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Landscape Evaluation and Restoration Planning

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Abstract Contemporary land managers are beginning to understand that landscapes of the early 20th century exhibited complex patterns of compositional and structural conditions at several different scales, and that there was interplay between patterns and processes within and across scales. Further, they understand that restoring integrity of these conditions has broad implications for the future sustainability of native species, ecosystem services, and ecological processes. Many too are hungry for methods to restore more natural landscape patterns of habitats and more naturally functioning disturbance regimes; all in the context of a warming climate. Attention is turning to evaluating whole landscapes at local and regional scales, deciphering their changes and trajectories, and formulating scale-appropriate landscape prescriptions that will methodically restore ecological functionality and improve landscape resilience. Here, we review published landscape evaluation and planning applications designed in EMDS. We show the utility of EMDS for designing transparent local landscape evaluations, and we reveal approaches that have been used thus far. We begin by briefly reviewing six projects from a global sample, and then review in greater depth four projects we have developed with our collaborators. We discuss the goals and design of each project, its methods and utilities, what worked well, what could be improved and

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related research opportunities. It is our hope that this review will provide helpful insights into how spatial decision support technologies may be used to evaluate and plan for local and perhaps larger-scale landscape restoration projects.

Keywords Landscape analysis · Restoration planning · Reference variation · Departure analysis · Future range of variability · Historical range of variability · Vegetation pattern · Vegetation structure · Climate change · Spatial decision support · EMDS

1 Introduction

Over the last several centuries, human settlement, development, and management have altered the ecological patterns and processes of forested landscapes across the U.S. such that every ecosystem has been touched by at least one of these influences. Wildfire suppression, management practices that excluded wildfire (e.g., road and rail construction), and domestic livestock grazing have altered even wilderness and roadless areas. In the western U.S., these influences occurred in the late 19th and 20th centuries. Today, few forests on public lands fully support their native flora and fauna, and wildfires and insect outbreaks are especially unprecedented in their periodic severity and spatial extent. In response, there is public mistrust of foresters and land managers, and a succession of environmental laws has ensued to constrain forest management. Additionally, there is little shared insight as to methods or philosophies that could guide landscape restoration and maintenance in a manner that cooperates with native ecosystem structure and function.

Toward development of a shared vision and goals, scientists, public land managers, and citizens are beginning collaborative partnerships to develop a common understanding of the causes and consequences of past management on national forests, and of their possible future trajectories with climatic warming. Here, we review several applications developed with EMDS for landscape evaluation and restoration planning in forests of the Inland Northwest U.S. These applications can be used to:

(1) strategically and tactically plan for landscape restoration,
(2) evaluate the status and trends of forest-landscape vegetation and habitat conditions,
(3) evaluate the vulnerability of conditions to wildfire, insect, and pathogen disturbances, and
(4) conduct these evaluations in the context of recent historical and likely future climates.

Our goal in presenting these examples is to show the broad utility of EMDS in landscape evaluation and planning environments. We refer readers to the references for additional details of the projects. First though, we begin by providing a brief background on the settlement and management history of this region and related effects. This context clarifies the origins of specific restoration goals and potential pathways to achieve them.

1.1 Background

Subsistence agriculture, hunting, and burning activities dominated early aboriginal management of the Holocene North American landscape. These activities enabled colonization of the continent and cultural development over thousands of years, but not without attendant landscape impacts associated with hunter-gatherer, nomadic, and subsistence lifestyles (Pyne 1982; Sauer 1971; White 1991, 1992, 1999). Burning by Native Americans created new and expanded existing herblands, meadows, and open wooded expanses, thereby enhancing harvest of edible plants, nuts, and berries. It also increased sighting distances in the event of sneak-attacks by marauding tribes, and improved forage for wild ungulates, which enhanced hunting both near and away from encampments. Intentional burning was also employed along major travel routes to improve food supplies while traveling and to increase travel ease and safety. Indian burning lacked direct spatial controls on burned area or fire effects, and burns often travelled farther and killed more forest than intended. Nonetheless, Native Americans were the first fire managers, and their use of intentionally lighted fires greatly aided their travels and lifestyles.

In the mid-19th century, settlement and management of the Great Plains, and the Pacific, Rocky Mountain, and Intermountain West by Euro-American settlers accelerated to a fever pitch with the discovery of lush and productive prairies on the plains, and in the intermountain valleys, rich gold and silver ore deposits, and abundant acres for homesteading and a fresh start (Pyne 1982; Robbins 1994, 1997, 1999; White 1991). Westward migration, Native American expatriation from ancestral homelands by the U.S. cavalry, and forced settlement onto reservations produced the final downfall of the indigenous population. However, the major depredation to aboriginal populations had already been done via the introduction of exotic diseases by trappers and fur traders in the late-1700s (Hunn 1990; Langston 1995; Robbins 1994, 1997, 1999).

With settlement came land clearing for homesteads, expansion of agriculture, timber harvesting (Hessburg and Agee 2003; Langston 1995; Robbins 1997, 1999), and early attempts at wildfire suppression, which became highly effective only after the 10 a.m. rule was enacted as federal policy between 1934 and 1935 (Pyne 1982; van Wagtendonk 2007). This policy of suppressing fires by 10 a.m. of the next burn period after detection forever changed the role of wildfire, especially as it applied to primeval western landscapes. The rule was removed in the early 1970s, but moderately aggressive wildfire suppression is still practiced in the U.S.

Natural variability in wildfire frequency, duration, severity, seasonality, and extent were unavoidably altered by decades of fire exclusion, wildfire suppression, and broadly-popularized fire-prevention campaigns. Wildfire exclusion by cattle grazing, road and rail construction, successful wildfire prevention and suppression policies, and industrial-strength selective logging, beginning in the 1930s and continuing for more than 50 years, contributed not only to extensive alteration of natural wildfire regimes, but also to changes in forest insect and pathogen disturbance regimes, causing them to shift significantly from historical analogues. For example, the duration, severity, and extent of conifer defoliator and bark beetle outbreaks increased substantially (Hessburg et al. 1994), becoming more chronic and devastating to timber and habitat resources (e.g., see Hummel and Agee 2003).

Selective logging accelerated steadily during and after the Second World War. Fire exclusion and selective logging primarily advanced the seral status and reduced fire tolerance of affected forests with the removal of fire-tolerant species and the largest size and age classes (Hessburg and Agee 2003). It also increased the density and layering of the forests that remained because selection cutting favored the regeneration and release of shade-tolerant and fire-intolerant tree species such as Douglas-fir, grand fir, and white fir (Hessburg et al. 2005). Recent warming and drying of the western U.S. climate has exacerbated these changes (McKenzie et al. 2004; Westerling and Swetnam 2003; Westerling et al. 2006), and will continue to do so.

Changes from pre-settlement era variability of structural and compositional conditions affected regional landscapes as well. Prior to the era of management, regional landscape resilience to wildfires naturally derived from mosaics of previously burned and recovering vegetation patches from prior wildfire events, and a predictable distribution of prior fire event sizes (Moritz et al. 2011). This resilience yielded a finite and semi-predictable array of pattern conditions (Hessburg et al. 1999a, b, c, 2000a) that supported other ecological processes at several scales of observation.

As a result of these many changes, land managers faced substantial societal and scientific pressure to improve habitat conditions and viability of native species, and the food webs that support them. Because alternatives to managing for historical analogue or related conditions are untested or untestable (Millar et al. 2007; Stephens et al. 2010), public land managers have been required to restore a semblance of the natural abundance and spatial variability of habitats. This has largely been reinforced by endangered species and environmental laws.

On the other hand, public mistrust over decades of commodity-driven management on public lands paralyzes most attempts at large-scale landscape restoration, and with some good reason. Restoration prescriptions for thinning, underburning, and slash disposal are often seen as blanket remedies, and another form of landscape oversimplification by management, which is the current problem. The time is ripe for more transparent evaluation of landscape patterns, processes, changes in their interactions and associated restoration planning, and even riper for management applications to be conducted experimentally and transparently, with full access to scientific methods and adaptive learning.

Below, we briefly highlight several examples in which EMDS was used to conduct landscape evaluations for decision-making in a variety of planning contexts. In these examples, tools within the EMDS modeling framework were used to develop evaluations that considered the effects of various management strategies or tactics on the natural or developed environment, or to select specific lands or man-made features for management, management avoidance, or modification. These examples illustrate how EMDS might be used at a variety of scales with varied goals in mind. Hopefully it becomes apparent that if the management goals and contexts can be clearly articulated, a logical and transparent application can be developed in EMDS to represent it.

1.2 Previous Examples of Evaluations Using EMDS

Stolle et al. (2007) developed an EMDS application to evaluate natural resource impacts that might be caused by conventional management practices (site preparation, planting, and harvesting) in a forest plantation. Using logic networks designed with the NetWeaver developer tool (Miller and Saunders 2002, see also Chapter 2), they evaluated the effects of management activities on ambient soil and site conditions as a means of representing the inherent risks associated with standard management practices of commercial plantation forestry. They mapped *fragility areas* on a forest property that were sensitive to standard forestry practices (according to an established set of criteria), which enabled them to implement low-impact management of the natural resources, while producing an economic return.

Girvetz and Schilling (2003) used EMDS to build a knowledgebase that evaluated the environmental impact of an extensive road network on the Tahoe National Forest, CA, USA. Using spatial data for natural and human processes, the authors evaluated the assertion that any road has a high potential for impacting the environment. They used modeled potential environmental impact to negatively weight roads for a least-cost path network analysis to more than 1500 points of interest in the forest. They were able to make solid recommendations for providing access to key points of interest, while streamlining and reducing the road network and reducing its environmental impacts.

Janssen et al. (2005) developed an EMDS model to provide decision support for wetland management in a highly managed wetland area of the northern Netherlands. Because legislation in the European Union has mandated the importance of preserving wetland ecosystems, they funded development and implementation of an operational wetland evaluation decision-support system to support the European policy objectives of providing ongoing agriculture, expanding recreation opportunities, maintaining residential opportunities, and conserving wetland habitats. They compared three possible management alternatives for their influence on water quality and quantity, the local climate and biodiversity, and social and economic values: (1) modern peat pasture (current), (2) historical peat pasture, and (3) dynamic mire. The model adequately framed management options and provided needed context for decisions about future land allocations.

Wang et al. (2010) developed an integrated assessment framework and a spatial decision-support system in EMDS to support land-use planning and local forestry decisions concerning carbon sequestration. The application integrated two process-based carbon models, a spatial decision module, a spatial cost-benefit analysis module, and an Analytic Hierarchy Process (AHP) module (Saaty 1992, 1994). The integrated model provided spatially-explicit information on carbon sequestration opportunities and sequestration-induced economic benefits under various scenarios of the carbon-credit market. The modeling system is demonstrated for a case study area in Liping County, Guizhou Province, China. The study demonstrated that the tool can be successfully applied to determine where and how forest land uses may be manipulated in favor of carbon sequestration.

Staus et al. (2010) developed an EMDS application to evaluate terrestrial and aquatic habitats across western Oregon, USA, for their suitability of meeting the ecological objectives spelled out in the Northwest Forest Plan (USDI 1992; USDA 1994), which included maintenance of late-successional and old-growth forest, recovery and maintenance of Pacific salmon (*Oncorhynchus* spp.), and restored viability of northern spotted owls (*Strix caurina occidentalis*). Areas of the landscape that contained habitat characteristics supporting these objectives were modeled as having high conservation value. The authors used their model to evaluate the ecological condition of 36,180 township and range sections (~260 ha each) across the study domain. They identified 18 % of study area sections as providing habitats of high conservation value. The model provided information that could be considered in future land management decisions to spatially allocate owl habitats in the western Oregon portion of the Northwest Forest Plan area. Furthermore, their results illustrated how decision-support applications can help land managers develop strategic plans for managing large areas across multiple ownerships.

White et al. (2005) developed an EMDS knowledge base for evaluating the conservation potential of forested sections in the checkerboard ownership area of the central Sierra Nevada in California, USA (see also Chapter "Forest Conservation Planning"). Four primary topics were evaluated including each section's (1) existing and potential terrestrial and aquatic biodiversity value, (2) existing and potential mature forest connectivity, (3) recreation access and passive use resource opportunities, and (4) risks of exurban development, unnatural fire, and management incompatible with mature forest management. Results of evaluations of each primary topic were networked in a summary knowledgebase. The knowledgebase allowed the science team to recommend arrangements of sections within the checkerboard ownership that showed the highest promise of conserving important terrestrial and aquatic species and habitats, in the long term.

2 Four Detailed Examples

In sections that follow, we review in more detail four EMDS model applications that we and our collaborators developed to evaluate landscapes in unique contexts for the purpose of determining restoration needs and treatment priorities.

In Sect. 3, we present an approach to estimating the extent to which present forest landscape patterns in the Inland Northwest have departed from the conditions that existed before the era of modern management ($\sim$1900). In Sect. 4, we describe the use of EMDS to evaluate existing patterns of forest vegetation in a random sample of watersheds of one ecoregion against a corresponding broad envelope of historical reference conditions for the same ecoregion. In a third application (Sect. 5), changes in spatial patterns of various patch types of forested landscapes were evaluated in two watersheds in eastern Washington, USA, with respect to the patterns of two sets of reference conditions; one representing the broad variability of pre-management era ($\sim$1900) conditions, and another representing the broad variability associated with one plausible warming and drying climate-change scenario. Finally, in Sect. 6, we present an EMDS application designed to provide decision support for landscape restoration of a managed dry forest area in the eastern Cascade Mountains of Washington State.

3 Evaluating Changes in Landscape-Level Spatial Patterns

In Hessburg et al. (2004), we present a landscape evaluation approach to estimating the extent to which present-day forest landscape patterns have changed from the variety of conditions that existed before the era of modern management ($\sim$1900). Our goal in this foundational project was to approximate the range and variation of these recent historical patterns, use that knowledge to evaluate present forest conditions, and assess the trajectory and ecological importance of any significant changes. The approach was based on the Wu and Loucks (1995) hierarchical patch dynamics paradigm, which we briefly summarize here because it frames the analytical approach.

The paradigm holds that an ecosystem can be viewed as a multi-level hierarchy of patch mosaics. An ecosystem's overarching dynamics derive from emergent properties of concurrent patch dynamics occurring at each level in a hierarchy. Across the temporal scales of a hierarchy, regional spatial patterns of biota, geology, geomorphic processes, and climate provide top-down constraint on ecological patterns and processes occurring at a meso-scale. Likewise, fine-scale patterns of endemic disturbances, topography, environments, vegetation, and other ecological processes provide critical bottom-up context for patterns and processes occurring at a meso-scale. At all spatial and temporal scales of the hierarchy, ecosystems exhibit transient patch dynamics and non-equilibrium behavior. This is due to a mix of both stochastic and deterministic properties of the supporting land

and climate systems and ecosystem processes at each level. Lower level processes are incorporated into the next higher-level structures and processes, and this happens at all levels.

Landscape patterns at each level in a hierarchy are never the same from year to year, and they never repeat in the same arrangements. However, transient dynamics are manifest as envelopes of pattern conditions at each level (literally, a naturally occurring range of variation), owing to the recurring patterns and interactions of the dominant top-down and bottom-up spatial controls (Hessburg et al. 1999a, c). Thus, patterns don't repeat in the same spatial arrangements, but they do exhibit predictable spatial pattern characteristics, for example, in the percentage area in different cover species, size class, or structural conditions, the range in patch sizes, or the dispersion of unique patch types.

Moreover, because contexts and constraints are non-stationary, the processes and patterns they reflect are non-stationary as well. In a warming climate, for example, the envelope of pattern conditions at each level in a patch dynamics hierarchy may be reshaped by the strength and duration of warming, with the existing patterns as initial context. Reshaping within a level can be figuratively represented as an envelope of conditions that drifts directionally in a hyper-dimensional phase space. Because this is impossible to illustrate, we illustrate a simpler cartoon of conditions shifting in a two-dimensional phase space (Fig. 1). Relatively small amplitude and short-term changes (multi-annual to multi-decadal) in climatic inputs will do little to reshape the envelope, but large amplitude and long-term changes (centenary to multi-centenary and longer) have much greater likelihood of significantly reshaping pattern envelopes.

In this project, we developed an approach to estimating the non-equilibrium conditions associated within a meso-scale landscape in a forest patch dynamics hierarchy. For simplicity, we termed the conditions for the climatic period ending in the early 20th-century "reference conditions." Typical variation in these conditions was termed "reference variation" (RV). For our estimate of RV we chose the median 80 % range of a diagnostic set of five class and nine landscape spatial-pattern metrics (McGarigal and Marks 1995), because most historical observations typically clustered within this middle range. The class metrics were: the percentage of the total landscape area (%LAND), patch density per 10,000 ha (PD), mean patch size (MPS, ha), mean nearest-neighbor distance (MNN, m), and edge density (ED, m·ha-1). The landscape metrics were: patch richness (PR) and relative patch richness (RPR), Shannon's diversity index (SHDI) and Hill's transformation of Shannon's index (N1, Hill 1973), Hill's inverse of Simpson's λ, N2, (Hill 1973; Simpson 1949), Simpson's modified evenness index, and Alatalo's evenness index, R21, (Alatalo 1981), a contagion index (CONTAG); and an interspersion and juxtaposition index (IJI). We supplemented the FRAGSTATS source code (McGarigal and Marks 1995) with the equations for computing the N1, N2, and R21 metrics.

The focal level of the study was forest landscapes of meso-scale watersheds and their spatial patterns of structure, species composition, fuels, and wildfire behavior attributes. Structural classes were an approximation of stand succession and

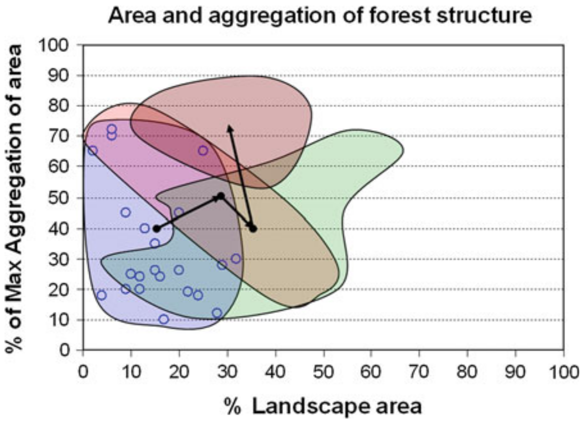


Fig. 1 Graphical representation of how landscape area and aggregation of area of a single forest structural component might vary in phase space (for example, old multilayered forest or stand initiation structure) as the climate of an ecoregion shifts. Within the concept of historical or natural range of variation, clouds or envelopes of conditions exist in phase space, for any number and combination of structural and compositional features, across a broad range of metrics, and no two are alike. The same is true for current and future ranges of variation. This broad dimensionality is readily captured in data space, quantified, and then may be used to detect significant changes in spatial patterns and variability in those patterns

development phases. Cover types reflected forest overstory species and mixes. Estimates of surface and canopy fuels reflected the available fuels to support wildfires and either surface or crownfire behavior. We focused on patterns of living and dead vegetation at this level because many of the most important changes in the dynamics of altered forest ecosystems are reflected in the living and dead structure of the affected structural and compositional landscapes (Spies 1998). We stratified landscapes into ecoregions to reflect top-down biogeoclimatic constraint on forest structural patterns and related disturbances (Hessburg et al. 2000b, 2004). Study landscapes were 4,000–12,000 ha subwatersheds.

We developed a repeatable quantitative method (outlined in Table 1) for estimating RV in historical forest vegetation patterns and of vulnerability to disturbance. The objective was to estimate a RV so that we could evaluate the direction, magnitude, and potential ecological importance of the changes observed in present-day forest landscape patterns (Keane et al. 2002, 2009; Landres et al. 1999). To automate this approach, we programmed a departure analysis application in EMDS that compared the spatial pattern conditions of a test landscape with the estimated RV that would be expected within its ecological subregion (Reynolds 1999a, 2001a). Via automation, this analysis could be repeated for any number of subwatersheds within the same ecoregion. By means of the comparison with RV, we could identify vegetation changes that were beyond the range of the RV estimates. Changes that fell within the range of the RV estimates were assumed to be within the natural variation of the interacting land and climate

Table 1 Outline of methods used in Hessburg et al. (2004) for estimating departure of present forest landscape patterns from historical (circa. 1900) reference conditions

Step	Action	References
1	Stratified Inland Northwest U.S. subwatersheds (5,000–10,000 ha) into ecological subregions using a published hierarchy	Hessburg et al. (2000b)
2	Mapped the historical vegetation of a large random sample of the subwatersheds of one subregion (ESR4 – the Moist and Cold Forests subregion) from 1930–1940s aerial photography	Hessburg et al. (1999a)
3	Statistically reconstructed the vegetation attributes of all patches of sampled historical subwatersheds that showed any evidence of prior timber harvest	Moeur and Stage (1995)
4	Ran spatial pattern analysis on each reconstructed historical subwatershed calculating a finite, descriptive set of class and landscape metrics in a spatial analysis program (FRAGSTATS)	McGarigal and Marks (1995) Hessburg et al. (1999a)
5	Observed the data distributions from the spatial pattern analysis output of the historical subwatersheds and defined reference conditions based on the typical range of the clustered data	Hessburg et al. (1999a, b)
6	Defined reference variation as the median 80 % range of the class and landscape metrics for the sample of historical subwatersheds	Hessburg et al. (1999a, b, c)
7	Estimated ESR4 reference variation for spatial patterns of forest composition (cover types), structure (stand development phases), modeled ground fuel accumulation (loading), and several fire behavior attributes	Hessburg et al. (1999a, b, c) Huff et al. (1995) O'Hara et al. (1996) Hessburg et al. (2000a)
8	Programmed ESR4 reference conditions into a decision support model (EMDS)	Reynolds (1999a, b) Reynolds (2001a, b)
9	Mapped the current vegetation patterns of an example watershed, Wenatchee_13, from the Wenatchee River basin, also from ESR4	Hessburg et al. (1999a)
10	Objectively compared a multi-scale set of vegetation maps of the example watershed with corresponding reference variation estimates in the decision support model	Hessburg et al. (1999a, b)

system, and dominant ecosystem processes. Changes that were beyond the range of RV estimates were termed "departures" that could be explored in more detail for their potential ecological implications.

We also programmed transition analysis on the test landscapes' historical and current maps of cover type and structural class to discover the path of each significant change. To conduct transition analysis, we converted the polygon maps of historical and current cover type and/or structural class to raster format (30-m resolution). These raster maps were combined such that each pixel had a historical and current cover type (and/or structural class) identity. We computed the number of pixels for each unique type of historical-to-current transition, divided this number by the total number of pixels, and multiplied that result by 100 to derive a percentage of the subwatershed area in a transition type.

Using departure and transition analyses, we were able to highlight a variety of important changes to the test landscape. For example, we found that timber harvests had converted much area dominated by the ponderosa pine (*Pinus ponderosa*) cover type to Douglas-fir (*Pseudotsuga menziesii*); regeneration harvest had highly fragmented forest cover; and old forests of the western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), Douglas-fir, and ponderosa pine zones had suffered significant depredation from selective and regeneration harvesting (18 % reduction in area).

Departure and transition analyses of fuel loading, wildfire rate of spread, crownfire potential, flame length, and fireline intensity attributes under prescribed and wildfire (90th percentile) burn scenarios depicted an historical landscape that displayed large contiguous areas with very high fuel loading and high potential for crown fires under an average wildfire scenario, typically high to extreme flame lengths, and high to extreme fireline intensities. This ordinarily high fire danger could be accounted for by a preponderance of moist to wet growing environments and a low-frequency, high-severity, stand-replacement fire regime. Large fires were relatively uncommon and they were likely driven by extreme weather or severe climatic events. However, current conditions showed that past management activities in the test landscape had reduced the likelihood of large stand-replacing fires with the introduction of nearly 50 clearcut units.

Departure analysis using landscape metrics showed poor correspondence between the present-day combined cover type-structural class mosaic and the estimates of RV. Timber harvesting had increased patch type richness, diversity, dominance, evenness, interspersion, and juxtaposition of structural class patches, and reduced overall contagion in the cover type-structural class mosaic. The historical landscape was simply patterned, consisting of fairly large patches borne of infrequent, large, high-severity fires. Management had made it more complexly patterned and fragmented.

3.1 What Worked Well?

Overall, this EMDS application did a reasonably good job of evaluating landscape pattern departures. Changes in landscape vegetation patterns were compared to a RV that simultaneously considered 18 vegetation, fuel, and fire-behavior features (e.g., physiognomies, cover types, structural classes, and potential vegetation types, fuel loads, fire rate of spread, and crownfire potential) according to a diagnostic set of 14 class and landscape pattern metrics. Results of departure and transition analyses were intuitive and useful to explaining the ecological effects of 20th-century management and settlement.

Landscape evaluations like this one must examine a host of class and landscape pattern metrics applied across a variety of mapped conditions to accurately infer class and landscape-level changes, and their significance. Evaluation in EMDS enabled analysis across a large number of landscape dimensions, with multiple metrics on each dimension. Structuring evaluations in this manner was useful to inferring change in ecological functionality with change in structure or patterning. This application tackled a hyper-dimensional problem, and it did so with relative ease.

3.2 What Could be Improved?

The EMDS application was a relatively straightforward proof-of-concept. Once it was clear that complex evaluations could be structured for analysis and interpretation, one could clearly see how other important dimensions could be integrated into the evaluations. For example, a wildlife manager could develop RV estimates for a variety of habitat features and networking arrangements. Departure analyses could evaluate and translate changes in landscape vegetation patterns and features into important changes in keystone or focal plant and animal species habitats and those of functional groups of species. A multi-scale habitat analysis would allow managers to directly interpret scaled effects of altered vegetation patterns on species varying by body size, mobility, and home range.

Future evaluations could also include the characterization of RV of landscape vulnerabilities to various insect and pathogen disturbances (e.g., see Hessburg et al. 1999a, d, 2000a). This feature is developed in the fourth application discussed below. A more inclusive application structure might ultimately include the use of other insect, pathogen, or noxious weed modeling platforms for predicting host or habitat contagion, spread potential, and intensification in the context of variables and conditions unrelated to vegetation.

Finally, it would be of theoretical value to represent landscape pattern departures across broad physiographic gradients. An expanded evaluation of this sort would help scientists and managers better understand relative degree and variation in spatial controls contributed by regional biology, geology, geomorphology, and climate. For example, a gradient-oriented analysis would lead to testable hypotheses about the nature, degree, and mechanisms of climatic influence on pattern and process; an especially hot current topic.

3.3 Research Opportunities

Perhaps the greatest opportunity to advance this application would be to develop and incorporate empirical data that adequately represent RV estimates at multiple levels in the patch dynamics hierarchy. Admittedly, this would be a large and costly task, but it would provide an immense payoff. For example, spatial heterogeneity in vegetation and fuels conditions exists in the landscape within patches, multi-patch neighborhoods, and regional landscapes as well. Improved understanding of departures at these added levels would aid understanding of the degree and manner of cross-connections between spatial scales.

Understanding typical within-patch spatial heterogeneity would give scientists and managers better insight into the lower level structures and processes influential to those occurring at a higher level, and it would improve knowledge of the principal underlying mechanisms and pathways that drive changes in vegetation patterns and vulnerability to disturbances. It would also help managers to better achieve their vegetation and disturbance regime restoration goals by helping them to more aptly specify the multi-scale patterns and variability that their patch-level silvicultural and prescribed burning prescriptions can approximate.

The same arguments can be made at other levels as well. For example, one can observe that many present-day regional landscapes are synchronized for broad-scale and damaging biotic and abiotic disturbances that may produce long-term, game-changing effects (Allen et al. 2010). Only by evaluating the spatial and temporal pattern variability of regional and local landscapes and of patches and patch neighborhoods can observers begin to understand the scales of motivating factors, the degrees and patterns of spatial and temporal controls, and primary mechanisms driving these broad-scale and emergent processes.

4 Strategic Planning for Landscape Restoration

In this second example, Reynolds and Hessburg (2005) developed methods and an EMDS decision-support application to strategically plan for landscape restoration. We illustrated a two-phase approach to evaluating departure of present-day pattern conditions of 15 forested landscapes within a single ecoregion from pre-management-era reference conditions (RV), similar to but simpler than that described in the first application above. We then computed the restoration priority among the subwatersheds, in light of the departures and other technical and economic feasibility considerations. Methods for the departure analysis are summarized in the first application above. Here, we briefly summarize methods unique to this application.

To identify sample landscapes constrained by similar environmental contexts, we used the Hessburg et al. (2000b) ecological subregions to stratify subwatersheds (ca. 4,000–12,000 ha) of the eastern Washington Cascades into biogeoclimatic zones (Fig. 2a). Subwatersheds (Fig. 2b) were used as the basic sampling units because they provided a rational means to subdivide land areas that shared similar climate, geology, topography, and hydrology. Subwatersheds compose the (12-digit) 6th level in the established hierarchy of US watersheds (Seaber et al. 1987, National Hydrology dataset available at: http://nhd.usgs.gov/).

We selected ecological subregion #4 (ESR4) as the biogeoclimatic zone in which we sampled and estimated reference conditions (Fig. 2a). 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 $\mathrm{W{\cdot}m^{-2}}$;

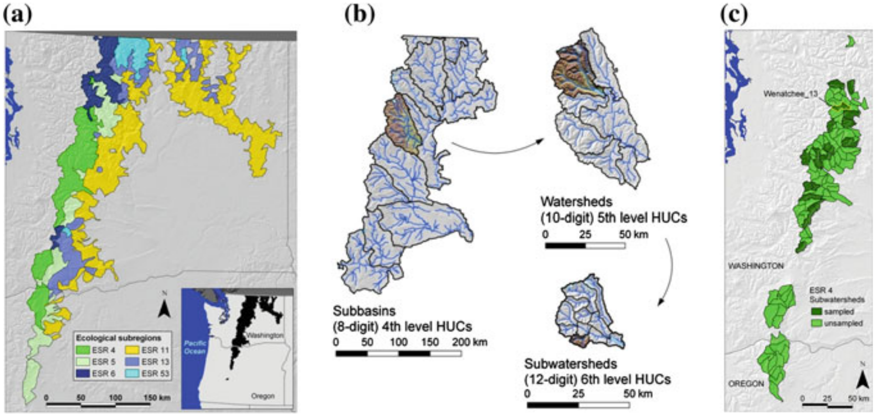


Fig. 2 Ecological subregions of the eastern Washington Cascades in the western United States (adapted from Hessburg et al. 2000b). **a** The ecological subregions (ESR) are defined as follows: *4* Warm/Wet/Low Solar Moist and Cold Forests, *5* Warm/Moist/Moderate Solar Moist and Cold Forests, *6* Cold/Wet/Low 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 sub-basins (4th level), watersheds (5th level), and subwatersheds (6th 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 ESR 4

Hessburg et al. 2000b). The subregion contained 93 subwatersheds. To map a sample of the historical and current vegetation, we randomly selected 15 of the 93 in order to sample at least 15 % (actual 16.1 %) of the total number of subwatersheds and 15 % (actual 19.2 %) of the subregions' area (Fig. 2c).

Four vegetation features for the historical and current conditions were interpreted from stereo aerial photography and mapped in each subwatershed: physiognomic class, cover class, structure class, and late-successional old-forest class. As in the first application above, present-day maps of each vegetation feature were compared against ecoregion RV estimates developed for each feature. As in the preceding application (Sect. 3), five class metrics and nine landscape metrics were used to compare the current and RV conditions. Using this diagnostic set of metrics, we could (1) detect key changes in landscape patterns that had potential ecological significance and (2) understand the specific class changes that were driving shifts in the mosaics.

The phase 1 objective of designing a NetWeaver knowledgebase for this problem was to assess how well current conditions in the sampled subwatersheds of ESR4 corresponded to pre-management era RV. We used the term integrity to express the degree of correspondence, and departures were integrity departures. Primary topics for evaluation, corresponding to mapped attributes were: physiognomic integrity, cover integrity, structural integrity, cover-structure combined integrity, and late successional/old-growth forest integrity. Class metrics of each attribute class and the landscape metrics were evaluated for the current condition of each landscape. An evaluation for any metric was done by comparing its value for the current condition to a ramp function for the same metric derived from the historical data. The result of an evaluation was an expression of the degree of support for correspondence of the current conditions to the RV encoded in the ramp function.

Phase 2 provided a decision model for assigning restoration priorities to subwatersheds. The model included four primary criteria: compositional integrity, structural integrity, feasibility of management, and fire risk (Table 2). All subcriteria of compositional and structural integrity criteria were measures of support from the landscape analysis. Subcriteria of fire risk and feasibility represented attributes of subwatersheds that were not part of the logic-based evaluation, but were included in the decision model as logistical considerations.

Pair-wise comparisons among primary and secondary criteria using standard methods for the Analytic Hierarchy Process provided weights for the decision model (Table 2). Simple Multi-Attribute Rating Technique (SMART) utility functions for rating criteria at the lowest level of the model were also specified. Utility functions for feasibility subcriteria gave greater preference to subwatersheds with shallow slopes, road access to stands, and satisfactory timber value, which could financially underwrite restoration costs. Utility functions for subcriteria of fire risk gave greater preference to subwatersheds with higher ratings for crown-fire potential and fuel loading, based on a rationale of protecting the existing forest resources. Fuel loading and crown-fire potential were attributed to individual vegetation patches using published methods (Huff et al. 1995; Hessburg et al. 1999b, 1999c).

Priorities for landscape restoration were based on: (1) the assessment of departures in compositional and structural integrity; (2) feasibility of management, which was composed of steepness of the watershed, road access, and value of the timber; and (3) fire risk, which was composed of crown-fire potential under an average wildfire burn scenario, and fuel loading. Feasibility and risk criteria were incorporated to inform the decision-making process with real-world criteria that could influence a manager's ability to make and execute restoration decisions.

4.1 What Worked Well?

The objectives for developing this decision model were to demonstrate that landscapes of any ecoregion could be evaluated on a common basis to determine key ecological departures and then assessed for restoration priority. The application met those objectives and highlighted the importance of using decision-support technology to assess technical and economic feasibility of any proposed restoration, also on a common footing. Because many parameters (844) were used in developing this demonstration model, departure analyses were simplified in comparison with the first application shown in Sect. 3. This was done to make the

Table 2 Structure of an analytic hierarchy process model for determining priorities for restoring subwatersheds in ESR4

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
Late-successional/ old-forest 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 were: compositional integrity, structural integrity, feasibility, and fire risk. Secondary decision criteria are shown indented under their primary criteria, and, because they were 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 was derived as the weighted average of the utility scores of the criterion's subcriteria

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

problem more tractable, and the added detail was not relevant to the demonstration. Departure analyses like those described in the first application can be easily incorporated into the second.

4.2 What Could be Improved?

The use of feasibility and effectiveness criteria in the decision model highlighted the need to adequately ground management decisions within their appropriate contexts. Contextual grounding might also include human social and aesthetic values, legal concerns, human safety values, life-cycle costs and benefits, impacts of restoration treatments on terrestrial and aquatic habitats, resources, and species, the period of those effects, and the expected time period of effective restoration. For example, Hessburg et al. (2007a) present a decision-support application that evaluated danger of severe wildland fire and prioritized 575 subwatersheds in the Rocky Mountain region for vegetation and fuels treatments. They showed that many subwatersheds, while in relatively poor condition with respect to fire hazard, expected fire behavior, and ignition risk, were not the best candidates for treatment when considered in the context of the amount of associated wildland–urban interface (WUI). Considering fire danger in the context of the people and structures that might be most impacted by the fires restructured watershed-treatment priority in a useful manner.

4.3 Research Opportunities

This example demonstrates a relatively straightforward application of EMDS in which logic is first used to assess the current state of landscape features with respect to a number of ecosystem properties of interest, and then management priorities are derived, which take into account practical considerations that are important to decision makers. This approach is strategic in the sense that it identifies which landscape features are the priority, but the solution by itself does not necessarily suggest what specific management actions should be implemented in any given feature to produce improved conditions (e.g., a form of operational planning). Consequently, an interesting research and development opportunity exists to expand EMDS functionality to support this type of operational planning.

Another area of system functionality that is ripe for further research and development is more explicit support for the adaptive management process. The current example is typical of most EMDS applications to date in that it assesses current condition. However, federal oversight agencies in the US, and presumably in other countries as well, are demanding that national land-management agencies do a much better job of monitoring project performance and cost effectiveness with respect to issues such as landscape restoration. To that end, one can envision using precisely the same logic specification to reassess a particular spatial extent at one or more points in time in the future, producing a new distribution of modeled outcomes at each point in time. Clearly, given two or more distributions of model outcomes, standard statistical tests could be used to test hypotheses for significant changes in distributions over time. In important respects, such capabilities have always been the holy grail of adaptive management. Because EMDS already supports multiple assessments, and assessments may be temporally defined, integrating hypothesis testing into the EMDS framework to better support adaptive management would be highly desirable.

5 Tactical Planning for Landscape Restoration

In a third application, Gärtner et al. (2008) demonstrated an approach to evaluating current landscape vegetation patterns with reference to two climate scenarios: one was retrospective, representing the pre-management era climate, a second was prospective, representing change to a warmer and drier climate. We used decision-support modeling in EMDS to set treatment priorities among the landscapes and select alternative treatments. The analysis did not seek to accurately predict climate change, but to interpret landscape consequences given a plausible scenario. We used a NetWeaver logic model to assess landscape departure from the two sets of reference conditions and a decision model developed in Criterium DecisionPlus (CDP) to illustrate how various landscape conditions could be prioritized for management treatments in light of two climate scenarios, taking into account not only considerations of landscape departure, but also logistical considerations pertinent to forest managers. Our methods represented a hedging approach managers might use to determine how best to proceed with restorative management in an uncertain climatic future.

The study area encompassed the 6,070 ha Gotchen Late-Successional Reserve (LSR, Hummel et al. 2001 and Hummel and Calkin 2005), and adjacent lands totaling 7,992 ha. The reserve is located east of the crest of the Cascade Mountain Range in Washington State, USA, on the Gifford Pinchot National Forest (Fig. 3). The study area is part of a regional network of LSRs established as one component of the Northwest Forest Plan, which required protection of the northern spotted owl (*Strix occidentalis caurina*) and associated species with an adequate distribution and arrangement of late-successional habitats (ROD 1994).

In this application, we evaluated landscape departure of two landscapes, comprising the bulk of the study area, from RV associated with one historical and one future climate reference condition. As in the prior two applications, the reference conditions represented broad envelopes of vegetation conditions common to an ecoregion. The landscapes were evaluated relative to these reference conditions in EMDS. We evaluated outputs from the decision model to determine which landscape should be treated first, and which landscape treatments might be most effective at favorably altering conditions in light of the two climate references.

The study area fell in ESR 4 as described in the preceding application (Fig. 3, Hessburg et al. 2000b). 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

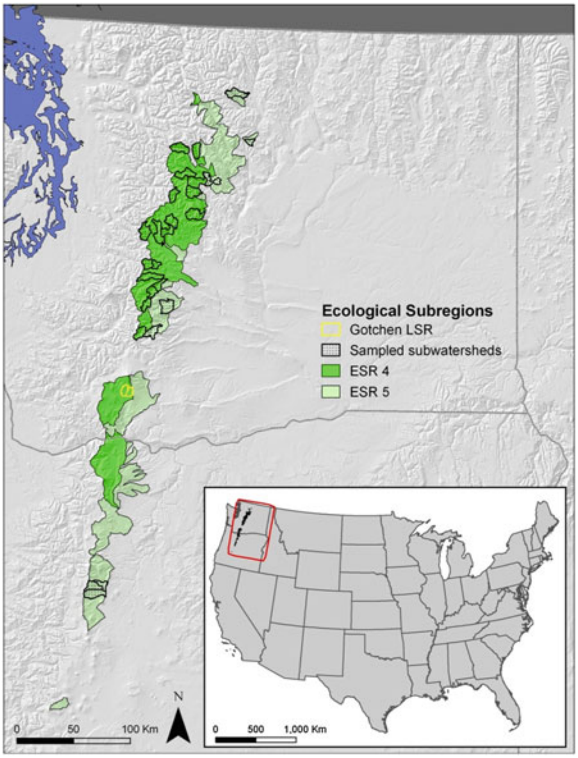


Fig. 3 Location of the Gotchen Late-Successional Reserve (study area) and Ecological subregions (ESR) *4* the subregion of the study area. *ESR 5* is shown as the subregion immediately to the east of *ESR 4* along the west-east temperature and precipitation gradient (Hessburg et al. 2000a)

growth, tree mortality, and high wildfire risk are often associated with protracted warming.

Empirical data from the next drier and warmer ecoregion (ESR 5) were used as a reference set to simulate the climate-change analogue for the study area. We reasoned that use of ESR 5 for these climate-change reference conditions was rational for several reasons: (1) ESR 5 sat adjacent to ESR 4 on the west to east climatic gradient of temperature and precipitation (Fig. 3); (2) ESR 5 received more solar radiation during the growing season and was drier than ESR 4; (3) ESR 5 was composed of the same forest species and structural conditions as were found in ESR 4 and was ordinarily influenced by fire regimes that are more similar to those forecast for a warming and drying climate-change scenario (Gedalof et al. 2005; Littell et al. 2009; McKenzie et al. 2004); and (4) ESR 5 landscapes had existed for a long time under these warmer and drier climatic conditions such that conditions reflected the natural spatio-temporal variation in landscape patterns that would exist under the influences of succession, disturbance, and the local climate.

Climatic conditions in ESR 5 represented a significant difference in total annual precipitation and average growing season daytime solar radiative flux (Hessburg et al. 2000b). ESR 5 was characterized as a warm (5–9 °C annual average temperature), moderate solar (250–300 $W{\cdot}m^{-2}$ annual average daylight incident

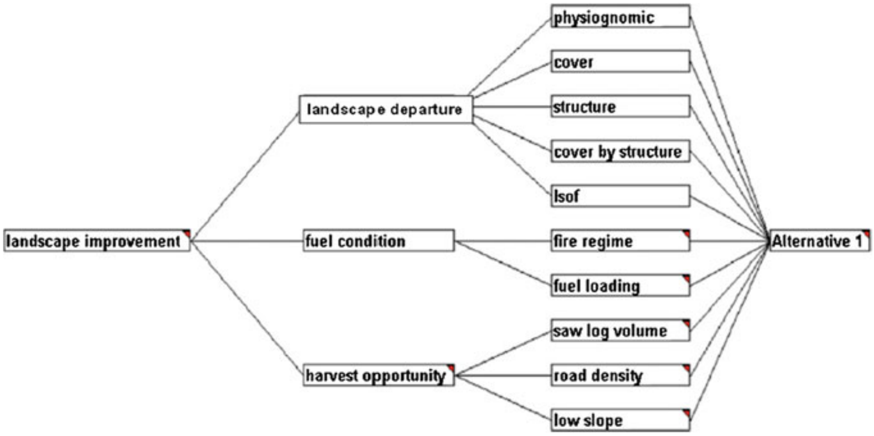


Fig. 4 Decision model to prioritize subwatersheds for landscape restoration

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. 2007b).

To map RV of ESRs 4 and 5, subwatersheds were randomly selected to represent at least 10 % of the total subwatersheds and area of each subregion. For each selected subwatershed, we mapped pre-management era vegetation by interpreting representative stereo aerial photographs. The resulting vegetation features enabled us to derive forest cover types (Eyre 1980), and structural classes (O'Hara et al. 1996), using methods detailed in Hessburg et al. (1999b, 1999c). Five different vegetation features were used to characterize the attributes of the historical subwatersheds of ESRs 4 and 5. 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. Five class and nine landscape metrics generated by FRAGSTATS (McGarigal and Marks 1995) were chosen to display spatial relations within classes and landscapes of these features. The metrics were the same as those outlined in preceding applications.

In a first phase, we evaluated landscape departure of the two subwatersheds in terms of departure of current conditions from the two climatically defined reference conditions. In a second phase, we determined which of the two subwatersheds exhibited a higher priority for restoration. The decision model for assigning restoration priorities included three primary criteria: landscape departure, fuel condition, and harvest opportunity (Fig. 4). All subcriteria of landscape departure were measures of evidence from the landscape analysis performed with the NetWeaver logic engine.

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 logistical considerations for management (Fig. 4). Fuel condition was evaluated in terms of probable fire regime and fuel loading. Harvest opportunity was evaluated in terms of available merchantable volume, road density, and proportion of subwatershed area with slope $\leq 10\ \%$. The slope specification was intended not so much as a feasibility but cost criterion, indicative of areas with easy access for ground-based harvesting and yarding equipment. Road density and slope were calculated from a digital elevation model and map layers provided by national forest staff. Fire regime was calculated as the proportion of the subwatershed that had a fire regime condition class >1. Fire regime condition class depicted the degree of departure from historical fire regimes (Schmidt et al. 2002).

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 plot data sets. The proportion of subwatershed area with a high fuel loading was calculated as the proportion of plots with a fuel load class >1, following methods of Ottmar et al. (1998). Sawlog volume (mean $m^3 \cdot ha^{-1}$) in stands was calculated with NED-2 (Twery et al. 2005), based on tree lists from the plot data.

We found little significant change in physiognomic or cover type conditions among the two test subwatersheds; but surprisingly, the evidence for no change was greater in the western subwatershed under the climate-change scenario, indicating that current spatial patterns of cover types, while not departed from ESR 4 historical conditions, would actually be closer to conditions that would be anticipated under the warming/drying climate-change scenario (Fig. 5). Similarly, we found significant evidence for structural class departures in both subwatersheds when historical reference conditions were considered, but departures were less evident in one of the two subwatersheds when the RV for the climate-change scenario was considered. Results for cover type by structure evaluation were analogous (Table 3). Evidence for limited late-successional/old-forest departure was strong in both subwatersheds using the historical RV scenario, but declined in both subwatersheds under the climate-change scenario, indicating that warmer and drier conditions would likely favor expanded area of these structures.

To determine which of the two subwatersheds had the highest priority for landscape restoration, we applied the decision model and its primary criteria to the selection process (Fig. 4). The eastern-most of the two evaluated subwatersheds received a higher priority rating for landscape improvement in the context of both the historical climate and climate-change scenarios. The overall decision score under the historical reference scenario was highest for the eastern subwatershed, but scores were nearly identical for the climate-change scenario. On balance, the two subwatersheds were found to be in relatively good condition, regardless of the climatic reference (Table 3).

Contributions of harvest opportunity and fuel condition to restoration priority were essentially the same for both subwatersheds in either scenario. The only features that changed the overall decision score were related to landscape departure.

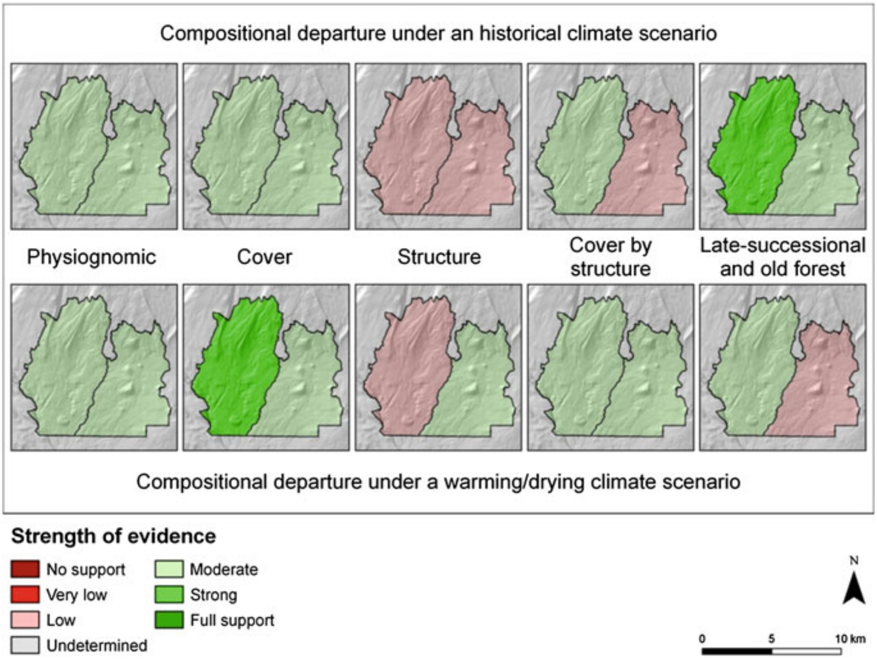


Fig. 5 Illustration of the landscape departure evaluation of the current Gotchen landscape relative to reference conditions representing pre-management era (*above*) and future warming climates (*below*). Each of the small figures shows the two subwatersheds of the Gotchen landscape; the coloration displays the degree of departure under the historical (*upper*) and warming (*lower*) climate conditions

Table 3 Contributions of subcriteria to decision scores of the eastern and western Gotchen watersheds when compared with the historical and future climate reference conditions

Watershed	Historical reference		Climate change reference	
	East	West	East	West
Physiognomic condition	0.037	0.024	0.023	0.012
Structural condition	0.098	0.094	0.073	0.081
Cover type-structural condition	0.039	0.034	0.013	0.01
Late-successional/old-forest condition	0.182	0.087	0.222	0.195
Fire regime condition	0.119	0.119	0.119	0.119
Fuel loading condition	0.089	0.094	0.089	0.094
Harvest opportunity	0.012	0.037	0.012	0.037
Overall decision score	0.576	0.489	0.551	0.548

Scores for landscape pattern departure differed slightly between the historical reference and climate-change scenarios, and in both cases the contributions of late-successional/old forest had the most impact on treatment priority.

5.1 What Worked Well?

The application met its objectives of evaluating the degree of departure in the watersheds relative to retrospective and prospective sets of reference conditions. Addition of the two tactically-oriented criteria to the decision model (vulnerability to severe wildfire and timber harvest opportunity) were helpful to assigning the relative priority of landscape restoration treatments between the two subwatersheds.

We found it noteworthy that the two sets of reference conditions were more similar than different in most aspects. That is, ranges of conditions were mostly overlapping rather than unique. This lends empirical credibility to the notion that envelopes of pattern conditions were historically nudged and reshaped rather than re-invented wholesale by shifting climatic regimes (Keane et al. 2009; Moritz et al. 2011). With the enormous legacy of spatial pattern alteration caused by past fire exclusion and suppression, timber harvest, road development, and livestock grazing elsewhere in the Inland Northwest, this may not be the case in a future climate unless spatial patterns are restored. Applications like that of Gärtner et al. (2008) may become highly useful to designing, evaluation, and comparing alternative recipes in a world of uncertain climatic outcomes.

5.2 What Could be Improved?

A general enhancement of the model would be to include specific threats to resource values—those currently existing as well as those imposed by restoration activities. Across a broad regional landscape, where numerous landscapes may be considered, and especially in the context of the western US, threats to resource values associated with wildfire should to be considered in any decision model of this type. Where the legacy of past management to native species, food webs, and habitats is a concern, models such as this one should evaluate existing threats to species, populations, and habitats, and compare these with any threats derived from restoration treatment intensity and distribution. Such an evaluation would aid manager calibration of treatment scenarios that optimized improvements over deleterious effects.

5.3 Research Opportunities

A novel aspect of this study was that the analysis of vegetation condition, as a prelude to making decisions about investments in restoration, was both retrospective (comparing existing conditions to an envelope of historical reference conditions) and prospective (comparing existing conditions to plausible reference conditions of a future climatic scenario). In light of the current reality of global climate change and its downscaled regional influences (McNulty and Aber 2001; Spittlehouse and Stewart 2003), it is reasonable and perhaps essential to 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 conditions and variability of a future climate scenario cannot be predicted with reasonable certainty. However, extending the example offered here, by including multiple plausible climate change scenarios, may help identify management strategies that demonstrate trade-offs associated with each scenario, minimize future risk, and conserve the greatest number of management, species, and process options for the future.

6 Decision Support for Project Planning

In this section, we present a fourth and final EMDS application that provides decision support for restoring a mixed coniferous forest landscape on the Naches Ranger District of the Okanogan-Wenatchee National Forest in eastern Washington, USA. The project (hereafter, "Nile Creek") was the first landscape restoration project developed under a newly minted, peer-reviewed, forest-wide restoration strategy (hereafter, the Strategy, USDA-FS 2010).

Under the Strategy, the objectives of landscape evaluations are to: (1) transparently display how projects move landscapes towards drought, wildfire, and climate resilient conditions; (2) describe and spatially allocate desired ecological outcomes (e.g., adequate habitat networks for focal wildlife species; disturbance regimes consistent with major vegetation types); (3) logically identify project areas, treatment areas, and the associated rationale; and (4) spatially allocate desired ecological outcomes and estimate outputs from implemented projects. Landscape evaluations under the strategy assemble and examine information in five topic areas: (i) patterns of vegetation structure and composition; (ii) potential for spread of large wildfires, insect outbreaks, and disease pandemics across stands and landscapes given local weather, existing fuel and host conditions; (iii) damaging interactions between road, trail, and stream networks; (iv) wildlife habitat networking and sustainability; and (v) minimum roads analysis, (i.e., which of the existing roads are essential and affordable for administrative and recreation access). Over time and as needed, additional topics are being added to this working prototype.

For simplicity, the strategy for landscape evaluation was implemented in approximately eight steps:

Step 1—determine the landscape evaluation area,

Step 2—evaluate landscape patterns and departures,

Step 3—determine landscape and patch scale fire danger, Step 4—identify key wildlife habitat trends and restoration opportunities,

Step 5—identify aquatic/road interactions,

Step 6—evaluate the existing road network,

Step 7—identify proposed landscape treatment areas (PLTAs), and

Step 8—refine PLTAs and integrate findings from steps 2–6 into landscape restoration prescriptions.

District specialists from multiple disciplinary fields worked in partnership to complete each of the steps. Steps 1–6 occurred concurrently and were completed prior to Steps 7 and 8. These steps were applied in the Nile Creek analysis area; we present the landscape-evaluation model for that area.

6.1 Determining the Landscape Evaluation Area

Determining the size of the evaluated area had implications for ecological and planning efficiency. Evaluating two or more subwatersheds (12-digit, 6th-field hydrologic unit code [HUC], 4,000–12,000 ha each) was recommended by Reynolds and Hessburg (2005) and Hessburg et al. (2005) based on the findings of Lehmkuhl and Raphael (1993), who 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 larger than 4000 ha to avoid this bias. Watershed size also coincided with previous watershed assessments, generally providing a range of elevations and forest types, and was useful in evaluating hydrological influences of anticipated forest restoration treatments.

Watershed size was large enough to evaluate many cumulative effects, but wide-ranging wildfires, native carnivore species and most salmonids required analysis of larger areas than subwatersheds (e.g., Ager et al. 2007; Gaines et al. 2003; Reeves et al. 1995).

Several future project areas could be acceptably planned via a single large-scale analysis, thereby reducing paperwork, decreasing planning time and cost, and increasing environmental analysis efficiencies leading to project implementation. The actual project area included three subwatersheds (the Dry-Orr Project) covering an area of ~29,000 ha. For brevity, this paper discusses landscape analysis in just one of these subwatersheds, Nile Creek, which encompasses an area of 8295 ha (Fig. 6, see also Hessburg et al. 2013).

The EMDS application for the Nile Creek project evaluated five primary topics in a NetWeaver logic model. The vegetation pattern departure, major insect and pathogen vulnerabilities, patch level fire attributes, and habitat availability for focal wildlife species topics evaluated how the current landscape compared to the pre-management era and future warming climate reference conditions. The fire movement potential topic was evaluated at a subbasin scale (see Fig. 2b). The aquatic-road interactions and minimum roads analysis required Forest-wide modeling efforts, which were not yet completed in time for this project area, and truncated versions were incorporated in this evaluation.

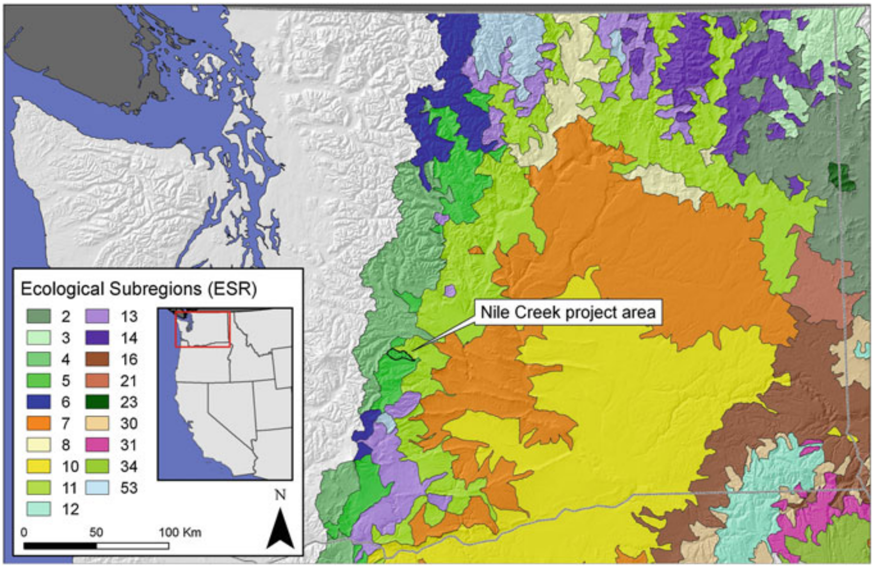
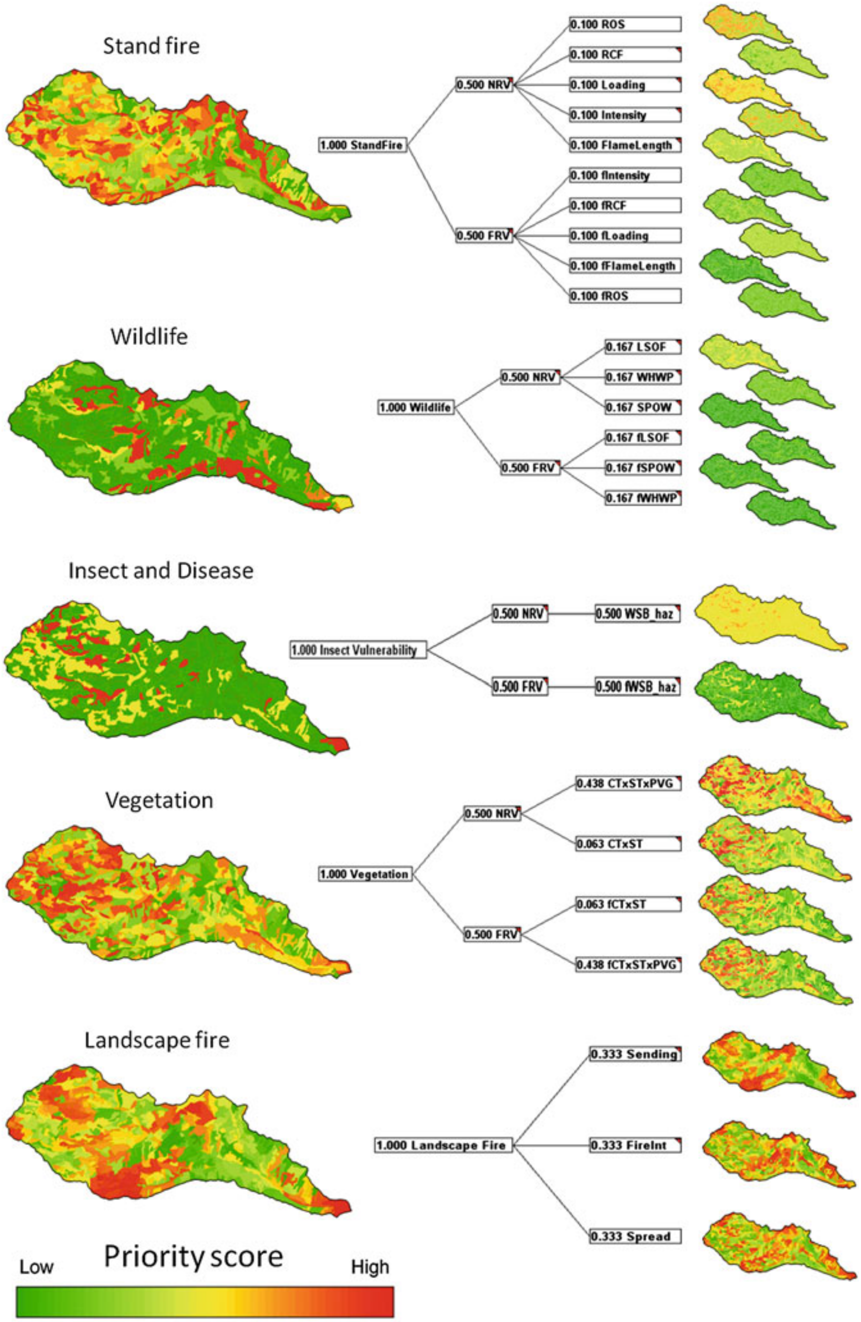


Fig. 6 Ecological subregions in eastern Washington, USA (from Hessburg et al. 2000b). The Nile Creek project area is outlined with stippling in ESR5

6.2 Evaluating Landscape Vegetation Patterns and Departures

As in preceding applications, we evaluated departure of the current vegetation conditions for the Nile Creek subwatershed from RV associated with one historical and one future climate reference condition. The project area fell in ESR 5 as described above (Figs. 3 and 6, Hessburg et al. 2000b), and we used the RV estimates of this ecoregion to represent natural variation in spatial patterns for the pre-management era. To consider the natural landscape patterns that might occur under a climate-change scenario, we adopted a scenario involving a climatic shift to drier and warmer conditions using reasoning described in the prior application (see Sect. 5, Gärtner et al. 2008). Empirical data from the next drier and warmer ecoregion (ESR 11) were used as a reference set to represent RV associated with the climate-change scenario for the project area (Hessburg et al. 2000b).

Two of eight available features–combined cover type-structure class (CTxSC) and combined potential vegetation type-cover type-structural class (PVGxCTxSC)–were subcriteria evaluated under vegetation pattern departure. Five class and nine landscape metrics generated by FRAGSTATS (McGarigal and Marks 1995) were chosen to display spatial relations and RV within classes of the two features, and within entire landscapes of these features. The metrics were the same as those outlined in preceding applications. Departures from the RV estimates of the two climate references across the full suite of metrics and vegetation features formed the basis of vegetation departure analysis (Fig. 7).


Stand fire
1.000 StandFire
0.500 NRV
0.100 ROS
0.100 RCF
0.100 Loading
0.100 Intensity
0.100 FlameLength
0.500 FRV
0.100 fIntensity
0.100 fRCF
0.100 fLoading
0.100 fFlameLength
0.100 fROS
Wildlife
1.000 Wildlife
0.500 NRV
0.167 LSOF
0.167 WHWP
0.167 SPOW
0.500 FRV
0.167 fLSOF
0.167 fSPOW
0.167 fWHWP
Insect and Disease
1.000 Insect Vulnerability
0.500 NRV
0.500 WSB_haz
0.500 FRV
0.500 fWSB_haz
Vegetation
1.000 Vegetation
0.500 NRV
0.438 CTxSTxPVG
0.063 CTxST
0.500 FRV
0.063 fCTxST
0.438 fCTxSTxPVG
Landscape fire
1.000 Landscape Fire
0.333 Sending
0.333 FireInt
0.333 Spread
Low
Priority score
High

◀ **Fig. 7** Five CDP models representing the contributions of network evaluations to treatment priority scores (range 0 [*darkest green*], to 1 [*darkest red*]) in the Nile subwatershed. Acronyms in the figure are: *Stand fire* the weighted results of subtopic departure analyses (weights are shown with each topic and subtopic); *NRV* the weighted results of all subtopics that evaluate departure from the natural range of variation; *ROS* wildfire rate of spread; *RCF* risk of crownfire, *Loading* surface fuel loading; *intensity* fireline intensity; *Flame length* flame length; *FRV* the weighted results of all subtopics that evaluate departure from the future range of variation; to avoid confusion, an "*f*" is placed immediately before a subtopic acronym to indicate that it is associated with the FRV portion of a departure analysis; *Wildlife* the weighted results of subtopic departure analyses for key wildlife habitat pattern and abundance; *LSOF* late successional and old forest; *WHWP* white-headed woodpecker; *SPOW* northern spotted owl; *WSB haz* western spruce budworm hazard departure; *CTxSC* departure of combined cover type and structural class conditions; *CTxSCxPVG* departure of combined cover type, structural class, and potential vegetation group conditions; *Sending*, *FireInt,* and *Spread* denote the varying degrees of fire sending (node influence), fireline intensity, and wildfire rate of spread occurring during the FlamMap simulations

We evaluated the vulnerability of each landscape and its component patches to a native insect relative to the historical and future climate reference conditions, using methods of Hessburg et al. (1999d, 2000a). Each patch was assigned to a vulnerability class based on vegetation factors that increased patch and vulnerability and landscape contagion with respect to the insect. In Nile Creek, we evaluated landscape vulnerability to the western spruce budworm (*Choristoneura occidentalis*). Damage associated with this insect had increased over the 20th century; District foresters wanted to understand the extent of the vulnerability increase. The product of this step was a map of patch vulnerability to the western spruce budworm for the current landscapes, which were compared against the two reference conditions for the same landscape vulnerability (Fig. 7).

6.3 Determining Patch and Landscape Scale Fire Danger

Patch-level expected wildfire behavior was modeled for all current and reference condition patches using methods detailed in Hessburg et al. (2000a) and Huff et al. (1995). Current conditions of patches were evaluated against reference ranges of conditions to determine departure under either climate scenario.

We modeled expected landscape fire behavior during a typical wildfire (97th-percentile burn conditions) at the scale of the entire subbasin (8-digit) 4th-field HUC. In the case of the Nile Creek project area, the larger Naches subbasin that surrounds Nile Creek was modeled; it encompasses an area of approximately 180,000 ha. Available forest-wide fuels layers were resampled to 90 m-resolution rasters and 97th-percentile fuel moistures and weather conditions were used to condition fuels for fire behavior modeling within the *FlamMap* fire modeling framework (Finney et al. 2007, and references therein).

Custom wind grids, created using *WindNinja* modeling software (Forthofer et al. 2009), were derived for the five most likely prevailing wind directions and used as input to the *FlamMap* model. For each of the wind directions, the subbasin landscape was ignited with 1000 randomly distributed fire starts one hundred times each, and fires were allowed to burn for six hours each until all of the landscape was exposed to multiple fires (~100,000 ignitions). Each model run created several raster outputs that were stored for further analysis, including: fireline intensity, active and passive crown fire activity, rate of spread, flame length, and node influence. The node influence is a value assigned to a given pixel in *FlamMap* that represents the number of pixels that burn during the simulation as a result of that pixel burning. Node influence is highly variable, depending on ignition location, fuel arrangement, simulation edge effect, and simulation duration. To create a meaningful node influence grid, all node influence outputs were composited from all ignitions, and from each wind direction. We created an additional composite layer, using all fires from each of the five wind directions that represented how similarly fires spread considering slope and fuel interactions. We termed this layer the congruence (of fire spread direction) layer. The flame length layer was also composited across the five different wind directions.

Finally, the composited node influence was combined with flame length and the congruence layer to create an index that showed the relative contribution of each pixel to the spread and intensification of fire. Areas with large clusters of high fire danger pixels (i.e., ≥80th-percentile scores for combined flame length, node influence, and congruence) were identified as priority treatment areas to interrupt the flow of wildfire across large landscapes.

6.4 *Identifying Wildlife Habitats and Restoration Opportunities for Focal Species*

In this evaluation, we: (1) determined the location and amount of habitat for focal wildlife species present within the landscape-evaluation area, (2) compared the current amount and configuration of habitats for focal species to historical and future climate reference conditions, and (3) identified habitat restoration opportunities and priorities that could be integrated with other resource priorities and carried forward into project planning.

Focal wildlife species were selected because they are either federally listed or identified as focal species by the USDA Forest Service, Pacific Northwest Region (USFS 2006) and their life-history requirements were appropriately assessed at the scale of our evaluation. The selected focal species are closely associated with forested habitats, and their populations are influenced by changes to forest structure, among other factors. Focal species included the northern spotted owl, northern goshawk (*Accipiter gentilis*), white-headed woodpecker (*Picoides albolarvatus*), American marten (*Martes americana*), pileated woodpecker (*Dryocopus pileatus*), Lewis‘s woodpecker (*Melanerpes lewis*), and black-backed woodpecker (*Picoides arcticus*). The habitat definitions that were used in the landscape evaluation for these species are described in USDA-FS (2010) and in Gaines et al. (2010). The products of this evaluation step were maps showing the location and amount of habitat for each of the focal species and maps and tabular data showing the degree of departure in habitat amounts and configuration between current and the two reference conditions. The applied class and landscape metrics used to estimate departures in the amount of habitats were those described above in preceding sections.

6.5 Evaluating Aquatic Ecosystem and Road Interactions

In this step, we identified the road segments that had the greatest impacts on streams, channel features and migration, and in-stream habitats to determine restoration priorities. The components of the aquatic/road interactions evaluation were hydrologic connectivity of roads and streams, fish distribution, slope stability and soil properties, and stream channel confinement. These components were evaluated using *NetMap* (Benda et al. 2007) and results were incorporated into project planning and alternative comparison, but outside of EMDS, due to timing issues. The hydrologic connectivity evaluation ranked the relative importance of flow routes connecting the road system to streams by combining a georeferenced roads layer with a flow-accumulation file generated from a 10-m digital elevation model (DEM). The evaluation of fish distribution linked current in-stream and other survey data with a current streams layer. This would enable later integration in EMDS of potential treatment areas with current fish distributions for listed and sensitive fish species. Slope and soil stability was modeled by combining an existing soils layer (SSURGO, USDA-NRCS 2005, 2006) with the DEM, and assigning slope breaks of 0–34.9, 35–60, and >60 %. Unstable soils and steeper slopes were used to identify slope and soil related hazards. Stream-channel confinement was evaluated using a layer developed by the local Forest that identified stream channels with <3 % gradient within 30-m feet of a road.

6.6 Integrating Landscape Evaluation Results in EMDS

Each of the described primary topics was evaluated using a relatively simple logic model (five networks total) that related class metrics of each primary topic (Fig. 7). The results were then combined in the single CDP decision model as a network of networks, as illustrated in Fig. 8. Results of landscape evaluation enabled the District planning team to attach a treatment priority to all patches in a subwatershed and to identify areas with clusters of high-priority patches, termed potential landscape treatment areas (PLTAs) that could form the nucleus of several project areas. In Fig. 9, we illustrate mapped PLTAs in the Nile subwatershed. The circled areas represent likely PLTAs emerging from the landscape evaluation.

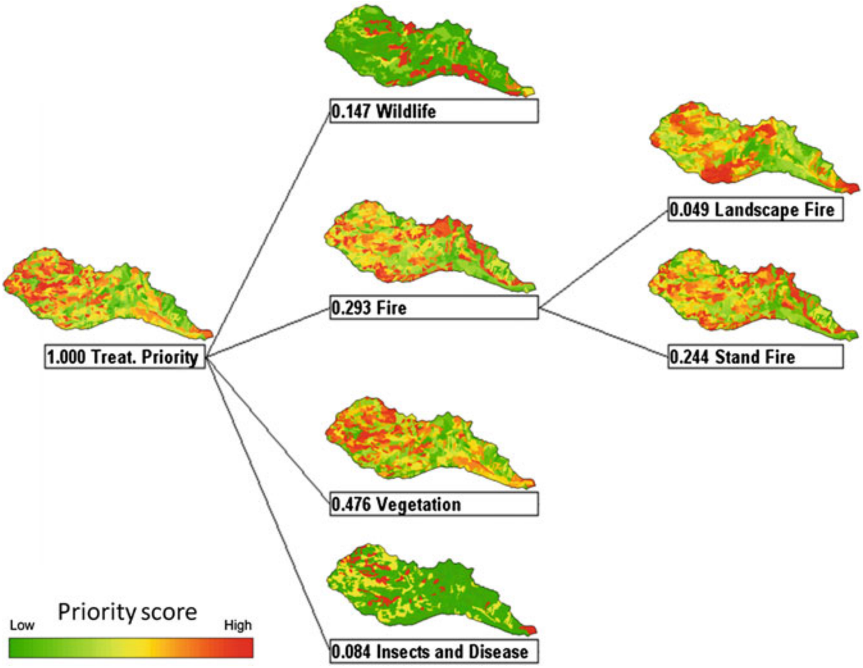


Fig. 8 Second stage CDP decision model for the Nile Creek project area. Landscape treatment priority scores of polygons within the Nile subwatershed (range 0 [*darkest green*], to 1 [*darkest red*]) were derived from primary criteria associated with four major topics (see also Fig. 7): *Wildlife, Fire, Vegetation,* and *Insects and Diseases.* Primary criteria were weighted by managers using the SMART utility in EMDS. Under the *Fire* criterion, the *Landscape Fire* and *Stand Fire* networks (Fig. 7) were evaluated as subcriteria, and weighted by District managers. The map on the far left shows the results of the entire CDP evaluation of priority treatment scores assigned to patches. These scores are later used for identifying proposed landscape treatment areas (PLTAs, Fig. 9) and potential restoration treatment locations

The results of evaluations of each primary topic provided information that could be used by all members of the interdisciplinary planning team to develop a prescription for each landscape (i.e., a landscape-level prescription). For example, results generated from the landscape pattern, fire, and habitat evaluations allowed the interdisciplinary team to quantify the amount, types, and spatial locations of treatments to accomplish multiple restoration objectives. These objectives included strategically altering large-scale fire behavior, increasing the amount and improving the networking of key wildlife habitats, restoring ecosystem functions by restoring landscape pattern and process interactions, reducing risk to human communities, and minimizing the road network needed to access treatment areas, provide access for fire protection, and provide for other administrative uses.

Upon completion of the initial landscape evaluation, identification of the PLTAs, and proposal of preferred landscape treatment options, the vegetation data was edited to reflect the effects of treatment. These edited landscapes were then

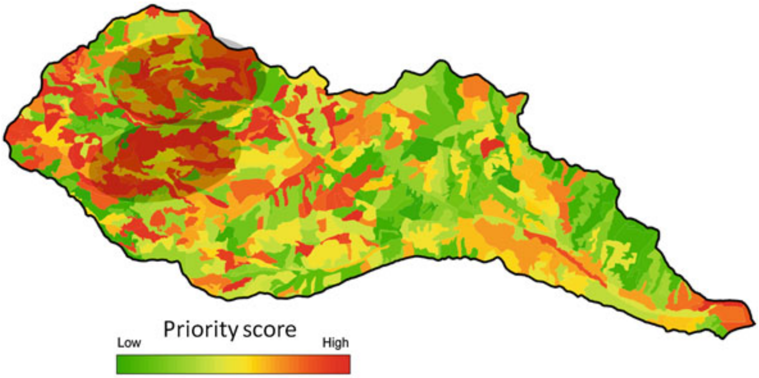


Fig. 9 Nile subwatershed patch-level priority scores resulting from CDP evaluation of subcriteria and criteria in EMDS. Landscape treatment priority scores of polygons within the Nile subwatershed (range 0 [*darkest green*], to 1 [*darkest red*]) were derived from primary criteria associated with four major topics (see also Figs. 7, 8): *Wildlife, Fire, Vegetation,* and *Insects and Diseases.* Circles show example potential landscape treatment areas (PLTAs) where restoration projects (*shaded areas*) might focus treatments appropriate to the need, to achieve multi-way and multi-level restoration goals

re-evaluated by the EMDS application, and managers were able to determine the degree to which progress was made toward restoration goals with regard to both climate scenarios. Using EMDS, the interdisciplinary team was then able to evaluate a variety of landscape prescriptions and treatment options, and to assess how the various options would affect fish habitats, insect and disease risks, landscape patterns, and the flammability of the larger landscape. The final product was a refined map of PLTAs and preferred options for landscape treatment for the Nile Creek project area. This process of landscape evaluation provided important advantages to the environmental analysis that followed in terms of transparency, efficiency, and credibility.

6.7 What Worked Well?

First and foremost, the development of the EMDS application improved communication within the interdisciplinary team, as it gave the members a concrete framework for organizing the analytical and decision space necessary for exploring restoration management opportunities. Resource managers were able to organize the logic and analysis needs for their area of expertise and share their submodels with the interdisciplinary team as primary topics that can feed into the overall application structure.

The use of EMDS in this application allowed for much better integration across resource disciplines and yielded transparent and repeatable landscape evaluation and decision-making processes. The alternative development portion of the process allowed the planning team to identify priority areas for restoration treatments that could achieve multiple objectives. The comparison of current conditions to historical range of variation (HRV) and the expected future climate range of variation (FRV) conditions in EMDS enabled the planning team to develop objective measures that could be used to describe resilient landscapes and measure progress towards achieving the restoration goals. Integration of a climate change scenario into EMDS allowed the incorporation of current climate-change science into the landscape evaluation process and informed project-level planning and decision-making.

The landscape evaluation allowed the interdisciplinary team and the decision-maker to strategically locate project areas to meet multiple restoration objectives. In addition, EMDS provided a mechanism to transparently display how emphasizing a certain resource more than another influenced prioritization and the spatial allocation of treatments.

To date, no other planning process has allowed managers on the Okanogan-Wenatchee NF to strategically and spatially locate treatments based on the complex and simultaneous interactions of multiple landscape conditions and resource variables. Managers were better able to describe restoration needs at a landscape scale rather than stand by stand. As a result, new opportunities for restoration treatments were discovered. For example, the District interdisciplinary team chose a PLTA in mesic forests to address patch types and arrangements rather than solely focused on thinning in dry forests, which had occupied much of the Forest focus in preceding years.

In comparison with previous planning efforts, the interdisciplinary team was better able to truly integrate concerns for multiple resources. Prior projects were largely driven by the need to manipulate vegetation for forest health improvement and wildfire mitigation. The landscape evaluation process more fully integrated planning, simultaneously emphasizing wildlife and aquatic habitat conditions, landscape and patch-scale fire behavior, vegetation and fuels patterns, and the pros and cons of continued road access, leading to restoration opportunities for a multiplicity of resources. The Nile Creek Project became a good example of simultaneous problem-solving rather than an exercise in trade-off analysis.

6.8 What Could be Improved?

A simple CDP decision model was developed in this EMDS application for want of time and additional resources. Alongside information reflecting knowledge about the state of the system, other criteria might have been included, such as those reflecting social and economic values, and other feasibility and efficacy criteria. Examples might include consideration of fire risks to human developments, effects on meeting other resource objectives where restoration is not the primary goal, matters of technical and economic feasibility and social acceptability, relationships to life-cycle costs and benefits, retreatment frequency and the duration of positive treatment effects, uncertainties associated with management outcomes and data quality, and trade-offs associated with more or less strategic placement of treatments.

6.9 Research Opportunities

Two opportunities for increasing the research and heuristic value of this project-level planning tool would include adding stochastic succession and disturbance dynamics to modeled landscape treatment prescriptions and to evaluate alternative landscape prescriptions against FRV conditions representing several plausible future climate scenarios. In the first instance, stochastic behavior could be added to modeled landscape-treatment scenarios by simulating them spatially in models such as the Landscape Succession and Disturbance Model–LANDSUM (see Keane et al. 2002; Barrett 2001) or many others. LANDSUM provides state-transition models for the potential vegetation types of a study area. Within each state-transition model (STM) are successional states defined by cover types and structural classes, a complete set of transition pathways that show all potential succession paths between states, and transition times related to each potential path. Initialized disturbance probabilities by disturbance severity determine the likelihood that any state will transition to any other state. In this context, landscape treatments would occur as prescribed, but other unplanned disturbances caused by wildfires, forest insects, and forest pathogens could occur as well. The net result would be annualized depictions of planned and unplanned vegetation outcomes, which would be a more accurate depiction of likely outcomes of implemented scenarios.

In a related manner, a range of climatic futures could also be simulated using a "climatized" version of LANDSUM (e.g., Cary et al. 2006) or other STM. Simulations would occur as described above, but in this case the conditioning climate would influence fire probabilities by means of a scalar applied to historical fire probabilities assigned from the climate change and area burned literature. The advantage of this sort of approach would be in developing hedging strategies for landscape management in an uncertain climatic future.

7 Final Thoughts

First, some readers will no doubt be curious about the level of effort needed to fully implement decision-support applications for landscape analysis such as those presented in our four detailed examples. Put simply, the effort can be daunting if the process must begin with collection of new field or satellite data. As a very rough guide, we suggest that each day of modeling and analysis is supported by

10 days of geoprocessing, and each day of geoprocessing is supported by 10 days of collecting and processing field data. In other words, designing, implementing, and running a landscape DSS typically represents a very modest fraction of the overall effort. Developing good quality, map-based information about the landscape(s) of interest, for each of the dimensions that may be co-considered is what takes the time and effort. If the needed data are already at hand, additional investment in DSS development can return disproportionately large value added relative to the investment.

There are at least a few strategic lessons to be gleaned from the four examples that have been presented. Addressing questions about ecosystem integrity or landscape departure with respect to vegetation required very high-dimensional logic representations in order to adequately address the facets of structure and composition. Indeed, all the logic models discussed evaluated 100s of input variables and 1000s of parameters. Contributing to the very large size of these models, five class metrics were used to evaluate each patch type, and nine landscape metrics were used to evaluate the spatial properties of patch types. Notice also that the same set of 14 metrics was used across all four examples for simplicity. As a practical matter, we consider that the utility of the metrics chosen is entirely dependent upon the questions being addressed, and there are over 100 to choose from. The last three examples demonstrated how decision models can usefully augment the logic-based analysis, thereby introducing practical management issues into the priority setting process, while simplifying the analysis by decomposing it into two relatively simpler problems—understanding the status of the systems in question, and then asking what might be done given the condition of the systems.

Finally, we conclude with a few thoughts on the sense in which our four landscape applications can be considered successful. Our first three examples were primarily developed as proofs of concept in research and development. From an internal perspective, we consider these applications successful at providing an interpretation and synthesis of large volumes of information that we think usefully encapsulated scientific understanding of large, complex, and abstract problems. Of course the "acid test" for decision-support applications is that managers find them useful, understand them, and actually put them into service addressing real-world management problems more efficiently and effectively than before. Our final example of project-level planning was highly successful in these terms.

This landscape evaluation tool is now being implemented on all seven Districts of the Okanogan and Wenatchee National Forests, on an area of more than 1.6 million ha, prior to implementing any landscape restoration project under its Strategy. Moreover, between the draft and final stages of this chapter, the US Fish and Wildlife Service in their Revised Recovery Plan and Critical Habitat Rule (CHR) for the northern spotted owl recommended that methods such as ours can serve as an example of how to assess and restore ecological patterns and processes to eastern Washington and Oregon forest landscapes (USFWS 2011, 2012).

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