5**	32.0	**27.2**	**21.6**	**25.1**	11.6	11.8	0.9	1.4
Very high	**2.6**	**0.6**	1.5	1.8	**0.2**	**0.5**	**1.6**	**2.2**	**5.7**	**3.9**	0.8	1.3	–	–	–	–	**0.4**	**1.2**	1.0	3.1	0.7	0.7	8.5	6.6	0.2	0.1
PM10 smoke production during current wildfires and prescribed fires[e]																										
Very low	**41.5**[c]	**87.2**[d]	**35.2**[c]	**95.6**[d]	**72.4**[c]	**90.7**[d]	**13.9**[c]	**81.3**[d]	**33.3**[c]	**85.5**[d]	**27.8**[c]	**87.7**[d]	**92.3**[c]	**100**[d]	**99.8**[c]	**100**[d]	**37.5**[c]	**97.5**[d]	**21.3**[c]	**75.5**[d]	**27.9**[c]	**91.1**[d]	**56.1**[c]	**79.0**[d]	**96.7**[c]	**99.8**[d]
Low	**20.9**[c]	**9.3**[d]	**22.4**[c]	**2.8**[d]	**15.5**[c]	**8.6**[d]	**9.9**[c]	**9.0**[d]	**20.2**[c]	**8.2**[d]	**21.5**[c]	**5.2**[d]	**7.7**[c]	**0.0**[d]	**0.2**[c]	**0.0**[d]	**28.1**[c]	**1.2**[d]	**41.3**[c]	**21.6**[d]	**32.3**[c]	**4.4**[d]	**16.5**[c]	**15.9**[d]	**1.8**[c]	**0.1**[d]
Moderate	**15.5**[c]	**0.1**[d]	**8.2**[c]	**0.1**[d]	**10.0**[c]	**0.0**[d]	**24.6**[c]	**0.3**[d]	**11.0**[c]	**0.4**[d]	**14.5**[c]	**0.4**[d]	–	–	–	–	**5.8**[c]	**1.0**[d]	**7.1**[c]	**0.4**[d]	**14.1**[c]	**0.2**[d]	**9.0**[c]	**0.1**[d]	0.0[c]	0.0[d]
High	**21.5**[c]	**3.5**[d]	**32.5**[c]	**1.6**[d]	**1.7**[c]	**0.7**[d]	**49.5**[c]	**9.4**[d]	**31.6**[c]	**5.9**[d]	**35.0**[c]	**6.7**[d]	–	–	**0.0**[c]	**0.0**[d]	**27.5**[c]	**0.3**[d]	**27.2**[c]	**2.6**[d]	**25.1**[c]	**4.3**[d]	**11.8**[c]	**5.0**[d]	**1.4**[c]	**0.2**[d]
Very high	**2.6**[c]	**0.6**[d]	**1.8**[c]	**0.0**[d]	**0.5**[c]	**0.0**[d]	**2.2**[c]	**0.0**[d]	**3.9**[c]	**0.0**[d]	**1.3**[c]	**0.0**[d]	–	–	–	–	**1.2**[c]	**0.0**[d]	**3.1**[c]	**0.0**[d]	**0.7**[c]	**0.0**[d]	**6.6**[c]	**0.0**[d]	**0.1**[c]	**0.0**[d]

[a] H, Historical condition; C, Current condition.

[b] Values shown in bold indicate significant increase or decrease ($p \leq 0.2$) from the historical to the current condition; '–' = no data.

[c] PM10 smoke production during current wildfires.

[d] PM10 smoke production during current prescribed fires.

[e] Fuel loading and fuel consumption classes (Mg/ha) are: very low <22.5; low = 22.5–44.9; moderate = 45–56.1; high = 56.2–67.3; and very high > 67.3. PM10 smoke production classes (kg/ha) are: very low = 0–224.2; low = 224.3–448.3; moderate = 448.4–672.5; high = 672.6–896.7; and very high >896.6.

Table 8

Historical (H) and current (C) percentage of area of fire behavior and crown fire potential attributes of subwatersheds sampled in Ecological Reporting Units of the mid-scale ecological assessment of the interior Columbia River basin

Attributes	Ecological reporting unit																									
	Blue Mountains		Central Idaho Mountains		Columbia Plateau		Lower Clark Fork		Northern Cascades		Northern Glaciated Mountains		Northern Great Basin		Owyhee Uplsnds		Snake Headwaters		Southern Cascades		Upper Clark Fork		Upper Klamath		Upper Snake	
	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C	H	C
Fireline intensity during wildfires[a]																										
Very low	26.4	27.4	14.9	14.9	50.2	51.1	4.0	3.6	21.5	19.9	**19.6**	**18.3**	**19.6**	**35.7**	**16.2**	**25.0**	18.2	20.1	**25.4**	**15.6**	**19.4**	**15.2**	**32.2**	**38.3**	31.0	33.6
Low	**11.3**[b]	**7.9**	15.4	15.3	**24.3**	**19.9**	2.4	1.7	**2.9**	**4.0**	2.4	2.8	**78.7**	**62.5**	**83.8**	**74.9**	**18.6**	**13.3**	0.1	0.2	3.2	3.9	20.1	17.4	67.0	63.6
Moderate	20.5	19.2	19.8	21.2	12.5	9.8	8.4	7.7	**23.4**	**19.1**	**20.6**	**15.5**	1.7	1.8	**0.0**	**0.1**	22.3	22.6	14.3	12.5	17.0	15.3	16.3	11.4	0.6	0.6
High	15.2	14.0	**24.0**	**20.2**	4.3	4.9	**49.5**	**28.4**	**19.2**	**23.6**	**26.1**	**29.6**	–	–	–	–	29.2	29.4	20.3	18.1	35.3	36.7	6.3	7.2	**0.5**	**0.8**
Very high	18.0	20.5	**23.7**	**26.0**	5.0	5.7	**27.4**	**48.1**	24.0	23.4	29.2	29.4	–	–	0.0	0.0	11.4	13.5	**33.7**	**26.9**	23.0	24.8	15.6	11.6	0.9	1.4
Severe	1.2	0.9	0.8	0.9	0.2	0.2	2.3	2.4	3.6	4.2	0.5	0.5	–	–	–	–	0.1	0.4	1.8	1.9	0.4	0.5	3.1	3.2	–	–
Extreme	7.3	7.9	1.4	1.6	**3.6**	**6.2**	6.0	8.1	5.3	5.8	**1.5**	**4.0**	–	–	–	–	**0.2**	**0.8**	**4.5**	**12.3**	**1.6**	**3.5**	6.4	10.8	–	–
Rate of spread during wildfires																										
Very low	24.4	24.0	**26.1**	**28.9**	37.0	36.4	4.8	5.0	**30.0**	**27.1**	24.9	24.1	13.0	19.3	**6.6**	**14.0**	33.6	35.3	25.4	17.6	24.8	23.2	21.8	24.1	21.7	26.5
Low	45.9	46.7	52.7	50.4	44.7	43.9	56.8	64.3	48.7	48.9	**56.0**	**51.5**	**86.3**	**78.9**	**93.1**	**85.8**	54.5	51.9	59.8	56.5	52.8	52.5	56.5	52.9	76.9	71.5
Moderate	29.7	29.3	21.2	20.6	18.3	19.6	38.4	30.5	**21.2**	**23.6**	**19.1**	**24.1**	0.7	1.9	**0.3**	**0.2**	11.9	12.8	**14.8**	**25.8**	22.4	24.2	21.7	22.9	1.5	2.0
High	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	**0.0**	**0.4**	**0.1**	**0.3**	–	–	–	–	0.0	0.1	**0.0**	**0.1**	**0.0**	**0.2**	0.0	0.1	–	–
Flame length during wildfires																										
Very low	24.0	26.0	12.8	12.6	**43.1**	**47.5**	3.8	3.6	20.5	19.1	**19.4**	**17.9**	**19.6**	**35.7**	**13.1**	**22.6**	**12.8**	**15.5**	**22.9**	**12.8**	**17.7**	**13.5**	**29.8**	**35.6**	**22.4**	**28.5**
Low	**14.3**	**11.2**	22.8	23.8	**31.5**	**23.6**	3.3	2.2	4.7	5.4	5.1	6.1	**80.0**	**63.9**	**86.9**	**77.4**	**32.1**	**23.7**	**2.6**	**5.3**	**6.4**	**8.5**	22.6	20.1	**75.6**	**69.0**
Moderate	18.5	18.3	13.5	14.2	11.6	9.7	7.4	7.2	**20.3**	**15.9**	**17.5**	**11.9**	0.4	0.5	–	–	**10.7**	**15.7**	14.1	13.0	**13.9**	**11.0**	15.2	9.5	0.6	0.3
High	**24.6**	**20.0**	**33.0**	**28.7**	5.7	6.9	**57.2**	**44.2**	**25.1**	**29.7**	35.3	37.3	–	–	–	–	35.4	35.1	32.2	34.9	44.0	44.3	9.2	10.9	1.1	1.7
Very high	**16.3**	**21.3**	**16.6**	**19.5**	**7.1**	**10.2**	22.3	35.1	26.7	26.1	**21.3**	**24.8**	–	–	–	–	8.9	9.5	27.9	32.9	**17.1**	**19.9**	20.0	18.6	0.4	0.5
Severe	**2.3**	**3.2**	1.2	1.3	**1.0**	**2.2**	6.0	7.7	**2.8**	**3.9**	**1.2**	**2.1**	–	–	–	–	**0.1**	**0.6**	**0.4**	**1.2**	**0.9**	**2.8**	3.2	5.3	–	–
Crown fire potential during wildfires																										
None	**35.3**	**31.8**	30.9	30.4	**68.2**	**60.2**	10.1	6.8	24.0	23.6	24.9	22.2	**85.9**	**78.3**	94.1	92.6	**38.0**	**33.7**	22.5	16.5	19.1	18.9	54.3	56.0	**96.9**	**95.9**
Very low	**7.1**	**9.4**	4.6	3.9	**11.0**	**16.5**	1.4	0.2	5.8	4.9	**8.4**	**3.9**	**14.1**	**21.8**	5.9	7.4	4.7	3.1	8.0	7.7	**8.7**	**6.7**	11.3	13.5	1.7	1.8
Low	**12.7**	**7.2**	**17.0**	**14.3**	5.2	5.4	**24.7**	**10.8**	**10.4**	**11.9**	12.0	12.0	–	–	–	–	**15.4**	**18.6**	19.7	20.1	15.0	14.3	6.1	6.3	**0.3**	**0.6**
Moderate	**16.4**	**18.8**	**8.9**	**6.8**	7.3	9.5	23.1	11.8	14.6	13.3	11.7	11.3	–	–	–	–	5.5	6.3	15.4	19.7	12.2	11.1	**16.6**	**11.1**	0.1	0.1
High	**5.4**	**3.8**	9.7	9.7	0.4	0.6	**0.7**	**2.7**	6.6	7.6	**11.0**	**13.8**	–	–	–	–	13.5	14.2	**1.7**	**3.0**	**12.3**	**15.5**	1.8	1.6	0.1	0.1
Very high	**14.3**	**17.0**	**18.6**	**22.5**	7.6	6.9	19.8	28.0	19.4	19.3	**18.3**	**20.6**	–	–	–	–	18.4	18.8	23.1	24.3	**21.0**	**23.7**	5.3	6.1	0.3	0.4
Severe	8.9	9.9	**10.4**	**12.5**	**0.4**	**0.9**	**20.3**	**39.7**	19.3	19.5	13.7	14.5	–	–	–	–	4.5	5.4	9.6	8.7	11.7	9.9	4.7	5.5	0.6	1.1

[a] Fireline intensity classes (kW/m) are: very low = 0.0–172.9; 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; and extreme >3459.2. Fire rate of spread classes (m/min) are: very low = 0.0–0.6; low = 0.7–2.4; moderate = 2.5–9.1; and high >9.1. Flame length classes (m) are: 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; and severe >3.4. Crown fire potential classes are a relativized index.

[b] Values shown in bold indicate significant increase or decrease ($p \leq 0.2$) from the historical to the current condition; '–' = no data.

- The most dramatic change in physiognomic conditions was the widespread decline in shrublands. Losses resulted from forest, woodland, and cropland expansion, and conversion to semi- or non-native herbland.
- Loss of historical herblands to agriculture was equally dramatic but had already occurred by the time of our historical sample.
- Shifts from early to late seral species were evident in many ERUs. Change in ponderosa pine, western larch, and Douglas-fir cover was associated with reduced patch area with medium and large trees.
- We observed a precipitous decline in area and connectivity of western white pine cover in northern Idaho and northwestern Montana, the heart of the historical range. Losses were attributed to early selective harvesting, an introduced blister rust, and mountain pine beetle mortality.
- Basin forests are now dominated by shade-tolerant conifers. Lacking significant pattern restoration, insects and pathogens favored by increased area and contiguity of patches of shade-tolerant conifers will continue to expand their role in shaping forest patterns by their growth and mortality affects, and by indirect influence on fire regimes.
- Patch area with old forest-structures declined sharply in all ERUs where they historically occupied more than a minor area. The same was true of patches with remnant large trees.
- In several ERUs, area with medium and large trees overshadowed or augmented losses to historical old-forest area. Our results suggested that 20th-century timber harvest activities targeted patches with medium- and large-sized trees regardless of their structural affiliation. There are at least two important ramifications: *First*, it has been broadly assumed that large trees are principally associated with old forests, where they contribute important living and dead structure. In some ERUs, old forest abundance was historically quite minimal (Table 3), but medium and large trees were distributed in other forest structures as a remnant after stand-replacing fires; in some cases, large trees comprised as much as 24% of the crown cover of forest structures, contributing important living and dead structure. Hence, some non-old forest structures of historical forest landscapes contributed a measure of late-successional functionality and connectivity with old forest. *Second*, where old forest area and area with remnant large trees has been depleted, the present and future supply of medium and large dead trees as snags and down logs is substantially diminished. This is especially true of snags and down logs of early seral species. We propose that terrestrial and aquatic species and processes requiring large dead tree structure may be adversely influenced by this reduction unless the shortfall is remedied through recruitment.
- In several ERUs, we observed a marked reduction in landscape vulnerability to dwarf mistletoes of early seral species. Comparisons of historical and current subwatersheds showed that timber harvest reduced crown cover of large early seral trees while one or more shade-tolerant understory strata developed. There are likely wildlife microhabitat ramifications.
- Area and mean patch size of stand-initiation structures dramatically declined where natural stand-replacing fires have been excluded. Such reduction was evident despite widespread timber harvest activity. With recent emphasis on conserving dwindling areas of late-successional and old forests in the Interior Northwest, the role of stand initiation structures on the landscape may have been underestimated. The immediate effect of stand replacing fires is to simplify landscape patterns and restore early seral conditions. After such a fire, forests are regenerated with a new cohort of early seral seedlings, saplings, grasses and shrubs. Subsequently, environmental and disturbance gradients interact recreating some of the lost pattern complexity, but expanses of interior forest emerge as a reminder of prior disturbance. Absent disturbances of this magnitude, where do the interior forests of the future come from?
- The absence of wildfires has had profound effects on forest and woodland area and connectivity at subwatershed to regional scales. The history and legacy of fire suppression and prevention programs is well known, but fire exclusion effects have been more difficult to pin down because many interacting factors played a role. As a result, fire prevention and suppression efficacy may have been overstated, and the role of factors responsible for exclusion of fire understated. Basic ecological studies are needed that explore in greater detail effects of road

networks and domestic livestock herbivory on historical *and* current exclusion of fires and accretion of trees.

- Patches of current forest cover types and structural classes are more fragmented than before. Patch densities are now higher, mean patch sizes are smaller, the largest patch of any given cover or structural class is smaller, and edge density is greater. These combined outcomes point to reduced landscape contagion as a consequence of timber harvest and road construction. Landscape pattern metrics confirmed the presence of highly fragmented landscapes in the current condition and pointed to increased pattern complexity among patch types in managed landscapes, and decreased complexity in roadless and wilderness-dominated landscapes.

5. Management implications

Several important management implications emerge from our assessment of basin conditions, but before we discuss implications, we summarize what was learned from assessment. First, we showed that spatial patterns of historical landscapes were indeed variable, and that those patterns reflected variation resulting from patterns of environments and natural disturbance regimes. Second, we showed that ground fuel and fire behavior conditions can be explicitly linked to vegetation conditions, that fuel and fire behavior conditions changed throughout the basin, and that landscapes varied in the direction and magnitude of changes. Finally, we showed that fire, insect, and pathogen disturbances were commonly associated with historical landscapes, but that the area and pattern of area that was highly vulnerable to disturbance, and the degree of spatial isolation has changed. In the section that follows, we highlight several key issues surrounding current public land management of Interior Northwest forests and relevant implications from this assessment.

5.1. Fuels and fire behavior — examining and isolating the risks

Throughout the basin, there are currently many large, spatially continuous areas that display elevated ground fuel conditions and increased severity in fire behavior attributes. Prior to the 20th century period of active resource management, areas that were normally influenced by infrequent lethal fires and those of a mixed lethal–nonlethal type, also displayed relatively high fuel loads, crown fire potential, rate of spread, flame length, and fireline intensity. Active management has not made the entire landscape wildfire prone, rather, it has removed the degree of spatial isolation that patches prone to stand replacement once enjoyed (Fig. 12A–H). A reasonable target of restoration would be to restore a more typical pattern of isolation to affected landscapes. To that end, a systematic evaluation of forest susceptibility to stand replacement fire would be helpful. Such an evaluation is now possible using tools and analytical approaches developed during this assessment, and this information would be useful for allocating monetary and manpower resources.

5.2. The wildland–urban interface

Most people who live adjacent to National Forest lands of the basin live on or adjacent to dry woodlands, or dry to mesic forests. These specific settings have been most altered by 20th century management activities. As a result, surface fire regimes that once affected lands of the current wildland–urban interface have become lethal or at best mixed regimes, and forest residents are at risk at each outbreak of fire. In the context of declining fire suppression effectiveness, public land managers might consider as a first priority, restoring vegetation and fuels patterns in the wildland–urban interface. In addition, managers might consider working with local citizens and communities to halt what is currently a rapidly expanding zone of interface. The tacit assumption of citizens who take up private residence in the forest is that the public land manager will come to their aid at the outbreak of fire. At some point, the rescue role of public land managers must be clearly enunciated and the total extent of a wildland–fire interface zone defined. The safety and management implications of not doing so are large.

5.3. Fire and smoke — how much and when

Stated simply, the question before public land managers is not whether there will be fire and smoke

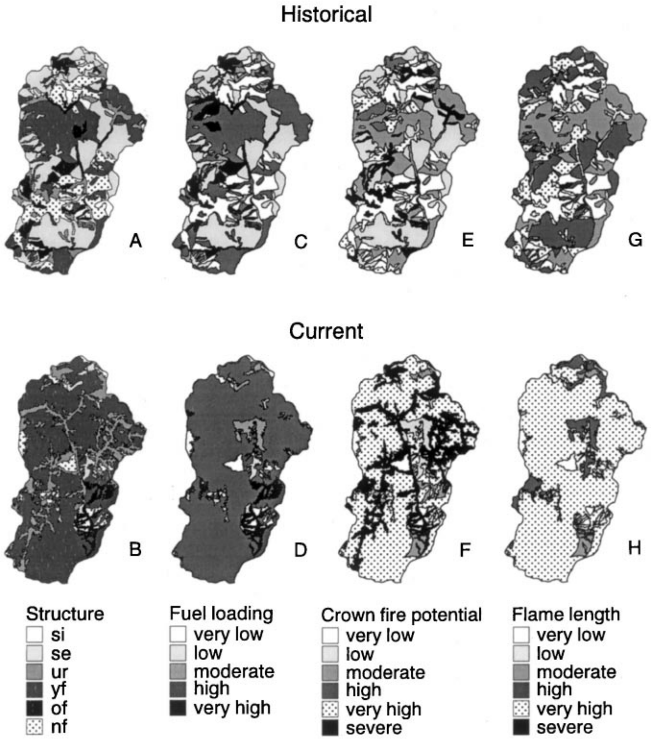

Fig. 12. Maps of subwatershed 55, Lower Grand Ronde subbasin, Blue Mountains ERU, displaying historical and current structural classes (A&B), fuel loading (C&D), crown fire potential under wildfire conditions (E&F), and flame length under wildfire conditions (G&H), respectively. Structural class abbreviations are: SI, stand initiation,SE, stem exclusion (both open and closed canopy conditions),UR, understory reinitiation, YFMS, young multi-story forest, of, old multi-story and single story forest, and nf, nonforest. Fuel loading classes are: very low <22.5 Mg/ha; low = 22.5–44.9 Mg/ha; moderate = 45–56.1 Mg/ha; high = 56.2–67.3 Mg/ha; and very high >67.3 Mg/ha. Crown fire potential classes were a relativized index. Flame length classes were: very low <0.6 m; low = 0.7–1.2 m; moderate = 1.3–1.8 m; high = 1.9–2.4 m; very high = 2.5–3.4 m; and severe >3.4 m.

in their future, but how do citizens want their fire and smoke. As Ottmar et al. (1999) and Huff et al. (1995) have shown, the air quality and smoke production tradeoffs between wild and prescribed fires are highly significant; prescribed burning can eliminate 50% or more of the particulate emissions generated by wildfires, and the timing, movement, and disposal of smoke released to the airshed is managed. According to Hann et al. (1997), it is unlikely that fire suppression efficacy will improve given current vegetation and fuels conditions. Provided there is sufficient management latitude, it will be up to resource managers to reduce to restore patterns of living and dead vegetation to conditions that are more attuned with natural fire regimes and biophysical environment conditions. In this scenario, citizens would learn to live with some measure of smoke on a regular basis as an alternative to uncertain fire- and smoke-free intervals punctuated by periods with extreme fires and smoke emissions of unchecked magnitude, distribution, and effect.

5.4. Insects and pathogens — which ones and how much

In the same way that healthy forests in many areas are visited by fires, healthy forests are visited by some native insects and pathogens. Insect and pathogen disturbances motivate forest succession, especially in the fire-free interval. Under natural disturbance regimes, these disturbances produced semi-predictable outcomes, and more importantly, insect and pathogen disturbances were either attuned with biophysical environment conditions and natural fire regimes or recalibrated them. Such is not the case today. Owing to effects of past management, current patterns of forest vegetation are out of synchrony with natural fire regimes, and current insect and pathogen disturbance regimes are anomalous.

There is no way to eliminate insect and pathogen disturbances from basin landscapes, and we would undoubtedly not wish to do so even if we were able. The byproduct of most insect and pathogen disturbances is microhabitat (snags, down wood) of varying quality and residence time essential to a variety of terrestrial and aquatic species. But management, by altering spatial and temporal patterns of vegetation structure, composition, and growing conditions, can influence the suite of agents operating on a landscape, but it cannot, and, from a purely ecological point of view, should not attempt to eliminate these disturbances.

5.5. Dynamic and reserve systems

In the Pacific Northwest, the northwest forest plan (NWFP) defines a network of late-successional reserves throughout the Cascade and Coast Ranges of Oregon, Washington, and California. While these lands are not explicitly set aside for custodial management, that is how they are managed. It is likely that such an approach is implementable west of the Cascade crest where most fire regimes are lethal, fire-free intervals may last 250–800 years or more, and the most common disturbances which are caused by native insects and pathogens result in canopy gaps. But east of the Cascade crest where this assessment has taken place, the picture is different. Wildfires and large-scale insect outbreaks are relatively common, and escaped wildfire frequency is increasing as a consequence of past management (Hann et al., 1997).

Results from both the interior Columbia Basin broad- (Hann et al., 1997) and mid-scale (Ottmar et al., 1999; Hessburg et al., 1999a) assessments suggest that in the interior, a two-pronged, dynamic and reserve system management approach may be needed to ensure recovery of the northern spotted owl and associated species. In the short term (e.g., 50–100 years), it is likely that areas currently functioning as late-successional and old forest habitats will be maintained with only limited success. Risk of disturbance and uncertainty of outcomes will be high. Over that period, some areas will be affected by stand-replacement fires, and will cease to function as late-successional habitat. For example, since, 1994, 10 of 140–180 (6–7%) northern spotted owl nest stands and neighborhoods were lost to uncontrolled wildfires on the Wenatchee National Forest alone. Patterns of structure and composition within the NWFP reserve network will continue to change as a result of uncontrolled fires, insect outbreaks, and other succession processes. What may be needed is an approach that marries a short term system of reserves with a long term strategy to convert from a reserve system to a continuous network of landscapes with dynamic properties. In such a system, late-successional elements with semi-predictable environmental settings (*sensu* Camp et al., 1997) are continuously recruited, but shifting in landscape position across space and time.

Indeed, the most significant fallout associated with 20th century resource management activities has been the effect of timber extraction and associated activities on native species biodiversity. Hardest hit have been late-successional and old forest communities of the Pacific and Interior Northwest. Old forest area has been seriously depleted by past harvest activity, and old forests of the future will be grown from existing conditions. But spatial and temporal patterns of interior forest vegetation and disturbance are dynamic. Adaptive ecosystem management scenarios (*sensu* Walters and Hollings, 1990) for the interior should therefore be informed by that insight, including scenarios to conserve old forest-dependent species.

Patches of late-successional and old forest structure are ephemeral landscape elements; they have specific contexts in space and across time. Future old forest will grow from some other condition; current old forests will become something else. Taking hold of this notion enables one to identify the dilemma of strategies that rely on a reserve system without backup. Because of the unfortunate legacy of past management actions, late-successional reserves must represent a special case for management. But the special case is an unforeseen consequence of past events, and in the interior, the likelihood of success in the long term is low.

5.6. *Healthy fish and healthy forests*

Is there really an aquatic conservation strategy separate from a landscape pattern restoration strategy? One conclusion of the interior Columbia basin aquatic (Lee et al., 1997) and landscape assessments (Hann et al., 1997) is the notion that disturbance regimes and succession processes associated with terrestrial and aquatic environments are intertwined. For example, in forested catchments hydrologic regimes are governed by spatial and temporal patterns of vegetation and disturbance. Wildfires and harvest activities have a direct bearing on the timing and flow of water through a catchment. But disturbance in upland settings can result in either positive or negative effects on aquatic conditions: some amount of disturbance across space and time results in the renewal and redistribution of essential aquatic habitats; too much, too often, or even too little disturbance, or the wrong kind in the wrong place, may result in damage and loss. Likewise, aquatic conservation strategies by specifying standardized buffer zones and custodial management of riparian zones of influence have a direct bearing on spatial and temporal patterns of vegetation in the catchment. But in neither case are the effects of either strategy jointly considered. While the tug-of-war between healthy aquatic systems and healthy forests is to be expected initially, reason suggests that as the debate comes of age, scientists and managers would pursue strategies that jointly consider long-term spatial and temporal patterns of upland vegetation and disturbance, *and* consequences to hydrologic regimes and aquatic habitats.

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References

Agee, J.K., 1993. Fire ecology of Pacific Northwest forests. Washington, DC, Island Press, 493 pp.

Agee, J.K., 1994. Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. Gen. Tech. Rep. PNW-GTR-320. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta, 52 pp.

Alatalo, R.V., 1981. Problems in the measurement of evenness in ecology. Oikos 37, 199–204.

Arno, S.F., 1976. The historical role of fire on the Bitterroot National Forest. Res. Pap. INT-187. Missoula, MT: USDA For. Serv., Intermountain Res. Sta. 29 pp.

Arno, S.F., 1980. Forest fire history in the northern Rockies. J. For. 78, 460–465.

Bailey, R.G., 1995. Description of Ecoregions of the United States. 2d ed. Misc. Publ. 1391. Washington, DC, USDA, For. Serv. 108 pp.

Burnham, K.P., Overton, W.S., 1979. Robust estimation of population size when capture probabilities vary among animals. Ecology 60, 927–936.

Camp, A.E., Oliver, C.D., Hessburg, P.F., Everett, R.L., 1997. Predicting late-successional fire refugia from physiography and topography. For. Ecol. Manage. 95, 63–77.

Cohen, J.D., Deeming J.E., 1985. The National Fire Danger Rating System: basic equations. Gen. Tech. Rep. PSW-82. Berkeley, CA: USDA For. Serv., Pacific Southwest Res. Sta., 16 pp.

Covington, W.W., Everett, R.L., Steele, R., Irwin, L.L., Daer, T.A., Auclair, A.N., 1994. Historical and anticipated changes in forest ecosystems of the Inland West of the United States. J. Sus. For. 2, 13–63.

Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The National Fire Danger Rating System-1988. Gen. Tech. Rep. INT-19. Ogden, UT, 63 pp.

ESRI, 1995. ARC/INFO version 7.0, User's manual. Redlands, CA: Environmental Systems Research Institute.

Everett, R.L., Hessburg, P.F., Jensen, M.E., Bormann, B., 1994. vol. I, Executive summary. Eastside Forest Ecosystem Health Assessment. Gen. Tech. Rep. PNW-GTR-317. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 61 pp.

Franklin, J.F., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. OSU Press, Corvallis, OR, 452 pp.

Hall, F.C., 1976. Fire and vegetation in the Blue Mountains — implications for land managers. In: Proc. 15th annual Tall Timbers Fire Ecology Conf., 16–17 October 1974, Portland, OR. Tallahassee, FL, Tall Timbers Res. Sta. 15, pp. 155–170.

Hann, W.J., Jones, J.L., Karl, M.G., Hessburg, P.F., Keane, R.E., Long, D.G., Menakis, J.P., McNicoll, C.H., Leonard, S.G., Gravenmeier, R.A., Smith, B.G., 1997. Landscape dynamics of the basin. In: Quigley, T.M., Arbelbide, S.J. (Eds.), An Assessment of Ecosystem Components in the Interior Columbia Basin and Portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta. Chp. 3, 2066 pp.

Harvey, A.E., Hessburg, P.F., Byler, J.W., McDonald, G.I., Weatherby, J.C., Wickman, B.E., 1995. Health declines in western interior forests: symptoms and solutions. In: Everett, R.L., Baumgartner, D.L. (Eds.), Proc. Symp. — Ecosystem Management in Western Interior Forests, 3–5 May 1994, Spokane, WA, Pullman, WA, Washington State University, pp. 163–170.

Heltshe, J.F., Forrester, N.E., 1983. Estimating species richness using the jackknife procedure. Biometrics 39, 1–11.

Hessburg, P.F., Mitchell, R.G., Filip, G.M., 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. Gen. Tech. Rep. PNW-GTR-327. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 72 pp.

Hessburg, P.F., Smith, B.G., Kreiter, S.G., Miller, C.A., Salter, R.B., McNicoll, C.H., Hann, W.J., 1999a. Historical and current forest and range landscapes in the Interior Columbia River Basin and portions of the Klamath and Great Basins. Part I. Linking vegetation patterns and landscape vulnerability to potential insect and pathogen disturbances. Gen. Tech. Rep. PNW-GTR-458. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 357 pp.

Hessburg, P.F., Smith, B.G., Miller, C.A., Kreiter, S.G., Salter, R.B., 1999b. Modeling change in potential landscape vulnerability to forest insect and pathogen disturbances: methods for forested subwatersheds sampled in the mid-scale interior Columbia River basin assessment. Gen. Tech. Rep. PNW-GTR-454. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 56 pp.

Hill, M.O., 1973. Diversity and evenness: a unifying notation and its consequences. Ecology 54, 427–431.

Huff, M.H., Ottmar, R.D., Alvarado, E., Vihnanek, R.E., Lehmkuhl, J.F., Hessburg, P.F., Everett, R.L., 1995. Historical and current forest landscapes of eastern Oregon and Washington. Part II. Linking vegetation characteristics to potential fire behavior and related smoke production. Gen. Tech. Rep. PNW-GTR-355. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 43 pp.

Keane, R.E., Reinhardt, E.D., Brown, J.K., 1994. FOFEM: A first order fire effects model for predicting the immediate consequences of wildland fire in the United States. In: Proc. 12th Conf. of Fire and Forest Meteorology, 26–28 October 1993, Jekyll Island, GA. Boston, MA; American Meteorological Society, pp. 628–631.

Lee, D.C., Sedell, J.R., Rieman, B.E., Thurow, R.F., Williams, J.E., 1997. Broadscale assessment of aquatic species and habitats. In: Quigley, T.M., Arbelbide, S.J. (Eds.), An assessment of ecosystem components in the interior Columbia basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., pp. 1057–1496 (Chapter 4).

Lehmkuhl, J.F., Hessburg, P.F., Everett, R.L., Huff, M.H., Ottmar, R.D., 1994. Historical and current forest landscapes of eastern Oregon and Washington. Part I. Vegetation patterns and insect and disease hazards. Gen. Tech. Rep. PNW-GTR-328. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 88 pp.

MathSoft Inc., 1993. S-PLUS user's manual, version 3.2. Seattle: StatSci, a Division of MathSoft, Inc.

McGarigal, K., Marks, B.J., 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Rep. PNW-GTR-351. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 122 pp.

Morgan, P., Aplet, G.H., Haufler, J.B., Humphries, H.C., Moore, M.M., Wilson, W.D., 1994. Historical range of variability: a useful tool for evaluating ecosystem change. In: Sampson, R.N., Adams, D.L. (Eds.), Assessing forest ecosystem health in the inland Northwest, New York (The Haworth Press), pp. 87–111.

O'Hara, K.L., Latham, P.A., Hessburg, P.F., Smith, B.G., 1996. A structural classification of inland Northwest forest vegetation. West. J. Appl. For. 11 (3), 97–102.

O'Laughlin, J., MacCracken, J.G., Adams, D.L., Bunting, S.C., Blatner, K.A., Keegan, C.E., 1993. Forest health conditions in Idaho. Rep. 11. Moscow, ID: U of I, Forest, Wildlife, and Range Policy Analysis Group, 244 pp.

Oliver, C.D., Larson, B.C., 1996. Forest Stand Dynamics. New York, Wiley, 520 pp.

Ottmar, R.D., Burns, M.F., Hall, J.N., Hanson, A.D., 1993. CONSUME users guide. Gen. Tech. Rep. PNW-GTR-304. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., 118 pp.

Ottmar, R.D., Schaaf, M.D., Alvarado, E., 1996. Smoke considerations for using fire in maintaining healthy forest conditions. In: Gen. Tech. Rep. INT-GTR-341. Ogden,UT: USDA For. Serv., Intermountain Res. Sta., pp. 2–28

Ottmar, R.D., Alvarado, E, Hessburg, P.F., Smith, B.G., Kreiter, S.G., Miller, C.A., Salter, R.B., 1999. Historical and current forest and range landscapes in the Interior Columbia River Basin and portions of the Klamath and Great Basins. Part II. Linking vegetation patterns and potential smoke production and fire behavior. Gen. Tech. Rep. PNW-GTR-XXX. Portland, OR: USDA For. Serv., Pacific Northwest Res. Sta., in press.

Quigley, T.M., Arbelbide, S.J. (Eds.), 1997. An assessment of ecosystem components in the interior Columbia basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405. Portland, OR, USDA For. Serv., Pacific Northwest Res. Sta. vol. 4, 2066 pp.

Robbins, W.G., Wolf, D.W., 1994. Landscape and the intermontane Northwest: an environmental history. Gen. Tech. Rep. PNW-GTR-319. Portland, OR, USDA For. Serv., Pacific Northwest Res. Sta., 32 pp.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: USDA For. Serv., Intermountain Res. Sta., 73 pp.

Rothermel, R.C., 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: USDA For. Serv., Intermountain Res. Sta., 161 pp.

Schaaf, M.D., 1996. Development of the fire emission tradeoff model (FETM) and application to the Grande Ronde River basin, Oregon. CH_2MHill Contract Report No. 53-82FT-03-2. On file with: CH_2MHill Co., 825 NE Multinomah Building, Suite 1300, Portland, OR 97232.

Shannon, C., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana, 117 pp.

Simpson, E.H., 1949. Measurement of diversity. Nature. 163, 688.

Skovlin, J.M., Thomas, J.W., 1995. Interpeting long-term trends in Blue Mountains ecosystems from repeat photography. Gen.

Tech. Rep. PNW-GTR-315. Portland, OR, USDA For. Serv., Pacific Northwest Res. Sta., 102 pp.

Turner, M.G., 1987. Landscape Heterogeneity and Disturbance. Springer, New York, NY.

Turner, M.G., 1989. Landscape ecology: the effect of pattern on process. Ann. Rev. Ecol. Syst. 20, 171–197.

Walters, C.J., Hollings, C.S., 1990. Large-scale management experiments and learning by doing. Ecology 71, 2060–2068.

Wickman, B.E., 1992. Forest health in the Blue Mountains: the influence of insects and diseases. Gen. Tech. Rep. PNW-GTR-295. Portland, OR, USDA For. Serv., Pacific Northwest Res. Sta., 15 pp.

Wissmar, R.C., Smith, J.E., McIntosh, B.A., Li, H.W., Reeves, G.H., Sedell, J.R., 1994. A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s–1990s). Northwest Sci. 68, 1–35.