Available online at www.sciencedirect.com
SCIENCE DIRECT
Forest Ecology and Management 207 (2005) 263–278
Forest Ecology and Management
www.elsevier.com/locate/foreco

Decision support for integrated landscape evaluation and restoration planning

Keith M. Reynolds[a,*], Paul F. Hessburg[b]

[a]USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR 973331, USA
[b]USDA Forest Service, Pacific Northwest Research Station, Wenatchee, WA 98801, USA

Abstract

The historical patterns of Inland Northwest United States forests have been dramatically altered by a little more than two centuries of human settlement and land use. Spatial patterns of forest structural conditions, tree species composition, snags and down wood, and temporal variation in these patterns, have been altered to such an extent that the natural ebb and flow of terrestrial habitats and their linkages has been disrupted. Closely coupled with these changes, fire and other disturbance processes in most dry and many mesic forest types have also shifted, with a bias for increased severity and extent. Here, in the context of planning restoration of some semblance of historical vegetation pattern–disturbance process interactions, we briefly revisit why it is theoretically sound to estimate the range and variation in historical forest spatial patterns. We call these estimates of range and variation, reference conditions or reference variation (RV), and discuss how forest managers might use them when evaluating current landscape patterns to identify changes that may have important ecological implications. We term such evaluations, departure analyses, and we describe how departure analysis is implemented in a decision support system (DSS) for integrated landscape evaluation and restoration planning. The initial phase of the DSS uses logic-based modeling to evaluate existing patterns of forest vegetation in subwatersheds of one ecoregion against a corresponding envelope of historical reference conditions for the same region, thereby highlighting key departures. The secondary planning phase uses results from the analysis phase in a decision model to prioritize watersheds for possible management actions related to landscape restoration and maintenance. We conclude from our example that there are at least two advantages to a decision-support approach that treats evaluation and planning as distinct but integrated phases: (1) the overall decision process is rendered conceptually simpler and (2) practical considerations of efficacy and feasibility of management actions can be easily accommodated.
© 2004 Elsevier B.V. All rights reserved.

Keywords: Criterion DecisionPlus; Decision support; EMDS; Historical range of variation; Landscape evaluation; Monitoring; NetWeaver; Restoration; Scenario planning

1. Introduction

Human settlement and forest management activities have drastically changed the patterns and processes of forest landscapes across the Inland

* Corresponding author. Tel.: +1 541 750 7434; fax: +1 603 853 2794.
E-mail address: kreynolds@fs.fed.us (K.M. Reynolds).

0378-1127/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2004.10.040

Northwest United States (Hessburg et al., 2000a; Hessburg and Agee, 2003). As a result, attributes of current disturbance regimes differ markedly from those of historical regimes, and current wildlife species and habitat distributions are inconsistent with historical distributions. For example, the duration, severity, and extent of wildfires and of defoliator and bark beetle outbreaks have increased, and large carnivores occupy only a small fraction of their historical range (Marcot et al., 1998, 2003; Wisdom et al., 2000). Just as human-caused changes in ecological processes have led to changes in landscape patterns, changes in patterns of forest vegetation have produced changes in ecosystem processes, particularly disturbances. Today, public land managers face substantial societal pressure to restore landscape patterns of living-and dead-forest structure, composition, and habitats. Motivations for restoration stem from a strong aversion to the risks and uncertainties, associated with current wildfire hazard and a budding concern for the functioning of ecological systems.

Ecological theory once asserted that the theories of stable equilibria and "the balance of nature" could explain ecosystem dynamics (e.g., see Lovelock, 1987; Milne and Milne, 1960), but these explanations are no longer considered valid. Wu and Loucks (1995) proposed an alternative framework, the hierarchical patch-dynamics paradigm (Hessburg et al., 2004). A key element of this framework, for our purposes, states that across a broad range of spatial and temporal scales, patterns enable and constrain ecological processes, and ecological processes create, maintain, modify, and destroy patterns. Thus, patterns and processes are tightly linked, and particular patterns and processes are linked to certain spatial and temporal scales. A second framework element states that lower-level processes are incorporated into higher-level structures and processes. This incorporation integrates the effects of lower-level processes and higher-level constraints imposed by geological and climatic systems to generate quasi-equilibrium patch dynamics. These dynamics are manifest as a finite range of conditions that is somewhat predictable as long as the underlying processes and constraints remain substantially unchanged. The principles asserted in these two elements of the framework suggest that landscape evaluations concerned with the restoration of ecosystems might be based on an evaluation of a set of ecological indicator measures against historically-based reference conditions for those same indicator metrics (Wu and Loucks, 1995).

The focal or observation level of this study is forest landscapes and their spatial patterns of structural classes (≈successional stages, O'Hara et al., 1996), cover types, and related conditions. We focus on patterns of vegetation at this level because important changes in the patch dynamics of forest ecosystems are often reflected in the structure of the affected landscapes (Spies, 1998). In this study of a single ecological subregion in the Inland Northwest U.S., we illustrate an integrated approach to: (1) evaluating departure of present forest landscape patterns from a set of pre-management-era (~1900 AD) reference conditions; and (2) management planning for ecological restoration. In previous work, Hessburg et al. (2004) focused on development of the scientific methods for estimating pattern departure in an individual watershed. Here, a more extensive landscape analysis is performed with version 3.0.2 of the Ecosystem Management Decision Support (EMDS; Reynolds, 2002; Reynolds et al., 2003b) system.

As illustrated in this study, the current implementation of EMDS supports an explicit two-phase, integrated approach to evaluation and planning in which evaluation is first performed with a logic engine and planning is subsequently performed with a decision-modeling component. This new approach, implemented in EMDS, teases apart the two questions, "What is the state of the system?" and for the planning team, "What are reasonable responses to mitigate revealed problems?" We use this particular study to demonstrate some of the advantages of making a practical distinction between evaluating and planning, in effect, treating these two phases of the adaptive management process as distinct, but integrable.

2. Materials and methods

In the first three methods subsections, we describe how subwatersheds in this analysis were stratified and selected (2.1), how maps of historical and current conditions were generated (2.2), and how reference conditions were developed from the historical data to provide a basis for evaluating current subwatershed

conditions (2.3). The first three subsections briefly summarize previous work reported in Hessburg et al. (1999a,b, 2000c, 2004), which should be consulted for details on theoretical background, descriptions of metrics, and the rationale for selection of metrics. In the last three subsections, we provide an overview of key EMDS components and their role in decision support (2.4), describe the logic for evaluating subwatershed conditions (2.5), and describe the decision model used to derive priorities for restoration of subwatersheds based on results of the landscape evaluation, and additional considerations relevant to the feasibility and efficacy of potential management actions (2.6). Reynolds et al. (2003b) describe details and features of the EMDS system components.

2.1. Stratification and selection of subwatersheds

To identify sample landscapes constrained by similar environmental contexts, we used the ecological subregions of Hessburg et al. (2000b) to stratify subwatersheds (ca. 5000–10,000 ha) of the eastern Washington Cascades into biological, geologic, and climatic zones (Fig. 1A). Subwatersheds (Fig. 1B) were used as the basic sampling units because they provided a rational means to subdivide land areas that share similar climate, geology, topography, and hydrology (Forman and Godron, 1986). Subwatersheds compose the 6th level in the established hierarchy of U.S. watersheds (Seaber et al., 1987). Lehmkuhl and Raphael (1993) showed that some attributes of spatial pattern are influenced by the size of the area being analyzed when analysis areas are too small. We used subwatersheds or logical subwatershed pairs larger than 4000 ha to avoid this bias.

We selected the ESR4 ecological subregion (Warm/Wet/Low Solar, Moist and Cold Forests; hereafter, "ESR4" or the "Eastern Cascades–Moist and Cold Forests" subregion) as the biogeoclimatic zone in which we sampled and estimated reference conditions (Fig. 1A). Landscapes of this subregion are dominated by Moist (67% of the area) and cold (21% of the area) forest types, with total annual precipitation of 1100–3000 mm/year, generally warm growing-season temperatures (mean annual daytime temperature, 5–9 °C), and relatively low levels of solar radiation (frequently overcast skies, 200–250 W m^{-2}; Hessburg et al., 2000a). The subregion contains 93 subwatersheds. To map historical and current vegetation, we randomly selected 15 subwatersheds in order to sample at least 15% (actual 16.1%) of the total number of subwatersheds and 15% (actual 19.2%) of the subregion's area (Fig. 1C). Hessburg et al. (2004) have previously shown the validity of the ecological stratification.

2.2. Mapping historical and current vegetation

For each selected subwatershed, we mapped recent historical (1930s–1940s) and current (1990s) vegetation by interpreting aerial photographs. The resulting vegetation attributes enabled us to derive forest cover types (*sensu* Eyre, 1980), and structural classes (*sensu* O'Hara et al., 1996; Oliver and Larson, 1996), using the methods of Hessburg et al. (1999a,b, 2000b). Vegetation types were assigned to patches at least 4 ha in size by means of stereoscopic examination of color (current) or black-and-white (historical) aerial photographs. The scales of these photographs were 1:12,000 (current) and 1:20,000 (historical). Photo-interpreters used available field inventory plot data to train and supervise their visual interpretations. The attributes of the interpreted vegetation were the same as those reported by Hessburg et al. (1999a). Patches were delineated on clear overlays, and were georeferenced. Overlay maps were then scanned, edited, edge-matched, and imported into GIS software to produce vector coverage with patch attributes. Nine of the 15 historical subwatersheds, comprising about 6.5% of the total area, showed evidence of timber harvesting, and nearly all the harvesting was light to moderate selection cutting. Hessburg et al. (2004) described the procedures we used to statistically reconstruct attributes of partially harvested historical patches.

2.3. Estimating reference conditions

Four different maps characterized the attributes of the historical subwatersheds of the eastern cascades—moist and cold forests subregion (Table 1). We chose five spatial metrics (Table 2), generated by FRAGSTATS (McGarigal and Marks, 1995) to display the area and connectivity relations of the individual attribute classes within a landscape mosaic in each map; such as the ponderosa pine (*Pinus ponderosa*) cover type in a map of all cover types. We characterized the features of the overall landscape

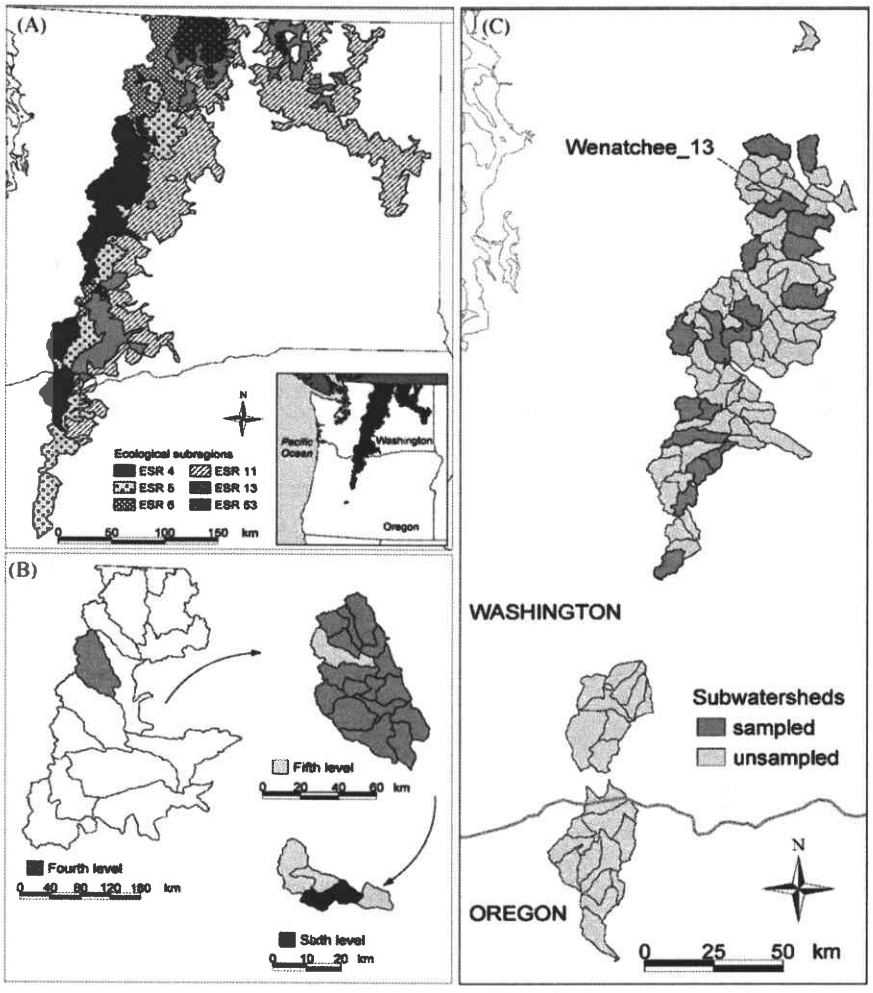

Fig. 1. Ecological subregions of the eastern Washington Cascades in the western United States (adapted from Hessburg et al., 2000b). (A) The ecological subregions (ESR) are defined as follows: 4 = Warm/Wet/Low Solar Moist and Cold Forests, 5 = Warm/Moist/Moderate Solar Moist and Cold Forests, 6 = Cold/Wet/Low and Moderate Solar Cold Forests, 11 = Warm/Dry and Moist/Moderate Solar Dry and Moist Forests, 13 = Warm and Cold/Moist/Moderate Solar Moist Forests, and 53 = Cold/Moist/Moderate Solar Cold Forests. (B) Hierarchical organization of subwatersheds (6th level), watersheds (5th level), and sub-basins (4th level) in the eastern Washington Cascades of the western United States (see also Seaber et al., 1987). The example shows the Wenatchee River sub-basin at the 4th level, the Little Wenatchee River watershed at the 5th level, and subwatershed Wenatchee 13 at the 6th level. (C) Subwatersheds included in this study were randomly selected from Ecological Subregion 4.

Table 1
Mapped attributes and their classes for historical subwatersheds of the eastern Cascades—moist and cold forests subregion (ecological subregion 4)

Mapped attribute	Classes
Physiognomic class	Forest, woodland, shrubland, herbland, and non-forest
Cover class	Douglas-fir, grand fir, lodgepole pine, ponderosa pine, silver fir, herbaceous, and non-forest
Structural class	Stand initiation, stem exclusion-open canopy, stem exclusion-closed canopy, understory reinitiation, young forest multi-story, and old forest multi-story
Late-successional/old-growth	Late-successional, old forest single-story, old forest multi-story, other forest, non-forest

Table 2
Class metrics used to characterize mapped attributes of historical subwatersheds of the eastern cascades—moist and cold forests subregion (ecological subregion 4)

Class metric	Units
Land area	Percentage
Patch density	Number per 10,000 ha
Mean patch size	ha
Mean nearest neighbor distance	m
Edge density	m ha^{-1}

mosaic in each map using nine metrics (Table 3). Landscape metrics characterized the spatial pattern relationships among the classes that composed the landscape mosaics. Six of the nine metrics we chose to display landscape patterns were already available in FRAGSTATS, and three additional metrics were added to the FRAGSTATS source code. Mean, median, range, and reference variation statistics were computed for each landscape metric of the 15 subwatersheds sampled for the subregion with the S-PLUS software (Statistical Sciences, 1993).

Five class metrics (Table 2) were chosen to display spatial relations within any class. The metrics were: land or class area, patch density, mean patch size, mean nearest-neighbor distance, and edge density. These metrics were useful in various combinations to illustrate class area and connectivity departures that may have ecological importance.

Nine landscape metrics (Table 3) were selected to characterize departures associated with the entire landscape mosaic. Two richness measures were used: patch richness tallies the number of unique patch types, while relative patch richness rescales patch richness by reflecting the proportion of the total possible within the subregion that are actually present. Both the Shannon diversity index and Hill's inverse of Simpson's lambda (Hill N2) incorporate patch type abundance into the diversity measure, but Hill N2 is also a dominance measure. Hill N2 responds to changes in the abundance of dominant patch types, while the Shannon diversity index responds to any changes in the number of unique patch types, including rare ones. Hill N1, Hill's transformation of the Shannon diversity index, is intermediate to the Shannon diversity index and Hill N2 in its sensitivity to changes in patch richness. The modified Simpson's evenness index reflects the evenness of area among patch types, including rare ones, while Alatalo's index looks primarily at evenness among the dominant patch types. The contagion index estimates the dispersion and interspersion of classes that comprise the landscape relative to the maximum possible, and the interspersion and juxtaposition index (IJI) considers the length of edge among contrasting classes. The latter two indices give a clear picture of the extent to which patches of differing types intermix with one another.

Using this limited suite of metrics, we could expect to detect changes in landscape patterns that had potential ecological significance and understand the specific class changes that were driving shifts in the mosaic. Elucidating specific class changes provides insights into possible mechanisms of changes.

2.4. Landscape evaluation with EMDS

EMDS version 3.0.2 (Reynolds et al., 2003b) is a decision support system for integrated landscape evaluation and planning. The system provides

Table 3
Landscape metrics used to evaluate landscape integrity of historical subwatersheds of the eastern cascades—moist and cold forests subregion (ecological subregion 4)

Landscape metric	Reference
Relative patch richness	McGarigal and Marks (1995)
Patch richness	McGarigal and Marks (1995)
Shannon's diversity index	McGarigal and Marks (1995)
Hill's transformation of Shannon index	Hill (1973)
Hill's inverse of Simpson's lambda	Simpson (1949); Hill (1973)
Modified Simpson's evenness index	McGarigal and Marks (1995)
Alatalo's evenness index	Alatalo (1981)
Contagion	McGarigal and Marks (1995)
Index of interspersion and juxtaposition	McGarigal and Marks (1995)

decision support for landscape-level analyses through logic and decision engines integrated with the ArcGIS® 8.1 geographic information system (GIS, Environmental Systems Research Institute[1], Redlands, CA). The NetWeaver logic engine (Rules of Thumb, Inc., North East, PA) evaluates landscape data against a formal logic specification (e.g., a knowledge base in the strict sense) designed in the NetWeaver Developer System, to derive logic-based interpretations of ecosystem conditions such as landscape integrity. The decision engine evaluates NetWeaver outcomes, and data related to feasibility and efficacy of land management actions, against a decision model for prioritizing landscape features built with its development system, Criterium DecisionPlus® (CDP, InfoHarvest, Seattle, WA). CDP models implement the analytical hierarchy process (AHP; Saaty, 1992), the simple multi-attribute rating technique (SMART; Kamenetzky, 1982), or a combination of the AHP and SMART methods.

2.5. Evaluation of subwatersheds

With respect to landscape evaluation, a NetWeaver knowledge base represents a problem specification as networks of topics, each of which evaluates a proposition. The formal specification of each topic is graphically constructed, and composed of other topics (e.g., premises) related by logic operators such as AND, OR, NOT, etc. NetWeaver topics and operators return a continuous-valued metric, commonly known as a "truth value" (Miller and Saunders, 2002), that expresses the strength of evidence (hereafter, support) that the operator and its arguments provide to a topic, or to another logic operator. The specification of an individual NetWeaver topic supports potentially complex logic models because both topics and logic operators may be specified as arguments to an operator. Considered in its entirety, the complete knowledge-base specification for a problem can be thought of a mental map of logical dependencies among propositions. In this map, all logical pathways terminate in primitive networks that directly evaluate data.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Our overall objective in design of the NetWeaver knowledge base for this problem was to assess how well current conditions in the sampled subwatersheds of ESR4 corresponded to historical reference conditions. We use the term integrity, to express the degree of correspondence. Primary topics for evaluation, corresponding to mapped attributes (Table 1), were: physiognomic integrity, cover integrity, structural integrity, cover by structural integrity, and late-successional/old-growth forest integrity.

Each class metric (Table 2) of each attribute class (Table 1) and each landscape metric (Table 3) under each attribute were evaluated for the current condition of each landscape. An evaluation for any metric was done by comparing the value of each metric for the current condition to a ramp function for the same metric derived from the historical data (Fig. 2A). The result of each evaluation was an expression of the support for correspondence of the current conditions to the reference conditions encoded in the ramp function. In logic applications such as NetWeaver, evaluations against functions such as these, return a measure of support, and are referred to as membership functions because they express an observation's degree of membership in a fuzzy subset (Miller and Saunders, 2002).

Each membership function in a primitive network was defined by four points in this study (Fig. 2A). The two points on the abscissa, x_1 and x_4, defined reference values of a metric at which an observed value provided no support (i.e., degree of correspondence = 0). Similarly, the two points on the abscissa, x_2 and x_3, defined a range of reference values within which the observed value of a metric provided full support (degree of correspondence = 1). Reference metric values that fell within the intervals (x_1, x_2) or (x_3, x_4) provided partial support. The four x-points, x_1, x_2, x_3, and x_4, were used to define the membership function of each class and landscape metric and were defined as the minimum, 10th percentile, 90th percentile, and maximum, respectively, of the distribution of reference values for the metric.

Each primary topic in the NetWeaver logic model was evaluated with respect to class and landscape integrity. The logic specification for integrity of primary topic t can be represented in equation form as:

$$p(t) \Leftarrow \mathrm{AND}(p_c(t), p_l(t)) \quad (1)$$

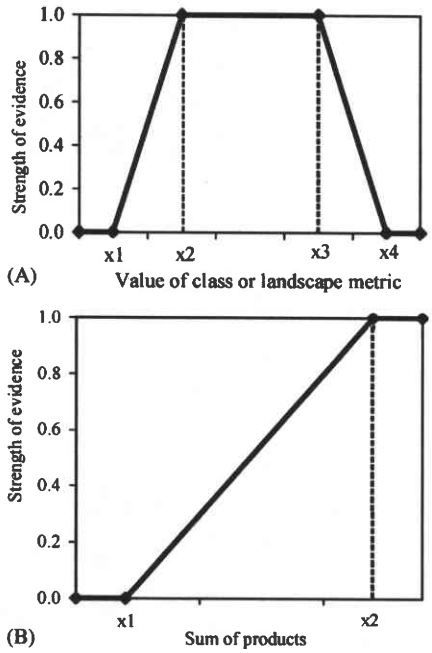

Fig. 2. Prototypical membership functions for determining strength of evidence that an observed value of a metric was within a suitable range. (A) For each metric, points x_1, x_2, x_3, and x_4 on the abscissa were determined from the historic range of variation of the metric, and represent the minimum, 10th percentile, 90th percentile, and maximum of the range of the metric, respectively. This prototype function was used in all network primitives (e.g., networks that directly evaluated data). (B) A specialized membership function designed to evaluate a sum of products (see Eq. (2) for an example of computing the sum of products for class metrics). The points x_1 and x_2 on the abscissa indicate the sums of weights (Eq. (3)) at which the sum of products provides no support and full support, respectively, for the proposition that the sum of products is acceptable.

in which $p(t)$ = support for integrity with respect to primary topic t, $p_c(t)$ = support for class integrity in topic t, and $p_l(t)$ = support for landscape integrity in topic t. Eq. (1) can be stated as, "the proposition for integrity of t is supported to the degree that its premises, $p_c(t)$ and $p_l(t)$, are supported". As we mentioned earlier, the logic specification of NetWeaver models is graphically constructed in the model development environment, but we use equivalent equations here and subsequently for compactness.

Support for overall class integrity within each primary topic ($p_c(t)$ in Eq. (1)) was evaluated by computing a weighted sum of proposition strengths, $p_i(c,t)$, for individual classes (e.g., forest, woodland, shrubland, etc., in the case of physiognomic classes):

$$\mathrm{sum}(c,t) = \sum_{i=1}^{n} w_i(c,t) p_i(c,t) \tag{2}$$

and comparing sum(c, t) to a membership function (Fig. 2B) in which the two abscissa values, x_1 and x_2, were computed as:

$$x_2 = \sum_{i=1}^{n} w_i(c,t) \quad \text{and}\, x_1 = -x_2 \tag{3}$$

Each weight term, $w_i(c, t)$, in Eq. (2) was set equal to the proportional area of class i in the landscape. The distinction between evaluating propositions with Eq. (1) versus Eq. (2) is significant: Eq. (1) treats its premises, $p_c(t)$ and $p_l(t)$, as limiting factors, whereas Eq. (2) treats the premises as making incremental contributions to the proposition, $p_c(t)$.

Individual terms, $p_i(c, t)$, in Eq. (2) were evaluated in a manner analogous to Eq. (4):

$$\mathrm{sum}(i,c,t) = \sum_{j=1}^{5} p_j(i,c,t) \tag{4}$$

In Eq. (4), each $p_j(i, c, t)$ term represents support for a class metric (Table 2), and has an implicit weight of 1. Also analogous to Eq. (2), sum(i, c, t) is compared to a membership function similar to Fig. 2B, but with $x_1 = -5$, and $x_2 = 5$ (e.g., sums of the implicit weights). The form of evaluation of landscape integrity ($p_l(t)$ in Eq. (1)) is nearly identical to Eqs. (2)–(4), except that the summation is performed over the nine landscape metrics (Table 3).

2.6. Landscape planning for restoration

The decision model for assigning restoration priorities to subwatersheds included four primary criteria: compositional integrity, structural integrity, feasibility of management, and fire risk (Table 4). All subcriteria of compositional and structural integrity criteria (Table 4) were measures of support from the landscape analysis performed with the NetWeaver logic engine. Subcriteria of fire risk and feasibility (Table 4) represented attributes of subwatersheds that were not part of the logic-based evaluation, but were included in the decision model as important logistical considerations.

Table 4
Structure of analytic hierarchy process model for determining priorities for restoration of subwatersheds in ecological subregion 4

Criterion[a]	Weight[b]	Description
Compositional integrity	0.25	Synthesis of cover and physiognomic integrities
Cover integrity	0.67	Strength of evidence for cover integrity from evaluation phase of analysis
Physiognomic integrity	0.33	Strength of evidence for physiognomic integrity from evaluation phase of analysis
Structural integrity	0.25	Synthesis of structural integrities
All forest integrity	0.67	Strength of evidence for structural integrity from evaluation phase of analysis
LSOF integrity	0.33	Strength of evidence for late-successional/ old-growth integrity from evaluation phase of analysis
Feasibility of management	0.25	Synthesis of feasibility factors
Steepness	0.25	Percent of subwatershed area with slope 30%
Road access	0.25	Percent of subwatershed within 250 m of any road
Timber value	0.50	Relative measure of timber value in a subwatershed
Fire risk	0.25	Synthesis of fire risks
Crown fire potential	0.75	Percent of subwatershed area with high, very high, or severe crown fire potential rating
Fuel loading	0.25	Percent of subwatershed area with high or very high fuel bed loading

[a] Primary decision criteria are compositional integrity, structural integrity, feasibility, and fire risk. Secondary decision criteria are shown indented under their primary criteria, and, because they are the lowest criteria in the model, also represent the attributes of subwatersheds that are being evaluated. Each attribute was evaluated against a utility function, specified with the simple multi-attribute rating technique. The decision score on each primary criterion is derived as the weighted average of the utility scores of the criterion's subcriteria.

[b] Each weight expresses the relative importance of a subcriterion with respect to its parent criterion. In the case of primary criteria, importance is with respect to the overall model goal of assigning restoration priorities.

Pair-wise comparisons among primary and secondary criteria, using standard methods for the Analytic Hierarchy Process (Saaty, 1992), provided weights for the decision model (Table 4). SMART utility functions for rating criteria at the lowest level of the model also were specified (Kamenetzky, 1982). Utility functions for feasibility subcriteria were designed to give greater preference to subwatersheds with shallow slopes, good road access to stands, and high timber values, which could financially support restoration costs. Utility functions for subcriteria of fire risk were designed to give greater preference to subwatersheds with higher ratings for crown-fire potential and fuel loading, based on a rationale of protecting investment in the existing forest resource. Fuel loading and crown fire potential were attributed to individual vegetation patches using standard published methods (Huff et al., 1995; Hessburg et al., 2000c; Ottmar et al., in press).

3. Results

Evaluations of physiognomic, cover, structural, and late-successional/old-forest attribute integrity involved evaluation of 43, 107, 68, and 43 class and landscape metrics, respectively, for each of the 15 subwatersheds. Due to the large size and scope of the analysis, we present summary results for the highest levels of evaluation (Fig. 3) in the following subsections, and give a narrative overview of pertinent underlying details with illustrative examples. The top row for overall integrity (Fig. 3) presents the logical composition of Class (row 2) and Landscape (row 3) evaluations based on the AND operator.

3.1. Evaluation of physiognomic conditions

An evaluation of physiognomic integrity is relevant to investigating the potential effects of land cover departures that may have ramifications for wildlife species that use large areas, and to ecosystem processes that operate at broad spatial scales. Departures in physiognomic condition were evaluated for the following classes: forest, woodland, shrubland, herbland, and non-forest/non-rangeland (e.g., rock, water, ice, urban/rural developed area; Table 1). Support for overall physiognomic integrity (i.e., synthesis of class and landscape integrities, Eq. (1)) in the current landscape was strong for 13 of the 15 subwatersheds (Fig. 3). The results of this evaluation indicated that changes in land cover were relatively minor for most subwatersheds at this rather broad scale. Only one subwatershed, WEN06, had low

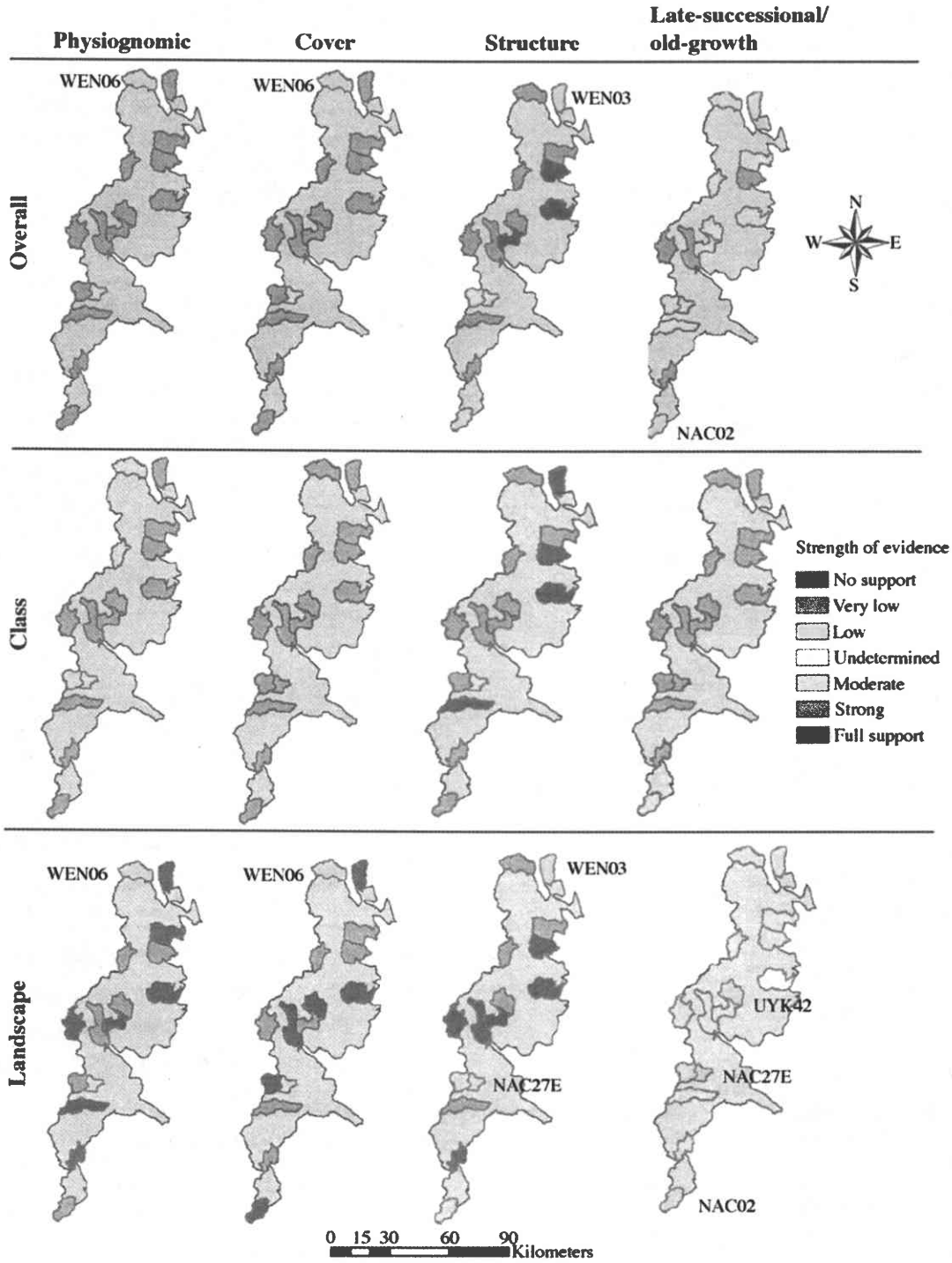

Fig. 3. Evaluation of overall, class, and landscape integrity (rows) for physiognomic, cover, structure, and late-successional/old-growth forest types (columns) by subwatershed, ESR 4. Map symbology for strength of evidence for integrity is: no support = 0.00; very low = (0.00, 0.25), low = (0.25, 0.50); undetermined = 0.50; moderate = (0.50, 0.75); strong = (0.75, 1.00); full support = 1.00.

support for overall physiognomic integrity, and this was primarily conditioned by poor correspondence of several landscape metrics to their reference conditions (Fig. 4A). There was strong support for integrity within physiognomic classes for 11 of the 15 subwatersheds (Fig. 3). Support was only moderate for the other four subwatersheds, with departures from reference conditions being most pronounced for non-forest and herb physiognomic classes (Fig. 4B). Seven of the 15 subwatersheds demonstrated full support for landscape integrity.

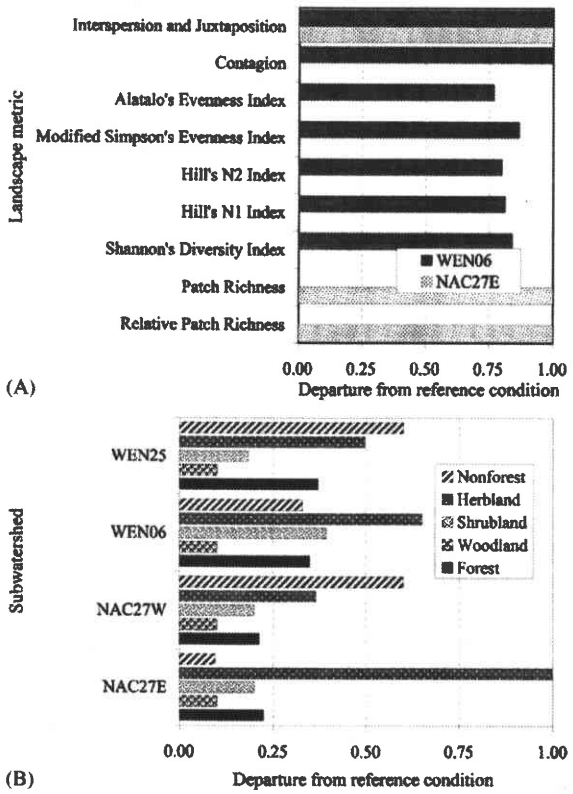

Fig. 4. Support for landscape integrity. (A) Departures of landscape metrics (Table 3) from reference conditions for subwatersheds displaying low to moderate support for overall landscape integrity (Fig. 3) of physiognomic classes (Table 1). The abscissa is still a measure of strength of evidence, but the logic has been inverted by negation to show departure from, rather than correspondence with, reference conditions. Missing bars indicate no departure from reference condition. (B) Departures of class metrics (Table 2) from reference conditions for subwatersheds displaying low to moderate support for class integrity (Fig. 3) of physiognomic classes (Table 1). Departures are summarized by physiognomic class.

3.2. Evaluation of cover conditions

Results for overall cover integrity (Eq. (1)) were very similar to those for physiognomic integrity (Fig. 3). In fact, based on map symbology, results appear to be identical, but there are minor variations in actual observed values. Lowest support was again seen in WEN06 (Fig. 3), and this was again due to significant departures from reference conditions within the landscape metrics (Fig. 5). Support for integrity in cover classes was uniformly strong; there was full support for landscape integrity in 6 of the 15 subwatersheds, and strong support for landscape integrity another seven subwatersheds (Fig. 3).

Evaluation of cover integrity, together with physiognomic integrity, amounts to an evaluation of compositional integrity, which relates to shifts toward fire intolerance in the landscape with decreasing integrity. Although we do not display a map for compositional integrity, the synthesis (Eq. (1)) of physiognomic integrity and cover integrity results in a map identical to the two components, physiognomic integrity and cover integrity. Therefore, we conclude that there are only minor increases in fire intolerance within 13 of the 15 subwatersheds, a moderate increase in NAC27E, and a pronounced increase in WEN06.

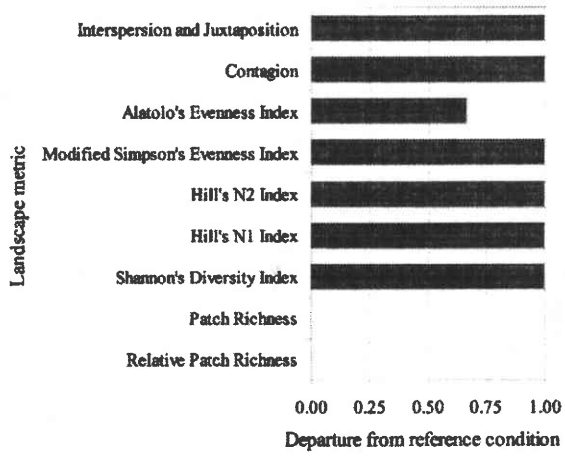

Fig. 5. Departures of landscape metrics (Table 3) from reference conditions for subwatershed WEN06, which displayed low support for landscape integrity (Fig. 6) of cover classes (Table 1). Missing bars indicate no departure from reference condition. See explanation of abscissa in Fig. 4.

3.3. Evaluation of structural conditions

Structural integrity is associated with maintenance of key ecological functions of forests, so departures from full integrity portend current or future impairment to normal functioning. Support for overall structural integrity was more variable, compared to that for overall physiognomic or cover integrity (Fig. 3). Support was strong to full for 11 of the 15 subwatersheds, three subwatersheds displayed moderate support, while support was low for WEN03. Support for class integrity was strong to full for 14 of the 15 subwatersheds, but NAC27E only displayed moderate support, primarily due to large departures from reference conditions for herbland, young multi-story forest, and the stem exclusion/open canopy classes (Fig. 6A). Support for landscape integrity was low to moderate in 4 subwatersheds (Fig. 6B), with the rest evaluating to strong to full support.

3.4. Late-successional/old-growth evaluation

Evaluation of late-successional/old-growth forest classes focuses specifically on structural conditions that require a long time to develop. Numerous wildlife species depend on this habitat (Marcot et al., 1997; Wisdom et al., 2000), so integrity of these structural classes is an important litmus test for wildlife habitat. Compared to the three previous evaluations, overall integrity of late-successional/old-growth forest was the most impaired (Fig. 3). Support for integrity was low to moderate for 11 of the 15 subwatersheds. Because overall integrity is a synthesis of class and landscape integrity (Eq. (1)), one can see that overall integrity in this case is largely being conditioned by landscape integrity (Fig. 7) because support for class integrity was strong for 14 of the 15 subwatersheds (Fig. 3).

3.5. Landscape planning for restoration

Only one subwatershed, NAC27E, rated as very high priority for restoration (Fig. 8), and this was based on relatively high contributions to the decision score from criteria for fire risk, feasibility, and reduced structural integrity (Fig. 9). Three subwatersheds, NAC23, WEN03, and NAC27W, rated as high priority for restoration (Fig. 8), again primarily based on substantial contributions from criteria for fire risk, feasibility, and reduced structural integrity compared to other subwatersheds (Fig. 9). Based on sensitivity analysis provided by the Priority Analyst component of EMDS (Reynolds et al., 2003b), the decision model was considered very robust (Saaty, 1992). For example, the ordering of subwatersheds as alternatives for restoration was most sensitive to the compositional integrity criterion; the weight on this criterion would need to increase by 32% to cause a reordering of calculated priorities.

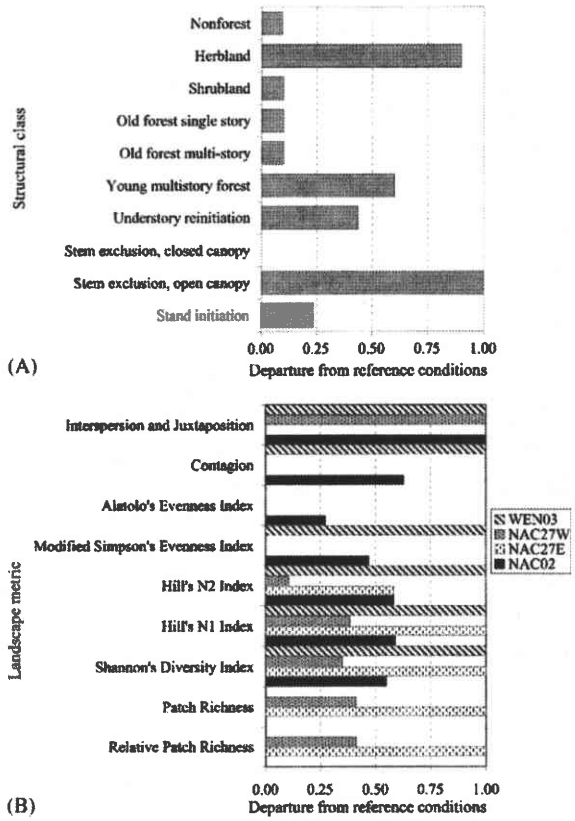

Fig. 6. Support for structural integrity. (A) Departures of class metrics (Table 2) from reference conditions for subwatershed NAC27E, which displayed moderate support for class integrity (Fig. 3) of structural classes (Table 1). See explanation of abscissa in Fig. 4. Departures are summarized by structural class. (B) Departures of landscape metrics (Table 3) from reference conditions for subwatersheds displaying low to moderate support for landscape integrity (Fig. 3) of structural classes (Table 1). See explanation of abscissa in Fig. 4.

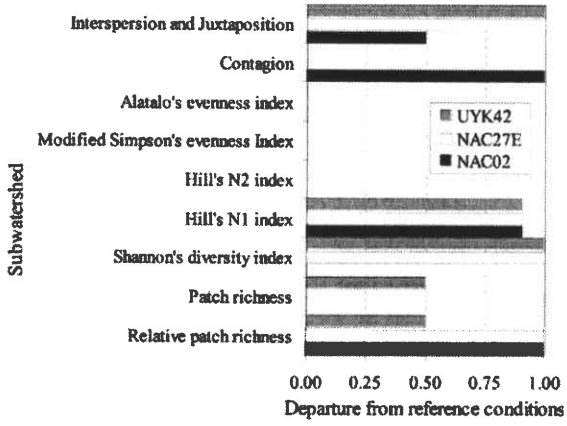

Fig. 7. Departures of landscape metrics (Table 3) from reference conditions for subwatersheds displaying low support for landscape integrity (Fig. 3) of late-successional/old-growth classes (Table 1). See explanation of abscissa in Fig. 4.

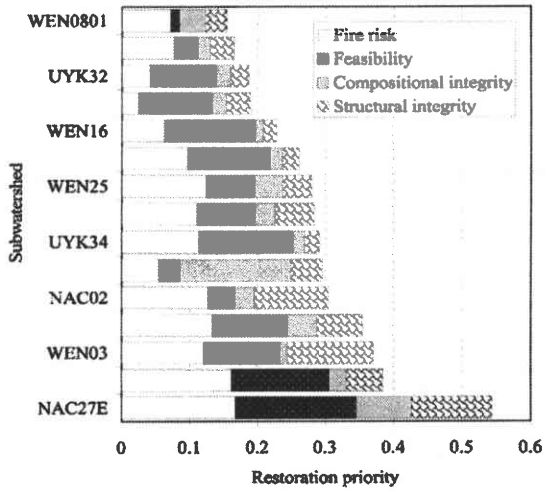

Fig. 9. Contributions of primary decision criteria (Table 4) to the overall goal of restoration priority. The sum of the contributions for each subwatershed is the overall decision score for the subwatershed.

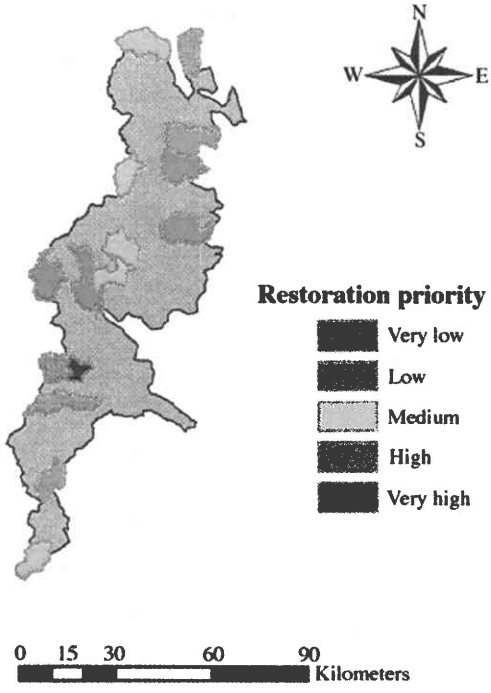

Fig. 8. Priorities for subwatershed restoration from the priority analyst component of EMDS. Symbology for priorities (very low, low, etc.) is based on the natural-breaks algorithm in ArcMap. Actual priority scores for subwatersheds are displayed in Fig. 9.

4. Discussion

Logic-based evaluation in EMDS significantly extends the analytical capabilities of GIS compared to conventional GIS overlay procedures, which generally implement a Boolean form of logic that returns a simple yes or no result (e.g., a stand of timber is, or is not, suitable for logging). Although Boolean logic is commonly used to perform evaluations in a GIS, its usage is more often for computational convenience than for reason of best fit to a problem analysis. Continuing with the timber stand selection example, consider the criterion of slope steepness. In a conventional overlay approach, a stand might be rejected for selection if it failed to meet the requirement of slope $\leq$30%, even though the slope of the stand in question was 30.01%. In contrast, the evaluation of slope, implemented in a NetWeaver logic model, allows the developer to express the result that a slope of 30.01% is nearly fully satisfactory. More generally, the strength of evidence metric allows the user to express a continuous measure of correspondence that is more consonant with how people naturally reason about such relations.

For large analytical problems such as our example, designing and implementing all the individual steps in

a large and complex overlay process is time-consuming and prone to error. The addition of the Model Builder component to ArcGIS 8.3 significantly expedites such complex overlay procedures by providing an intuitive graphic interface for designing the complete specification, and has the added advantage that the resulting model clearly documents the construction of the final solution. However, logic specifications for problem evaluation designed in NetWeaver not only perform a similar function of documenting the path to the final solution, but more readily support the more precise form of evaluation described above, and provide the basis for interactively tracing the details of the solution for any specific landscape element.

4.1. Key departures from the landscape evaluations

In general, evaluations of class metrics for departures in cover (physiognomic + cover type conditions) and structural (structural classes + late-successional and old forest) integrity of sampled ESR4 subwatersheds showed moderate to full correspondence with reference conditions. Similar evaluations of landscape metrics showed full to low correspondence with reference conditions, and the overall integrity of a few subwatersheds was found to be low because of a high number of departures among the landscape metrics. In short, past management had mostly affected the overall landscape mosaic, and the greatest restoration opportunities resided at that scale.

4.1.1. Assessment of physiognomic conditions

At the relatively coarse scale of physiognomic conditions, the correspondence between reference conditions and the existing condition of nearly all subwatersheds was strong, except for subwatershed WEN06 that displayed a high degree of departure. Class metrics for the current physiognomic conditions of WEN06 were outside of reference conditions (i.e., the 10th to 90th percentile of the historical conditions) in 19 of 34 instances but fell within the full range of the historical data in most cases. The departures in WEN06 all indicated a decline in area and patch size of forest and concurrent increases in area, patch size, and patch density of shrubland, herbland, and non-forest driven by widespread clearcut harvesting (Fig. 4B). Departures in class metrics of WEN06 were also reflected in the characteristics of the landscape mosaic; only two landscape metrics (PR, RPR) fell within reference conditions (Fig. 4A). The effects of large amounts of regeneration cutting were to dramatically increase patch type diversity (SHDI, N1), increase the number of dominant patch types (N2), increase evenness among all patch types (MSIEI), increase evenness among the dominant patch types (Alatalo's Index, R21), reduce contagion of most elements in the mosaic, and radically increase the interspersion and juxtaposition of most patch types with one another.

4.1.2. Cover type conditions

Departures in class metrics of WEN06 cover type conditions could be explained almost entirely by changes to physiognomies, especially the herbland, shrubland, and forest cover types. Increased area and connectivity of shrubland and herbland on forest environmental settings produced a host of new herb and shrub cover types with their attendant patch density, patch size, and edge relations. Concurrently, metrics showing the connectivity of specific forest cover types revealed reduced area, increased patch density, reduced patch size, increased edge, and reduced mean nearest neighbor distance, all outcomes one would expect to be associated with increased fragmentation. Departures among landscape metrics of the current WEN06 cover type mosaic (Fig. 5) mirrored those of the evaluation of physiognomic conditions (Fig. 4A).

4.1.3. Structural conditions

Support for structural class integrity was strong to full for all subwatersheds but NAC27E, while support for landscape integrity was low for subwatersheds WEN03 and NAC27E. Departures in landscape integrity in WEN03 showed the effect of large amounts of regeneration cutting which increased patch type diversity, increased the number of dominant patch types, increased evenness among patch types, including the most dominant patch types, reduced contagion of most elements in the mosaic, and increased the interspersion and juxtaposition of most patch types with one another. Departure in structural class integrity in NAC27E told an entirely different story of the effects of past management (Fig. 6A). Selection cutting of early seral overstory species like

ponderosa pine, western larch (*Larix occidentalis*), and Douglas-fir (*Pseudotsuga menziesii*) had increased the abundance of young multistory forest structure to a level of super-abundance (i.e., 46.1% of the current forested landscape versus a range of reference conditions of 5.9–32.8%), and fire exclusion had all but eliminated the stem-exclusion, open-canopy structure. Old forest multi-story and single-story abundance had been reduced to zero. Class metrics for the current structural conditions of NAC27E were outside of reference conditions in 21 of 50 instances and fell outside the full range of the historical data in 15 of the 21 cases. Departures among the landscape metrics of NAC27E offered a unique story there too. Selection cutting had simplified the landscape mosaic thereby dramatically reducing patch type diversity and dominance.

4.1.4. Late-successional/old forest (LSOF) conditions

Support for LSOF class integrity was strong for all subwatersheds but NAC02, while support for landscape integrity was moderate to low for all subwatersheds, with NAC02, NAC27E, and UYK42 landscape mosaics apparently being in the worst condition (Fig. 3). In NAC02, the evaluation of class metrics showed that timber harvesting had eliminated late-successional and old-forest structures, including old multi-story and single-story structures. This had the effect of increasing the abundance and connectivity of other forest structures to a supra-normal level. This was reflected in the patch-size, patch-density, and mean nearest-neighbor metrics. For the landscape mosaic, this had the effect of drastically simplifying the map, which was reflected in dramatic departures (i.e., reduction) in patch-type richness, diversity, and dominance, as well as reduced interspersion and juxtaposition of patch types comprising the mosaic. Departures in LSOF class integrity were alike in subwatersheds NAC27E and UYK42. Again, old-forest structures were eliminated by timber harvest, but the abundance of late-successional structures was within the ranges of reference conditions. Effects of these changes on the landscape mosaic were similar to those observed for subwatershed NAC02, with the exception that landscape contagion had increased substantially while dominance, diversity, interspersion, and juxtaposition declined. This was caused by simultaneous increases in abundance of forest structural conditions that were neither late-successional nor old forest in character, and connectivity of non-forest patches (i.e., clearcut areas not yet forested).

4.2. Discovering restoration priorities

We stated earlier that priorities for landscape restoration would be based on an assessment of some key departures in compositional and structural integrity; feasibility of management, which was composed of steepness of the watershed, road access, and value of the timber; and fire risk, which was composed of crown fire potential under an average wildfire burn scenario, and fuel loading (Table 4). The incorporation of feasibility and risk criteria was to inform the decision-making process with real-world criteria that would influence our ability to make restoration decisions for other than purely ecological reasons. When risk and feasibility criteria were considered, we found that subwatershed NAC27E was the clear frontrunner for restoration, but to our surprise, we learned that subwatersheds were shuffled in their priority when risk and feasibility considerations were allowed to enter the mix (Figs. 8 and 9). For example, NAC23 turned out to be the second priority subwatershed for restoration; departures in compositional and structural integrity were mild at worst, but fire risk was high as was feasibility of management by our measures. Likewise, the third priority subwatershed, WEN03, had the most significant departures in structural integrity, but the least significant departures in compositional integrity, and relatively high fire risk and feasibility.

4.3. Landscape evaluation and restoration planning in EMDS

Reynolds (2001) discussed various advantages to performing landscape analyses with EMDS. In the present context, two reasons stand out in particular. First, logic-based models accommodate large analytical problems that involve abstract concepts such as integrity, and that require the synthesis of large amounts of diverse information. In this study, for example, six knowledge bases were used to evaluate 225 class and landscape metrics against membership

functions requiring a total of 844 parameters, and results were synthesized into 4 primary topics representing dimensions about which landscape integrity might be evaluated. Second, although logic models evaluated by EMDS can become large and complex, the logic engine allows both developers and users of the system to trace the derivation of conclusions in a highly intuitive browser interface that readily conveys both the structure of the logic and the basis for conclusions.

As illustrated in this study, the current implementation of EMDS supports an explicit two-phase, integrated approach to evaluation and planning in which evaluation is first performed with the NetWeaver logic engine and planning is subsequently performed with the Priority Analyst component. Design for the current implementation of EMDS was motivated by the senior author's previous experiences, working with management teams who were using earlier versions of the system. In particular, it became clear that attempts to use what was then essentially an application for landscape evaluation for determining things such as restoration priorities were not very workable. It was simply too confusing for management teams to simultaneously evaluate conditions and establish priorities. The nature of the confusion is understandable, considering that setting priorities during planning requires goals, objectives and the application of values. Evaluation is not value-free either, because interpretation requires the application of judgment, which also depends on values, but the values applied in the two phases are generally different. For example, evaluation typically requires judgments about what is acceptable, whereas planning typically requires judgments about what is desirable (Reynolds et al., 2003a).

An additional benefit to separate, but integrated evaluation and planning phases in the overall decision process is that it is easier to explicitly address the feasibility of management choices in the planning phase with such a framework (Reynolds, 2002). Explicit consideration of additional factors such as feasibility of management or fire risk are potentially important in the planning phase of a restoration project, because those landscape features in the worst condition with respect to integrity, are not necessarily the best candidates for restoration, given various constraints such as time, budget, logistics, and even political realities. For example, considering only impairments to integrity, subwatershed WEN06 would clearly have been given top priority, but, when feasibility and fire risk are also considered, it drops to sixth place among the set of alternatives (Fig. 9).

This study has presented the first published example of an EMDS 3.0.2 application. Compared to previously published reports, based on applications of earlier versions of the system such as Reynolds et al. (2000), this study describes a significant evolutionary step in the design of decision-support technology for adaptive management by illustrating a practical approach to integrated evaluation and planning. Although the concept of integrated evaluation and planning described in this study is, in fact, relatively simple, it is potentially powerful insofar as it clarifies and simplifies evaluation and planning activities in forest management applications.

Acknowledgements

We acknowledge research support from President Clinton's Northwest Forest Plan under the aegis of the NOCLAMMS Project, and from the Managing Disturbance Regimes Program of the USDA Forest Service, Pacific Northwest Research Station. We are grateful for thoughtful reviews of an earlier draft of the manuscript by Jerry Franklin (University of Washington), Tom Spies, and Bob Keane (U.S. Department of Agriculture, Forest Service Research).

References

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

Eyre, F.H. (Ed.), 1980. Forest Cover Types of the United States and Canada. Society of American Foresters, Washington, DC.

Forman, R.T.T., Godron, M., 1986. Landscape Ecology. Wiley, New York.

Hessburg, P.F., Agee, J.K., 2003. An environmental narrative of Inland Northwest US forests 1800–2000. For. Ecol. Manage. 178, 23–59 (Special Feature).

Hessburg, P.F., Smith, B.G., Kreiter, S.D., Miller, C.A., Salter, R.B., McNicholl, 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. General Technical Report

PNW-458. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Hessburg, P.F., Smith, B.G., Salter, R.B., 1999b. Detecting change in forest spatial patterns from reference conditions. Ecol. Appl. 9, 1232–1252.

Hessburg, P.F., Salter, R.B., Richmond, M.B., Smith, B.G., 2000a. Ecological subregions of the Interior Columbia Basin, USA. Appl. Veg. Sci. 3, 163–180.

Hessburg, P.F., Smith, B.G., Kreiter, S.D., Miller, C.A., McNicoll, C.H., Wasienko-Holland, M., 2000b. Classifying plant series–level forest potential vegetation types: methods for subbasins sampled in the mid-scale assessment of the interior Columbia Basin. Research Paper PNW-524. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Hessburg, P.F., Smith, B.G., Salter, R.B., Ottmar, R.D., Alvarado, E., 2000c. Recent changes (1930s–1990s) in spatial patterns of interior northwest forests, USA. For. Ecol. Manage. 136, 53–83.

Hessburg, P.F., Reynolds, K.M., Salter, R.B., Richmond, M.B., 2004. Using a decision support system to estimate departures of present forest landscape patterns from historical conditions: An example from the Inland Northwest Region of the United States. In: Perera, A.H., Buse, L.J., Weber, M.G. (Eds.), Emulating Natural Forest Landscape Disturbances: Concepts and Applications. Columbia University Press, New York, NY, Chapter 13.

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

Huff, M.H., Ottmar, R.D., Lehmkuhl, J.F., Hessburg, P.F., Everett, R.L., Alvarado, E., Vihanek, R.H., 1995. Historical and current forest landscapes of eastern Oregon and Washington. Part II: potential fire behavior and smoke production. General Technical Report PNW-355. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Kamenetzky, R., 1982. The relationship between the analytical hierarchy process and the additive value function. Decision Sci. 13, 702–716.

Lehmkuhl, J.F., Raphael, M.G., 1993. Habitat patterns around northern spotted owl locations on the Olympic Peninsula. Washington. J. Wildl. Manage. 57, 302–315.

Lovelock, J.E., 1987. Gaia: A New Look at Life on Earth, 2nd ed. Oxford University Press, Oxford.

Marcot, B.G., Thomas, J.W., 1997. Of spotted owls, old growth, and new policies: a history since the Interagency Scientific Committee report. General Technical Report PNW-408. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Marcot, B.G., Croft, L.K., Lehmkuhl, J.F., Naney, R.H., Niwa, C.G., Owen, W.R., Sandquist, R.E., 1998. Macroecology, paleoecology, and ecological integrity of terrestrial species and communities of the interior Columbia River basin and northern portions of the Klamath and Great Basins. General Technical Report PNW-410. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Marcot, B.G., Wales, B.C., Demmer, R., 2003. Range maps of terrestrial species in the interior Columbia River basin and northern portions of the Klamath and Great Basins. General Technical Report PNW-583. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

McGarigal, K., Marks, B.J., 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. General Technical Report PNW-351. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Miller, B.J., Saunders, M.C., 2002. The NetWeaver Reference Manual. Pennsylvania State University, College Park, PA.

Milne, L.J., Milne, M., 1960. The Balance of Nature. Alfred A. Knopf Press, New York.

O'Hara, K.L., Latham, P.A., Hessburg, P.F., Smith, B.G., 1996. A structural classification for Inland Northwest vegetation. West. J. Appl. Forest. 11, 97–102.

Oliver, C.D., Larson, B.C., 1996. Forest Stand Dynamics—Update Edition. Wiley, New York.

Ottmar, R.D., Alvarado, E., Hessburg, P.F., Smith, B.G., Kreiter, S.D., Miller, C.A., Salter, R.B., in press. Historical and current forest and range landscapes in the interior Columbia River Basin and portions of the Klamath and Great Basins: Linking vegetation patterns to potential smoke production and fire behavior. PNW-XXX. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Reynolds, K.M., 2001. Using a logic framework to assess forest ecosystem sustainability. J. Forest. 99, 26–30.

Reynolds, K.M., 2002. Prioritizing salmon habitat maintenance and restoration activities. In: Schmoldt, D.L., Kangas, J., Mendoza, G., Pesonen, M. (Eds.), The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making. Kluwer Academic Publishers, Boston, MA, pp. 199–217.

Reynolds, K., Jensen, M., Andreasen, J., Goodman, I., 2000. Knowledge-based assessment of watershed condition. Comp. Electr. Agric. 27, 315–333.

Reynolds, K.M., Johnson, K.N., Gordon, S.N., 2003a. The science/policy interface in logic-based evaluation of forest ecosystem sustainability. For. Policy Econ. 5, 433–446.

Reynolds, K.M., Rodriguez, S., Bevans, K., 2003b. User Guide for the Ecosystem Management Decision Support System, version 3.0. Environmental Systems Research Institute, Redlands, CA.

Saaty, T.L., 1992. Multicriteria Decision Making: The Analytical Hierarchy Process. RWS Publications, Pittsburgh, PA.

Seaber, P.R., Kapinos, P.F., Knapp, G.L., 1987. Hydrologic Unit Maps. Water-Supply Paper 2294. U.S. Geological Survey, Washington, DC.

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

Spies, T.A., 1998. Forest structure: a key to the ecosystem. Northwest Sci. 72, 34–39.

Statistical Sciences, 1993. S-PLUS Users Manual, v3.2. StatSci, a division of MathSoft Inc., Seattle, WA.

Wisdom, M.J., Holthausen, R.S., Wales, B.C., Hargis, C.D., Saab, V.A., Lee, D.C., Hann, W.J., Rich, T.D., Rowland, M.M., Murphy, W.J., Eames, M.R., 2000. Source habitats for terrestrial vertebrates of focus in the interior Columbia basin: broad-scale trends and management implications. General Technical Report PNW-485. USDA Forest Service, Pacific Northwest Research Station Portland, OR.

Wu, J., Loucks, O.L., 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. Quart. Rev. Biol. 70, 439–466.