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Decision support for evaluating landscape departure and prioritizing forest management activities in a changing environment

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ABSTRACT

We evaluated changes (hereafter, departures) in spatial patterns of various patch types of forested landscapes in two subwatersheds ("east" and "west") in eastern Washington, USA, from the patterns of two sets of reference conditions; one representing the broad variability of pre-management era (~1900) conditions, and another representing the broad variability associated with one possible warming and drying climate-change scenario. We used a diagnostic set of class and landscape spatial pattern metrics to compare current spatial patterns of test subwatersheds against the two sets of reference conditions. In a companion decision support model built with the EMDS modeling system, we considered the degree of departure in the subwatersheds, relative to the two sets of reference conditions along with two additional criteria (vulnerability to severe wildfire and timber harvest opportunity), to determine the relative priority of landscape restoration treatments, and the potential for timber harvest to underwrite the treatments. In the decision support model, the current spatial pattern conditions of physiognomic types, cover types, forest structural classes, and those of late-successional and old forest patches of the two subwatersheds were compared against the two sets of reference conditions. The degree of departure in spatial patterns of physiognomic conditions was moderate in both subwatersheds in the pre-management era and climate-change comparisons. The situation was similar for the cover-type departure analysis, but spatial patterns of cover types increased in similarity to the reference conditions in the western subwatershed under the climate-change scenario. Spatial patterns of structural conditions showed a high degree of departure in both subwatersheds when compared to either set of reference conditions, but similarity improved in the eastern subwatershed under the climate-change scenario. Spatial patterns of late-successional + old forest structure were strongly similar to the broad envelope of conditions represented by the pre-management era reference in the western and moderately similar in the eastern subwatershed, but declined in both subwatersheds when compared with the climate-change reference conditions. When the degree of departure in spatial patterns of all patch types was considered along with vulnerability to severe wildfire and timber harvest opportunity, the eastern subwatershed rated higher priority for landscape improvement using either set of reference conditions. We conclude by considering uncertainties inherent in the analysis approach, types of sensitivity analysis needed to investigate model performance, and broad implications for forest managers.

1. Introduction

Forest landscapes throughout the interior Western United States provide both context and constraint to a host of ecological processes, plant and animal interactions; they are places where humans interact with biota and their physical environments (Hann et al., 2001). Conserving native species, key ecological patterns, processes, and human habitats alike, involves managing risk. To identify risks to native species, water and air quality, landscape structure and functionality, and other human interests and values an understanding of natural variation – and the factors controlling it – is essential. The degree of natural variation in ecological conditions is also non-stationary (Millar et al., 2007); i.e., as the

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regional climate shifts in substantive ways, there is likely concordant shifting in the envelopes of conditions that define so-called natural variation. When natural variation is understood in this way, several elements become apparent: (1) landscape patterns of vegetation conditions that are concordant with the regional climate, patterns of disturbances, and other interacting ecological processes represent a very broad array of conditions, not a narrow one; (2) relatively short-lived climate anomalies (e.g., interdecadal and shorter duration) probably distort that broad envelope to a relatively small degree, but longer term and severe anomalies have the potential to distort it a great deal; (3) significant departures in conditions should be evaluated at multiple scales of space and time because climate, management, and environmentally induced changes to patterns and processes may not occur or be detected at the same scales. This study is a first attempt to develop analytical methods to evaluate multi-scale changes in vegetation conditions of two test landscapes relative to two sets of reference conditions: one that represents the broad range of conditions that occurred in these and similar biophysical landscapes during the pre-management era (~1900), and another that represents the broad range of conditions that could occur in similar landscape under a climate-change scenario.

Such information is important to understanding how past and future management may affect wildlife habitat, timber availability, recreation and amenity opportunities, species and landscape diversity, and other ecological services that forest landscapes provide. All these factors are affected by the current and future condition of forests at site, stand, and landscape scales.

On managed public lands, there is an additional need to communicate expected outcomes of management alternatives before they happen (Shifley et al., 2006). Thus, tools that provide transparent explanations of probable landscape changes as well as clear guidance on selection of management tools and strategies can be a significant benefit to natural resource managers (Oliver and Twery, 1999). Numerous decision support systems (DSS) have been developed in the past 30 years to support management of natural resources, but the majority have been developed to support project-scale management, and most only provide support for certain specific steps in the decision-making process (Mowrer et al., 1997; Rauscher, 1999).

In this study, we use the term landscape "departure" to describe a lack of correspondence between the current state of a landscape and a broad envelope of reference conditions. The point of using reference conditions and comparisons with those conditions is to highlight that a very broad range of equiprobable landscape patterns occurs when the climate of a region interacts with its biophysical settings, vegetation, and disturbance processes (Hessburg et al., 2004). In analysis, if correspondence with reference conditions is high, the degree of departure is low, and the converse is also true. This concept of departure analysis is based on the hierarchical patch dynamics paradigm of Wu and Loucks (1995) and is illustrated in Hessburg et al. (1999c,d). Departure analysis using historical reference conditions seeks to discover the primary ways that current structural and compositional patterns of a given landscape differ from those that would be expected considering the recent historical climate, biophysical settings defined by that climate and disturbance processes that were in synchrony with that climate.

Amid mounting evidence of a shifting regional climate, it is reasonable to do similar departure analysis, now asking how current patterns of a given landscape differ from those that would be expected under a plausible future climatic regime. We evaluate landscape departure in our analysis of conditions in a forest reserve located in the rain shadow of the Cascade Range in eastern Washington (United States, US). We focus on landscape departure associated with vegetation patterns under historical disturbance regimes (historical climate scenario) versus those anticipated under one plausible climate-change scenario because these two scenarios provide contrasting land management targets to test prior to implementation.

1.1. Objectives

We demonstrate an approach to evaluating current multi-scale landscape patterns with reference to an historical (pre-management era) climate scenario and a hypothetical warm–dry climate-change scenario, and use of decision modeling to set priorities among landscapes and alternative treatments. For purposes of illustrating the approach, we use a hypothetical, but plausible, climate-change scenario. Our analysis is not about accurately predicting climatic change, but about interpreting landscape consequences, given a plausible scenario.

We use the logic modeling component of the Ecosystem Management Decision Support (EMDS) system (Reynolds et al., 2003) to assess landscape departure from reference conditions under the two climate scenarios. We then used the decision modeling component of EMDS to illustrate how various landscape conditions (e.g., composition, structure, crown cover) can be prioritized for management treatments, taking into account not only considerations of landscape departure, but also logistical considerations that might be pertinent to forest managers.

1.2. Environmental context

Fire historically played an important role in shaping the patterns and processes of the landscape of the interior northwestern US. However, through the influence of Euro-American settlement and land management, fire regimes have changed (Hessburg and Agee, 2003). Federal fire-exclusion policies in the US, starting in the early 20th Century (1930s), have extended fire-free intervals in western states (Covington et al., 1994), and in the mid-elevation forests on the eastern slopes of the Cascade Mountains (Agee, 2003; Hessburg and Agee, 2003). This policy resulted in the widespread occurrence of shade-tolerant and fire-intolerant forest stands, consisting of such species as grand fir (*Abies grandis* (Dougl. ex D. Dun) and Douglas-fir (*Pseudotsuga menziesii* (Mirb. J France) (Camp et al., 1997). This reduction in fire occurrence, combined with livestock grazing, caused significant increases in tree density. Subsequent stand development resulted in the creation of more frequently occurring multi-layered fire-intolerant forest canopies (Hessburg et al., 2000c), replacing previously more open, fire-tolerant stands that once formed the landscape matrix (Hessburg et al., 2007). High competition for growing space (Oliver and Larson, 1996), and periodic and often severe drought stress these dense stands. Moreover, shade-tolerant and fire-intolerant stands are vulnerable to attack by several pathogens and defoliating insects (Hessburg et al., 1994). Mortality caused by insects and pathogens regulates density and species composition in response to stressors, and it increases surface fuel loads (Hessburg et al., 1994). In addition, these denser forests comprised of shade-tolerant species are in spatially contagious arrangements, and are prone to more severe fire behavior because surface fuels and canopy fuels are more abundant, ladder fuels are widely distributed, crown bulk density tends to be high, and the potential for crown fire ignition and spread is elevated (Huff et al., 1995).

In addition to the extant increased insect, disease, and fire danger, there is an increasing risk of landscape alteration associated with a changing climate. As a consequence of climatic change, forests may face rapid alterations in the timing, intensity, frequency, and extent of disturbances (Dale et al., 2001). Two climate-change scenarios are widely discussed as possible for the Pacific Northwest region: a shift to a warmer and wetter climate, or a shift to a warmer and drier climate (Bachelet et al., 2003). It is unclear whether such warming projections will expand or contract the influence of the Pacific Ocean on interior forest ecosystems. Ecosystems of the region are influenced by intense interdecadal climate fluctuations like the El Niño Southern Oscillation and the Pacific Decadal Oscillation (Hessl et al., 2004). As a result, tree species and landscapes of the region are already adapted to considerable climatic variability that may occur during their lifetime. Nonetheless, significant climatic change is likely to produce changed patterns of forest structure, composition, and even physiognomic conditions within the landscape as a consequence of disturbances that occur during periods of climatic shifting (Wright and Agee, 2004).

2. Material and methods

2.1. Study area

The study area encompassed a 6070 ha late-successional reserve (LSR) (Hummel et al., 2001) and adjacent lands, totaling 7992 ha. The reserve is located east of the crest of the Cascade Mountain Range in Washington State, USA (Fig. 1). Landforms of the Cascades are the result of widespread volcanic activity and glaciations (Hessburg et al., 1999a). The geological substrate of the area consists of volcanic deposits covered by coarse-textured, sandy loam soils ranging from 0.15 to 1.2 m in depth (Gifford Pinchot National Forest Soil Resource Inventory 1971, cited in Hummel et al., 2001). The nearest weather records were obtained from the USDA-Forest Service, Mount Adams Ranger Station, in Trout Lake, Washington, which receives about 116 cm of precipitation annually (Hummel and Calkin, 2005). Most

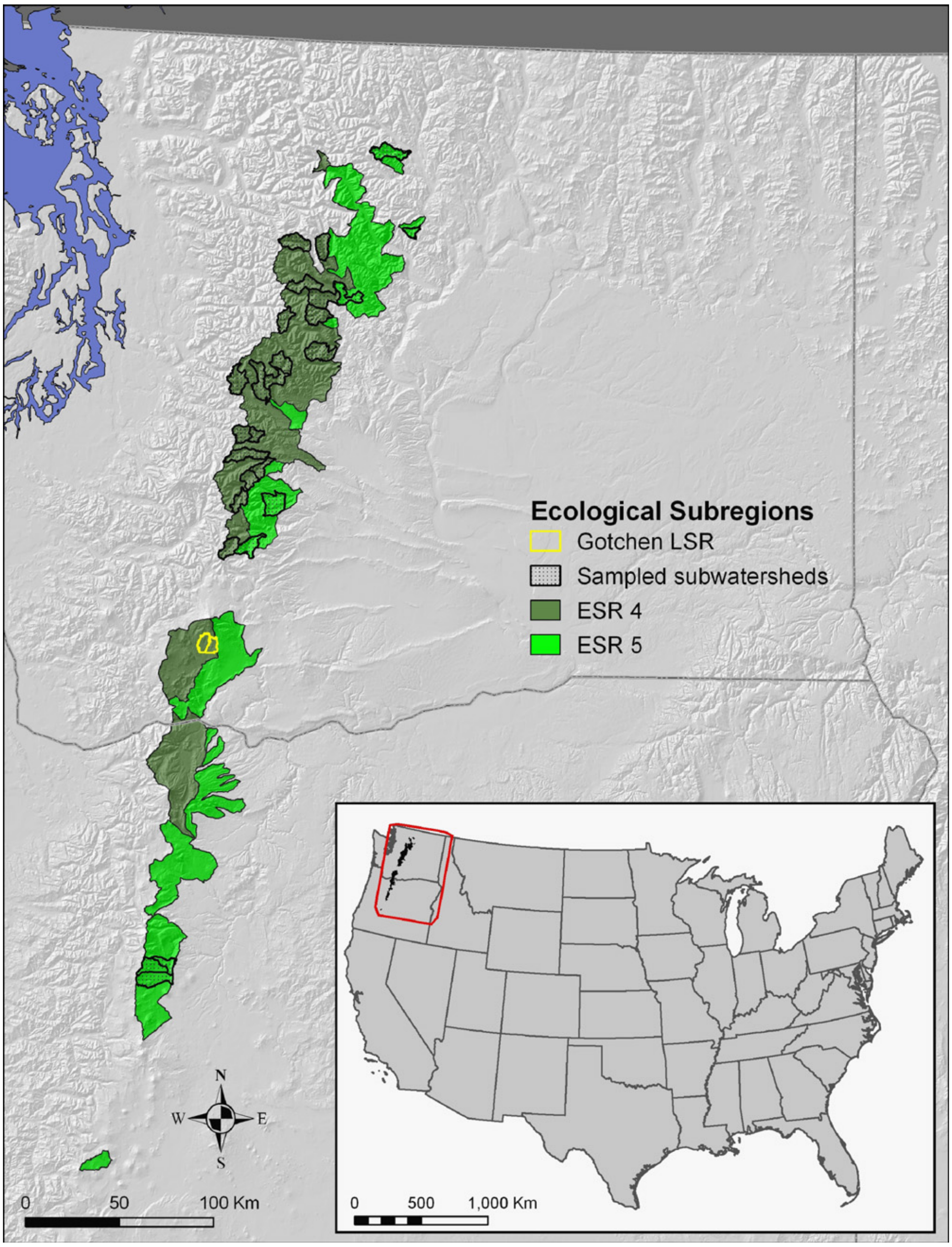

Fig. 1. Location of the Gotchen Late-Successional Reserve (study area) and Ecological subregions (ESR) 4 the subregion of the study area. ESR 5 is shown as the subregion immediately to the east of ESR 4 along the west-east temperature and precipitation gradient.

of the LSR falls within the grand fir series (Franklin and Dyrness, 1988). Current vegetation varies as a result of aspect, elevation, and physiography, and generally resembles the grand fir/creeping snowberry/vanilla leaf (*A. grandis/Symphoricarpos mollis/Achlys triphylla*) or grand fir/big huckleberry (*A. grandis/Vaccinium membranaceum*) associations described in Franklin and Dyrness (1988). Subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*) forests occur in the highest elevations.

The study area is part of a regional network of LSRs established as one component of the Northwest Forest Plan, with the objective to protect the northern spotted owl (*Strix occidentalis caurina*) and other species with an adequate distribution and arrangement of late-successional habitats (USDA and USDI, 1994).

2.2. The EMDS system for landscape analysis and planning

The Ecosystem Management Decision Support (EMDS) system, developed by the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, is an extension to ArcMap (ArcGIS® geographic information system, GIS, Environmental Systems Research Institute,[1] Redlands, CA) that provides integrated decision support for environmental analysis and planning at multiple spatial scales (Reynolds et al., 2003). The evaluation component of EMDS, implemented by Rules of Thumb (North East, PA), uses the NetWeaver logic engine to evaluate logic models represented by networks of topics concerning the state of landscape features. In design of a NetWeaver application, a topic for evaluation is represented by a testable proposition. The statement of a particular proposition is qualitative, but the formal logic specification underlying a proposition makes the semantic content of the proposition clear and precise (Reynolds et al., 2003).

The planning component Criterium DecisionPlus® (CDP), implemented by InfoHarvest (Seattle, WA), evaluates decision models based on the Analytic Hierarchy Process (AHP, Saaty, 2001), components of which may optionally implement the Simple Multi-Attribute Rating Technique (SMART, Kamenetzky, 1982). AHP models structure a decision problem as a hierarchy of criteria and subcriteria, and have been widely used for about 25 years in business and government for setting priorities, decisions about resource allocation, and alternative selection. Typically, when applying the AHP method, weights on a set of subcriteria are derived as the eigenvector solution to a matrix of all possible pairwise comparisons of the relative importance among subcriteria with respect to their contribution to the parent criterion. The SMART method evaluates attributes of alternatives with utility functions and, in the context of landscape planning, facilitates evaluating any number of alternatives (Reynolds, 2005).

2.3. Analysis process

In this application, we evaluate landscape departure of the study area with respect to historical and future climate reference conditions. The reference conditions represent a broad envelope of vegetation conditions during the recent historical climate (ca. 1900) and those that might be associated with a hypothetical future climate. The landscapes in the study area are evaluated relative to these reference conditions in EMDS. We evaluate outputs of the decision model to determine which landscape to treat first, and which landscape treatments might be most effective at favorably altering conditions within that landscape. Following subsections detail steps in the process.

[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.

2.3.1. Landscape conditions under historical and climate-change scenarios

Subwatersheds, composing the 6th level in the established hierarchy of U.S. watersheds (Seaber et al., 1987), were used as units for landscape analysis and planning, and were stratified by ecological subregion (Hessburg et al., 2000a) for computing historical or future reference conditions, because they provide a rational means for subdividing land areas that share similar climate, geology, topography, and hydrology (Formann and Godron, 1986). Administrative borders of the study area did not conform to the geographic borders, so we combined portions of six subwatersheds to form two artificial subwatersheds of sufficient area (the western subwatershed encompasses 4417 ha and the eastern one 3576 ha). This was necessary to avoid the problem of some spatial pattern metrics being influenced by areas that are too small (O'Neill et al., 1988; Turner, 1989; Lehmkuhl and Raphael, 1993). The FRAGSTATS spatial analysis program (McGarigal and Marks, 1995) was used to compute class and landscape metrics used in all landscape analyses.

The study area falls in ecological subregion 4 (ESR 4, Fig. 1, Hessburg et al., 2000a). Ecological subregions (ESR) are land units influenced by the same higher order geology and landform features, and share similar composition of potential vegetation and contribution of climate attributes (Hessburg et al., 2000a). ESR 4 is characterized as a warm/wet/low solar radiation, moist and cold forest subregion (hereafter referred to as the moist and cold forests subregion). Landscapes of this subregion are dominated by moist (67% of the area) and cold (21% of the area) potential forest vegetation types, with a total annual precipitation of 1100–3000 mm (wet), warm growing season temperatures (mean annual daytime temperature 5–9 °C), and relatively low levels of solar radiative flux (frequently overcast skies, 200–250 W m^{-2}) (Hessburg et al., 2004).

To consider the natural landscape patterns that might occur under a climate-change scenario, we adopted a change scenario involving a climatic shift to drier and warmer conditions because limiting factors for forest growth, tree mortality, and high wildfire risk are associated with protracted dry periods. Empirical data from the next drier and warmer ecoregion (ESR 5) were used as a reference set to simulate the climate-change scenario for the study area. We reasoned that the use of ESR 5 for these climate-change reference conditions was rational for several reasons: (1) ESR 5 sits adjacent to ESR 4 on the west to east climatic gradient of temperature and precipitation; (2) ESR 5 receives more solar radiation during the growing season and is considerably drier than ESR 4; (3) ESR 5 is composed of the same forest species and structural conditions as are found in ESR 4 but, is ordinarily influenced by fire regimes that are likely under our climate-change scenario; and (4) ESR 5 landscapes have existed for a long time under these warmer and drier climatic conditions such that conditions reflect the natural spatio-temporal variation in landscape patterns that would exist under the influences of succession, disturbance, and the local climate.

ESR 5 (Fig. 1) is characterized as warm/moist/moderate solar radiation moist and cold forests (Hessburg et al., 2004). Climatic conditions in ESR 5 represent a significant difference in total annual precipitation, and average growing season daytime solar radiative flux (Hessburg et al., 2000a). ESR 5 was characterized as a warm (5–9 °C annual average temperature), moderate solar (250–300 W m^{-2} annual average daylight incident shortwave solar radiative flux), moist (400–1100 mm/year total annual precipitation), moist and cold forests (predominantly occupied by moist and cold forest potential vegetation types) subregion, but subwatersheds included dry forests (Hessburg et al., 2007).

Table 1
Mapped feature and their classes for historical subwatersheds of Ecological Subregions (ESRs) 4 (historical climate reference conditions) and 5 (climate-change reference conditions)

Feature	Classes
Physiognomic class	Forest, woodland, shrubland, herbland, and nonforest.
Cover class	Douglas-fir, grand fir, lodgepole pine, ponderosa pine, silver fir, herbaceous, and nonforest.
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, nonforest

2.3.1.1. Mapping current and historical vegetation. To map representative historical and current vegetation conditions of ESRs 4 and 5, subwatersheds were randomly selected to represent at least 10% of the total subwatersheds and area of each subregion (Hessburg et al., 2004).

For each selected subwatershed, we mapped recent historical (1930s–1940s) and current (1990s) vegetation by interpreting aerial photographs. The resulting vegetation features enabled us to derive forest cover types (Eyre, 1980), and structural classes (O'Hara et al., 1996; Oliver and Larson, 1996), using methods detailed in Hessburg et al. (1999a,b, 2000b). The classifications can be found in Table 1. Vegetation conditions 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. Photographic scales were 1:12,000 (current) and 1:20,000 (historical). Photo-interpreters used available field-inventory and stand examination plot data to train and supervise their visual interpretations. Attributes of the interpreted vegetation were the same as those reported by Hessburg et al. (1999a). Patches were delineated on clear overlays, digitized, and georeferenced in a geographical information system (GIS). Overlay maps were then scanned, edited, edge matched, and imported into GIS software to produce vector coverages 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 imputation modeling procedures used to reconstruct attributes of partially harvested historical patches.

2.3.1.2. Estimating reference conditions. Five different vegetation features were used to characterize the attributes of the historical subwatersheds of ESRs 4 and 5 (Table 1). Five class metrics generated by FRAGSTATS (McGarigal and Marks, 1995) were chosen to display spatial relations within any class of these features. The five features were the physiognomic condition, the cover-type condition, the structural class condition, the combined cover type by structural class condition, and the late-successional and old forest condition. The metrics were: class area, patch density, mean patch size, mean nearest-neighbor distance, and edge density (Table 2). As an evaluation set, these metrics were useful in combination to illustrate class area and connectivity departures that may have ecological importance.

Nine landscape metrics were also selected to characterize departures associated with the entire landscape mosaic (Table 3). Using this suite of metrics, we expected to detect changes in landscape patterns that had potential ecological significance, and to understand the specific class changes that were motivating shifts in the mosaic.

Table 2
Class metrics used to characterize mapped features of historical subwatersheds of Ecological Subregions (ESRs) 4 and 5

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

Table 3
Metrics for evaluation of landscape pattern

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)

2.3.1.3. Evaluating landscape departure of subwatersheds with EMDS. A NetWeaver logic model 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 that expresses the strength of evidence (hereafter, evidence) that the operator and its arguments provide to a topic, or to another logic operator (Miller and Saunders, 2002). Considered in its entirety, the complete knowledge-base specification for a problem can be thought of as a mental map of logical dependencies among propositions, in which all logical pathways terminate in primitive networks that directly evaluate data.

Our overall objective in design of the NetWeaver logic model for this problem was to assess how far current conditions in the subwatersheds depart from historical reference conditions of ESR 4, and from the climate-change reference conditions of ESR 5. Thus, the overarching proposition under evaluation was 'The landscape exhibits low support for departure from reference conditions'. Primary topics for evaluation in this sense, corresponding to mapped features (Table 1), were: physiognomic departure, cover-type departure, structural class departure, cover type by structural class departure (representing the intersection of these features), and late-successional/old-growth forest departure.

Each class metric (Table 2) of each feature class (Table 1) and each landscape metric (Table 3) under each feature were evaluated for the current condition of each landscape. An evaluation for any metric was done by comparing the value of the metric for the current condition to a membership function for the same metric derived from ranges of the historical data (Fig. 2A). The result of each evaluation was an expression of evidence for no departure of the current conditions from the reference conditions encoded in the membership function.

Each membership function in a primitive network was defined by four points (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 evidence (i.e., complete departure). 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 evidence (no departure); values of a metric that fell within the intervals (x_1,

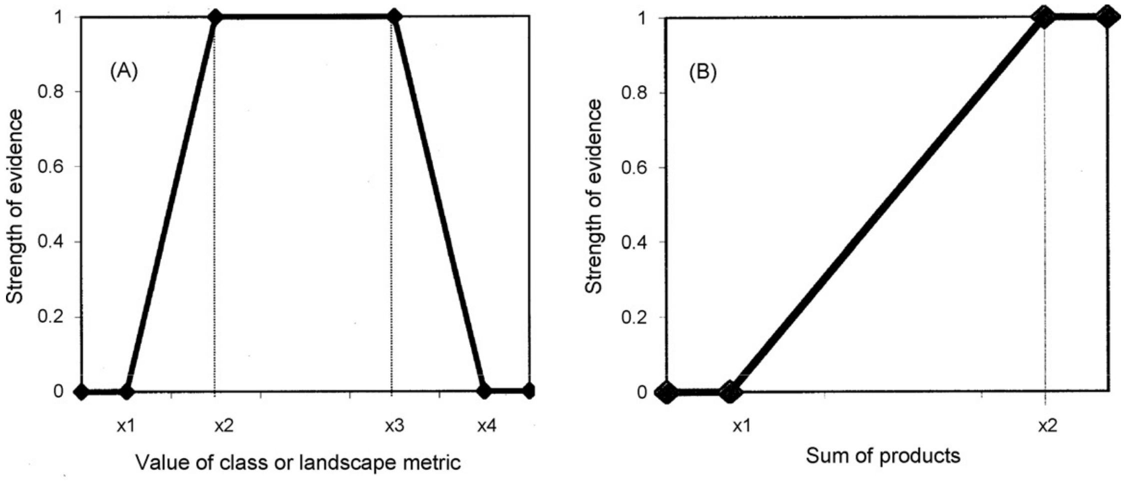

Fig. 2. Membership functions for determining strength of evidence that an observed value of a metric was within a suitable range. (A) For each metric, points x_1, x_2, x_3, and x_4 on the abscissa were determined from the historic range of variation of the metric, and represent the minimum, 10th percentile, 90th percentile, and maximum of the range of the metric, respectively. This function was used in all 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.

x_2) or (x_3, x_4), indicated some degree of support (partial evidence). The four x-points 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 departure. The logic specification for departure of primary topic t can be represented in equation form as:

$$p(t) \Leftarrow \text{AND}(p_c(t), p_l(t)) \tag{1}$$

in which $p(t)$ = evidence for no departure with respect to primary topic t, $p_c(t)$ = evidence for no class departure in topic t, and $p_l(t)$ = evidence for no landscape departure in topic t. Eq. (1) can be stated as, "the proposition for no departure of t is supported to the degree that its premises, $p_c(t)$ and $p_l(t)$, are supported." Although the logic specification of NetWeaver models is graphically constructed in the model development environment, we use equivalent equations here and subsequently for compactness.

Evidence for no class departure 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):

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

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:

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

Each weight term, $w_i(c,t)$, in Eq. (2) was set equal to the proportional area of class i in the landscape. In other words, Eq. (3) defines the parameters for the membership function for Eq. (2) whose possible range is [−1, 1]. 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):

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

In Eq. (4), each $p_j(i, c, t)$ term represents evidence for no departure in 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 the evaluation of landscape departure ($p_l(t)$ in Eq. (1)) was nearly identical to Eqs. (2)–(4) with the exception that the summation was performed over the nine landscape metrics (Table 3).

2.3.2. *Restoration priorities*

In the previous step, we evaluated landscape departure of the two subwatersheds in terms of departure of current conditions from reference conditions for the historical climate scenario and a plausible climate-change scenario. In the next step, we determined which of the two subwatersheds exhibited a higher priority for restoration. The decision model for assigning restoration priorities to subwatersheds included three primary criteria: landscape departure, fuel condition, and harvest opportunity (Fig. 3). All subcriteria of landscape departure were measures of evidence from the landscape analysis performed with the NetWeaver engine.

2.3.2.1. Evaluation of fuel condition and harvest opportunity. Subcriteria of fuel condition and harvest opportunity represented attributes of subwatersheds that were not part of the logic-based evaluation, but were included in the decision model as important logistical considerations for management (Fig. 3). Fuel condition was evaluated in terms of fire regime and fuel loading, whereas harvest opportunity was evaluated in terms of available merchantable volume, road density, and proportion of subwatershed area with slope ≤10%. The specification of slope <10% was intended not so much as a feasibility criterion as a cost criterion, indicative of areas with easy access for ground-based equipment. The Mount Adams Ranger District, Gifford Pinchot National Forest, provided a GIS-layer and a digital elevation model to calculate road density

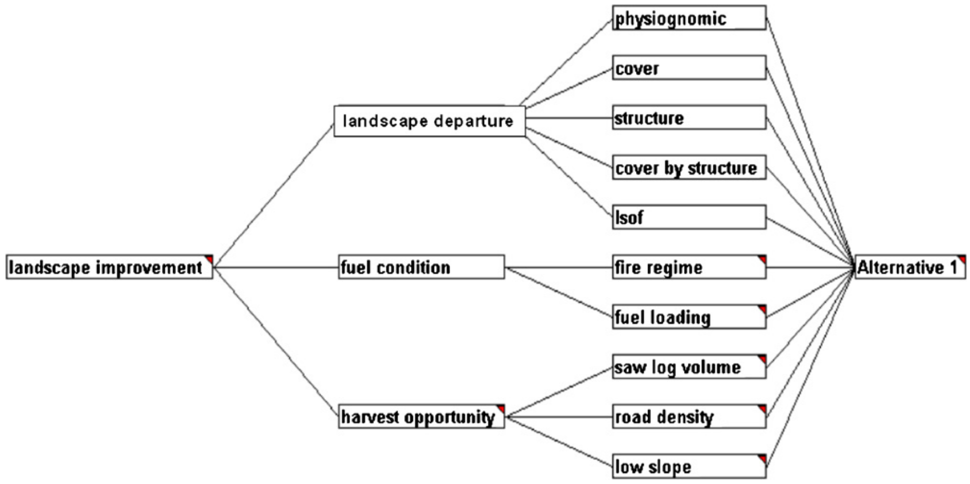

Fig. 3. Decision hierarchy for prioritizing subwatersheds for landscape management.

and slope. Road density was defined as kilometers of road per square kilometer in low-elevation stands. The second, low slope, referred to the proportion of watershed area in low-elevation stands with slope ≤10%. Fire regime was calculated as the proportion of the subwatershed that had a fire regime condition class >1. Fire regime condition class depicts the degree of departure from historical fire regimes, possibly resulting in alterations of key ecosystem components (Schmidt et al., 2002). Condition classes 1, 2, and 3 indicate no, moderate, and strong departure, respectively.

Stand-level tree-inventory data were collected following Hummel and Calkin (2005). From the stand-level data, we estimated fuel load and sawlog volume in each subwatershed using available data sets of 122 and 108 plots in the western and eastern subwatersheds, respectively. The proportion of subwatershed area with a high fuel load was calculated as the proportion of plots with a fuel load class >1, following methods of Ottmar et al. (1998). Sawlog volume (mean cubic meters per hectare) in the low-elevation stands was calculated with NED-2 (Twery et al., 2005), based on the tree lists of the plots.

2.3.2.2. Evaluating attributes of an alternative with SMART. Using standard AHP methods (Saaty, 2001), pair-wise comparisons of primary and secondary criteria (Fig. 3) provided weights for the

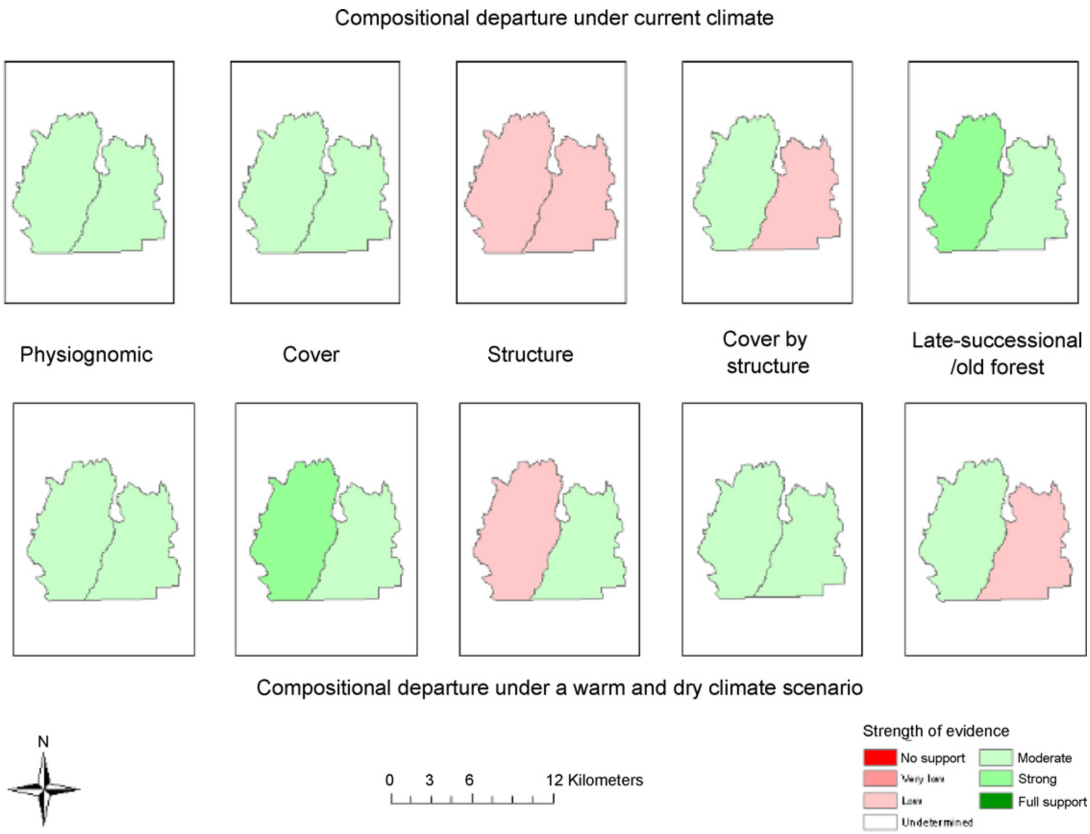

Fig. 4. Evaluation of landscape departure for current and hypothetical future climate. Each of the small figures shows the two subwatersheds of the Gotchen landscape, the coloring displays the degree of departure for the different vegetation conditions.

Table 4
Weighting of primary and secondary criteria and explanatory statements

Criterion	Weight primary criterion	Weight secondary criterion	Explanation
Landscape integrity	0.70		Highest priority primary criterion—addresses the full functionality of the landscape in terms of structure, composition, and vulnerability to disturbances
Late-successional old forest		0.41	Highest priority secondary or subcriterion in the Gotchen Late-Successional Reserve
Structural class		0.15	Is most responsive to silvicultural treatment and disturbances
Cover type by structural class		0.09	Represents the simplest combined attribution of forest structure and composition
Physiognomic type		0.05	Used to evaluate broad vegetation types
Fuel condition	0.24		Second highest priority primary criterion
Fire regime		0.12	Indicates vegetation and fire regime departure
Fuel load		0.12	High values indicate high fire vulnerability
Harvest opportunity	0.06		Least important primary criterion because the point of the reserve is to maintain late-successional habitat
Saw log volume		0.04	Most important secondary criterion under harvest opportunity
Road density		0.02	Indicates ease of access for management
Low slope		0.01	Indicates ease of access for management

decision model. Each weight (Table 4) represents the contribution of a subcriterion to the score of its parent criterion. Note that the sum of the weights on primary criteria is 1, and the sum of weights on the secondary criteria of any criterion adds up to the criterion weight. Thus, the weight on any criterion (primary or secondary) represents an allocation of importance of that criterion to the overall goal of assigning priority.

In the case of primary criteria, their importance was evaluated with respect to the overall model goal of assigning priorities for restoration or improvement. All secondary decision criteria represent the features of the subwatersheds being evaluated (Fig. 3). Each attribute was evaluated against a SMART utility function (Kamenetzky, 1982). The overall decision score was computed as the weighted average of the utility scores, with the weights being given by subcriterion weights (Table 4). Utility functions for road density, sawlog volume and low slope were designed to give greater preference to subwatersheds with shallow slopes, good road access, and high sawlog volumes in stands needing treatment, which could support restoration costs. Utility functions for the subcriteria of fuel condition were designed to give greater preference to subwatersheds with higher ratings for fire regime and fuel load, based on the objective of protecting existing forest resources. For the landscape departure subcriteria, the response scales for the feature were defined to correspond to the membership function of the NetWeaver model.

3. Results

3.1. Landscape departure

Fig. 4 summarizes the synthesis of class and landscape compositional departures from reference conditions analysed for the two evaluation subwatersheds. There was moderate evidence for no physiognomic departure in both subwatersheds in both the historical climate and climate-change scenarios (Fig. 4), indicating that little change had occurred in the spatial patterns of life forms and physiognomies relative to either set of reference conditions. The situation was similar for cover-type departure, but evidence for no cover-type departure actually increased in the western subwatershed under the climate-change scenario, indicating that current spatial patterns of cover types in the western subwatershed, while departed from ESR 4 historical conditions, would actually be closer to conditions that would be anticipated under the hypothetical climate-change scenario.

Evidence for no structural class departure was low in both subwatersheds when historical reference conditions were considered, but evidence for no departure increased somewhat in the eastern subwatershed under the climate-change scenario, indicating both subwatersheds are in need of some restorative treatments to patterns of structure, regardless of the reference used. Results for cover type by structure evaluation were analogous. Evidence for no late-successional/old forest departure was strong in the western and moderate in the eastern subwatershed under the historical reference scenario, but declined in both subwatersheds under the climate-change scenario.

If stand treatments are needed to maintain functionality of the landscape under current climate conditions, we would also want to make sure that these treatments coincide with demands of the future climate-change scenario. Therefore, we next examined relative differences in correspondence between reference conditions for the two subwatersheds in slightly more detail by decomposing compositional departure into its components of class and landscape departure (Fig. 5).

In this more detailed view (Fig. 5), there were few differences between the two subwatersheds with respect to changes in overall compositional departure, but some departures from reference conditions were evident. For example, when class departure was evaluated for the structural class feature (structure), cover type by structural class (CxS), and late-successional and old forest (lsof) features, correspondence with the climate-change reference conditions decreased in the western subwatershed. This was also true when landscape departure was evaluated for the late-successional and old forest (lsof) feature.

In the eastern subwatershed, when class departure was evaluated for the cover type by structural class (CxS), and late-successional and old forest (lsof) features, correspondence with the climate-change reference conditions also declined. This was also true when landscape departure of physiognomic types was evaluated.

3.2. Selecting a watershed for treatment

Ideally, investments in landscape improvement are directed to those landscape elements that will yield the most ecological as well as socio-economic benefits. To determine which of the two subwatersheds had the highest priority for improvement, we applied the decision model and its primary criteria to the selection process (Fig. 3). The eastern subwatershed received a higher priority rating for landscape improvement in the context of both

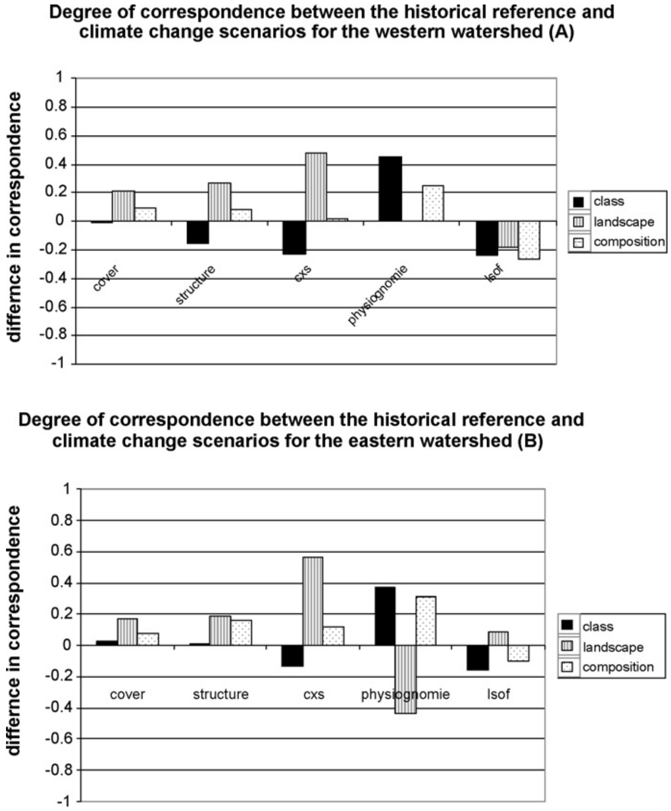

Fig. 5. Relative correspondence with historical and future climate reference conditions for the western (A) and the eastern (B) Gotchen watersheds.

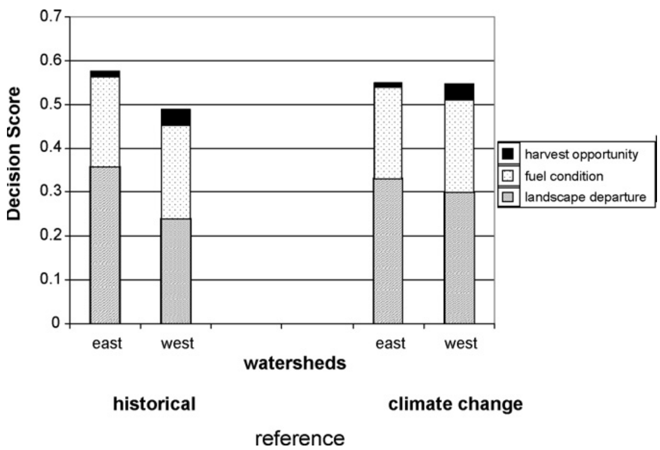

Fig. 6. Contributions of primary decision criteria to the overall goal of landscape restoration priority in relation to the historical and the climate-change reference.

the historical climate and climate-change scenarios (Fig. 6). The overall decision score under the historical reference scenario was higher for the eastern subwatershed, but scores were nearly identical for the climate-change scenario.

The contributions of harvest opportunity and fuel condition to restoration priority were essentially the same for both subwatersheds in either scenario (Table 5). The only features that changed the overall decision score were related to landscape departure. Scores for landscape pattern departure differed slightly between the historical reference and climate-change scenarios, and in both cases the contributions of lsof and physiognomic departure had the most impact on treatment priority.

Table 5
Contributions of the secondary criteria to decision scores of the eastern and western Gotchen watersheds when compared with the historical and future climate reference condition

Watershed	Historical		Climate change	
	East	West	East	West
Physiognomic	0.037	0.024	0.023	0.012
Structure	0.098	0.094	0.073	0.081
Cover by structure	0.039	0.034	0.013	0.01
lsof	0.182	0.087	0.222	0.195
Fire regime	0.119	0.119	0.119	0.119
Fuel loading	0.089	0.094	0.089	0.094
Harvest	0.012	0.037	0.012	0.037
Decision score	0.576	0.489	0.551	0.548

The decision model component of EMDS provides a standard AHP sensitivity analysis to judge the relative robustness of a specific decision model (Saaty, 2001), given the data values provided as input to the model and weights assigned to criteria and subcriteria (Reynolds et al., 2003). Priority scores of the subwatersheds for restoration were most sensitive to the criterion for harvest opportunity. The weight of this criterion would need to decrease by 13% under the climate-change scenario, and decrease by 30% under the historical scenario, to cause a reordering of the calculated subwatershed priorities. While there is no hard objective standard for assessing sensitivity of AHP model weights, a well accepted rule of thumb is that a model can be accepted as sufficiently robust if the weight on the most sensitive criterion would have to be altered by more than 10% in order to affect a reordering of alternatives (Saaty, 2001).

4. Discussion

At the highest level of our analysis, the two subwatersheds that constitute the Gotchen LSR were in relatively good condition with respect to physiognomic and cover-type departure (Fig. 4). However, fire exclusion, modest timber harvesting, and climatic trends since the early 1900s have, in varying degrees, contributed to higher levels of structural departure, including interactions between cover type and structural condition.

Our decision analysis was limited to three primary criteria: landscape departure, harvest opportunity, and fuel conditions (Fig. 3). In the study area that we used, the two subwatersheds were quite homogeneous with respect to high fuel loading conditions, so these features were of limited utility in distinguishing management priority. More generally, though, on a broader landscape where numerous landscapes are considered, and especially in the context of the western US, threats to resource values associated with wildfire certainly should to be considered in any decision model of this type. The western subwatershed was clearly preferable on the criterion of harvest opportunity (Fig. 6), but the eastern subwatershed received the higher overall decision score, based on much greater weight allocated to landscape departure (Table 4). Although harvest opportunity is a secondary criterion in some respects, forest managers might want to give this criterion greater weight on practical economic grounds.

For the purposes of demonstrating the modeling methodology, the authors assumed the role of forest managers to develop the weights for the decision model. In practice, however, EMDS applications typically involve some division of labor between scientists who have primary responsibility for developing the logic that yields an evaluation of landscape condition, and managers who bring additional practical logistical issues that should to be considered in the decision process.

Many readers at this point may be thinking, "This is all very interesting, but what about all the uncertainties inherent in such an analysis?" In fact, although it may not be apparent, our analysis is about conducting evaluations in the context of high uncertainty, so we explore this point further.

The overall modeling approach implemented in our example integrates two fundamentally different approaches to handling uncertainty. On the one hand, the parameters x_1 through x_4, used to define the membership functions of the logic model for assessing landscape departure (Fig. 2A), are statistically derived as percentiles of the observed distribution of their associated landscape metrics. Recall that each parameter was derived from a statistical sample of subwatersheds in each ESR. The metrics for each scenario are represented as a data cloud in a hypervolume that characterizes variability in all dimensions for the scenario, and the parameters can be understood as envelopes in the hypervolume that define certain critical regions used in the evaluation of landscape departure for the scenario. For example, the envelope defined by parameters x_2 and x_3 for all metrics in the hypervolume defines the interior region within the data cloud of metrics within which there is no evidence for departure. The distributions of metrics and parameters in the hypervolume relates to the statistical notion of uncertainty, which is concerned with uncertainty about the likelihood of events. On the other hand, there is a fundamentally different notion of uncertainty, lexical uncertainty, which has its origins in set theory (Russell, 1903) and is concerned with uncertainty about the definition of events (Zadeh, 1968) or, equivalently, the vagueness and imprecision inherent in human speech and cognition (e.g., strong departure from reference conditions). The obvious problem here is what is meant by strong departure? We used a logic-based approach to interpret and synthesize information to get at this relatively abstract question, and it is important to appreciate that the basic metric, strength of evidence, is a measure of lexical uncertainty. As a counter point, consider an alternative, statistically based approach in which we compute a subwatershed's distance from the centroid of the cloud of metrics that characterizes the range of variability among metrics in the ESR. One could come up with a measure of departure, but there is still the problem of what does that mean?

Finally, it worth noting that logic can be applied in this context in two rather different, but overlapping senses. In our analysis, we have emphasized logic as a way of producing an interpretation (e.g., strength of evidence for departure). However, logical argument has often been used in the sense of generating subjective probabilities (Zadeh, 1968), and we could have just as well taken that approach in formulating the problem and describing the results.

We used the historical range and variation of ESR 5 vegetation pattern conditions as a stand-in for pattern conditions that might occur under a warming climate scenario. We felt this comparison was plausible for reasons previously cited; however, other comparisons may be equally plausible. Our primary reason for choosing such an approach was that we hypothesized that the influence of a warming climate would be to nudge rather than wholesale re-invent the broad envelope of patterns extant during the period of warming. That is the difference we observed between the two sets of reference conditions for ESRs 4 and 5. But that was not our primary point. Our point was to develop a rational method for assessing trajectories of landscape pattern change under a climate-change influence, and use that information to inform decision making.

Sensitivity analysis is helpful to understand the potential strengths and weaknesses of any modeling exercise. The decision model component of EMDS includes a report on model sensitivity which we described in the results. A similar analysis could have been done for results from the logic model component, but we omit that analysis for brevity and to focus the paper on the methodology, not the actual results. However, for completeness, here we consider how the sensitivity of the logic model can be investigated. To narrow the scope of inquiry, let us take the data inputs and choice of topics treated in the logic as given. Two lines of inquiry remain: how do choices among (1) logic operators, and (2) parameters defining membership functions, influence the evaluation of departure? These two questions can be evaluated individually or concurrently. For example, in Eq. (1), there may have been indecision about whether the operator involved should be AND or UNION, and this choice is significant in terms of evaluating evidence for departure because the former treats its arguments as limiting factors, whereas the latter treats its arguments as additive and compensatory. These types of alternative representations are readily accommodated in EMDS because a single NetWeaver model can include as many such variations on model structure as desired. Indeed, two competing representations for the same logic network, as in our example from Eq. (1), can be seen as logically derived confidence bounds on the evaluation.

Now, let us consider varying parameter inputs to membership functions. As in the present study, we have frequently used percentiles of the distributions of metrics to determine the parameters of a logic model. The advantage in doing so is that specifying parameters in this way is relatively objective, but there is still the problem of which percentiles to choose. As with choices among operators, the choice of percentiles is likely to be significant in terms of influencing final interpretations generated by the model. In the present study, recall that we used percentiles of 0, 10, 90, and 100. Another obvious set of choices for percentiles could have been 10, 20, 80, and 90. Clearly, it would be easy to generate several such sets of choices to explore changes in model behavior with changes in parameters.

Finally, one of the more novel aspects of the present study is that the analysis of vegetation condition, as a prelude to making management decisions about investments in restoration, is both retrospective (comparing existing conditions to historical reference conditions) and prospective (comparing existing conditions to plausible reference conditions of a future climate scenario). In light of the current reality of global climate change and its downscaled regional influences (McNulty and Aber, 2001; Spittlehouse and Stewart, 2003), a more circumspect approach to our analysis might not only consider where a system has come from, but where it may be headed, and the tradeoffs associated with the changes. Logic- and scenario-based modeling, as illustrated in this study, may help surface ramifications of contemporary management that might otherwise be overlooked. The conundrum for forest managers is that the actual reference conditions of a future climate scenario cannot yet be predicted with any reasonable degree of certainty. However, extending our example to include multiple plausible scenarios may help identify management strategies that minimize future risk and conserve options for future management.

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