

Sensitivity Analysis of Land Unit Suitability for Conservation Using a Knowledge-Based System

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Abstract The availability of spatially continuous data layers can have a strong impact on selection of land units for conservation purposes. The suitability of ecological conditions for sustaining the targets of conservation is an important consideration in evaluating candidate conservation sites. We constructed two fuzzy logic-based knowledge bases to determine the conservation suitability of land units in the interior Columbia River basin using NetWeaver software in the Ecosystem Management Decision Support application framework. Our objective was to assess the sensitivity of suitability ratings, derived from evaluating the knowledge bases, to fuzzy logic function parameters and to the removal of data layers (land use condition, road density, disturbance regime change index, vegetation change index, land unit size, cover type size, and cover type change index). The amount and geographic distribution of suitable land polygons was most strongly altered by the removal of land use condition, road density, and land polygon size. Removal of land use condition changed suitability primarily on private or intensively-used public land. Removal of either road density or land polygon size most strongly affected suitability on higher-elevation US

Forest Service land containing small-area biophysical environments. Data layers with the greatest influence differed in rank between the two knowledge bases. Our results reinforce the importance of including both biophysical and socio-economic attributes to determine the suitability of land units for conservation. The sensitivity tests provided information about knowledge base structuring and parameterization as well as prioritization for future data needs.

Keywords Sensitivity analysis · Map removal · Knowledge base · Conservation suitability · Land suitability · Fuzzy logic · Ecosystem Management Decision Support

Introduction

The long-term success of conservation activities depends on the quality of the sites selected as reserves (Rodrigues 2000), with respect to both the overall ecological conditions and the conditions for specific targets of conservation. Site quality is a combination of many factors, such as size, departure of ecological patterns and processes from historical conditions, human impacts, and land use and manageability (Stoms and others 1998, 2002; Reynolds and Hessburg 2005). Many regions are limited in the existence, completeness, or accuracy of data available to address these factors (Belbin 1993; Reynolds 2001). For this reason, it is important to assess the relative contribution of mapped data layers to the calculation of any quantitative measure of site quality, such as land suitability. A land suitability analysis conducted for conservation purposes is intended to identify land units whose ecological conditions, including spatial characteristics (Malczewski 2004), are suitable for sustaining the patterns and processes necessary

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for long-term persistence of the targets. Development of models to estimate land suitability should include a determination of sensitivity to tradeoffs involved in the inclusion or exclusion of data layers.

Among methods for determining the suitability of land units for conservation purposes, knowledge-based (KB) systems based on fuzzy logic networks provide the following advantages. The reasoning structure embodied in a KB has value for assessing suitability when current knowledge exists about the relationships in a system, but in insufficient detail to construct an accurate mathematical model. KB reasoning can also incorporate incomplete information and provide an assessment of the influence of missing data (Reynolds 2001). Fuzzy logic representations of knowledge as degree of membership in sets described with continuous curves can be less arbitrary and more parsimonious than the categorical representations used in the rule-based systems of many other KBs (Jackson 1990; Schmoldt and Rauscher 1995). Fuzzy logic can accommodate the ambiguity and imprecision that may be involved in associating land attribute constraints with suitability (Malczewski 2004). We conducted a land suitability assessment of a large region, the interior Columbia River basin, by developing and applying fuzzy logic functions in a KB to input data layers to rate the conservation suitability of land polygons (Bourgeron and others 2003). Suitability was then used as a cost criterion in selecting candidate regional networks to represent vegetation cover types as targets of conservation (Humphries and others 2008).

In the process of building a KB, decisions are made regarding KB structure and parameterization, based on expert knowledge and the results of previous studies. Sensitivity analysis provides information about which model components are most influential in determining model output (Rose 1983), which, for our study, is land suitability. We conducted sensitivity analyses to explore key features of our KB model. Our objectives were to assess the sensitivity of the conservation suitability of land units to (1) changes in the parameters of fuzzy logic functions used in KB models, and (2) the successive removal of one or more data layers used as input into existing KBs to evaluate ecological conditions. We examined sensitivity to model parameters, which are likely to be a major source of uncertainty (Mahamah 1988) by measuring changes in suitability resulting from fixed perturbations in parameter values. Map removal tests provide a regional perspective on the impact of data layers on suitability, such as the particular distribution, configuration, and ownership of suitable land polygons identified when a data layer is removed. Such analyses can be used to examine the implications of choices made in constructing a KB, as well as the effect of data availability on the

conservation planning or site restoration process. This knowledge permits the designer and user of a KB to better understand the tradeoffs involved in emphasizing or de-emphasizing certain areas as candidates for conservation, e.g., focusing on public versus private lands.

Methods

Study Area

Our study area, the interior Columbia River basin (ICRB), is a 560,000 km² region of the Pacific Northwest, encompassing the U.S. portion of the Columbia River basin east of the crest of the Cascade Range, and also including portions of the Lahontan and Klamath basins south of the Columbia River basin (Fig. 1). The diverse array of ecosystems represented in the ICRB range from desert grasslands and shrublands to cold, wet forests and alpine vegetation, with elevations that range from 22 to 3677 m (Fig. 1) (Reid 1995; Hann 1997). The Cascade Range extends north–south along the western edge of the ICRB. The Rocky Mountains comprise the eastern edge of the study area in western Montana, Idaho, and Wyoming, and also cover large areas of northern and central Idaho. An extensive basalt upland, the Columbia Plateau, encompasses portions of eastern Washington and Oregon and southern Idaho. A large area of the ICRB (62%) is in federal, state, and tribal ownership (Quigley and Arbelbide 1997). Federally owned public land is more likely to be subject to environmental and conservation regulations than other ownerships.

Application Framework

We implemented KBs in an application framework, Ecosystem Management Decision Support (EMDS), which

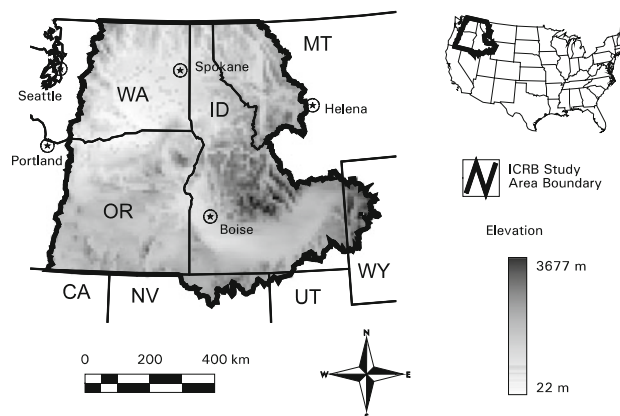


Fig. 1 Interior Columbia River basin study area in the Pacific Northwest, U.S., including elevation and major cities

provides analytical tools for examining the potential contribution of missing data to the determination of the conservation suitability of land units (<http://www.institute.redlands.edu/emds/>). KBs describing logical relationships (dependencies) among ecosystem states and processes of interest can be evaluated in EMDS (Reynolds 1999a). The processing of a KB is conducted in a GIS environment, in which a catalog of land unit attribute data is assembled, the spatial extent is defined, and maps, tables, and graphs of results are displayed. EMDS contains a scenario subsystem for performing ‘what if’ analyses by modifying input data or KB structure. In addition, a data acquisition manager subsystem can generate information concerning the influence of missing data on the results.

NetWeaver software was used in EMDS to develop KBs as interconnected dependency networks that represent hypothesized relationships of ecosystem states and processes to the conservation suitability of land units (Reynolds 1999b). Dependency networks at lower levels in the hierarchy, termed antecedents, are linked by relational nodes to generate higher-level states in the KB. Each dependency network in a KB is designed to test a proposition concerning an ecosystem state or process, for example, that the density of roads in a land unit is low enough for conservation purposes. Antecedents ultimately terminate in data links, in which a land unit attribute is compared to a fuzzy logic function (a quantitative representation of a proposition) to derive a truth value for each land unit that expresses the degree to which the proposition is supported by the data. Truth values, also called suitability ratings, range from -1 (proposition is completely false) to 1 (proposition is completely true). A truth value or suitability rating of 0 is designated as undetermined, indicating lack of evidence for or against the proposition. NetWeaver’s object-based representation of dependency networks confers modularity on KB structure, allowing complex KBs to be easily constructed from simpler components.

Input Data Layers

An existing database, compiled for an ecological assessment of the ICRB (the Interior Columbia Basin Ecosystem Management Project; Quigley and Arbelbide 1997) provided regional-scale data for our analyses (<http://www.icbemp.gov>). Land units for conservation selection were land polygons, delineated as biophysical environments by first clustering climate, hydrological, and biogeochemical variables into 37 biophysical classes, and then further stratifying by potential vegetation (Bourgeron and others 2001, 2003; Humphries and others 2008). The ICRB contained 686 biophysical environment classes in 17,227 land polygons, which ranged in size from 3 to 6943 km², with a mean of 32 km² and median of 10 km² in size.

Existing data layers, including current and historical vegetation cover types, current and historical disturbance (fire) regimes, and road density, were attributed to land polygons (see Humphries and others 2008 for a more detailed description of these data). Land use condition was available for federal lands only and was derived by combining eight management classes describing the effect of human activities on ecological conditions of these lands (US Forest Service, Bureau of Land Management, and National Park Service ownership; Hann 1997; <http://www.icbemp.gov>) into four categories: generally non-intensive human influence, some consumptive resource use, high levels of resource use and vegetation manipulation, and ecological conditions permanently altered by human activities. Non-federal lands were unclassified. In addition, we developed two indices of land polygon change by rating the degree of departure of current from historical conditions for vegetation cover types and disturbance regimes. Categories for the vegetation change index were ‘no change’, ‘acceptable change’ (i.e., change from a native vegetation cover type to another native vegetation cover type), and ‘unacceptable change’ (i.e., change from native to non-native vegetation). The disturbance change index included the same categories as the vegetation change index plus the category ‘marginally acceptable change’ and was based on the degree of change in the frequency and/or severity of fire.

Knowledge Bases

Two types of KBs were constructed to evaluate the suitability of land polygons for conservation (Fig. 2; Bourgeron and others 2003; Humphries and others 2008). The first type of KB (hereafter referred to as the LP_{KB}) determined the suitability of the overall ecological conditions of land polygons (Fig. 2a). The second type of KB (CT_{KB}) determined the suitability of land polygons for a particular vegetation cover type as a target of conservation (Fig. 2b). A separate CT_{KB} was constructed for each of 35 naturally vegetated cover types. In this paper, we illustrate the CT_{KB} using the interior ponderosa pine cover type, dominated by an ecologically and commercially important tree species, *Pinus ponderosa*. For both KB types, suitability ratings consisted of truth values ranging from -1 to 1 , derived from evaluating dependency networks in the KB. Land polygons with positive truth values (>0) were assumed to be suitable for conservation and those with negative truth values (<0) were assumed to be unsuitable. A value of zero represented undetermined suitability.

Suitability of a land polygon in the LP_{KB} was a function of the suitability of conditions in the land polygon itself, the suitability of its neighborhood (adjacent land polygons), and the suitability of its size (Fig. 2a). Five data

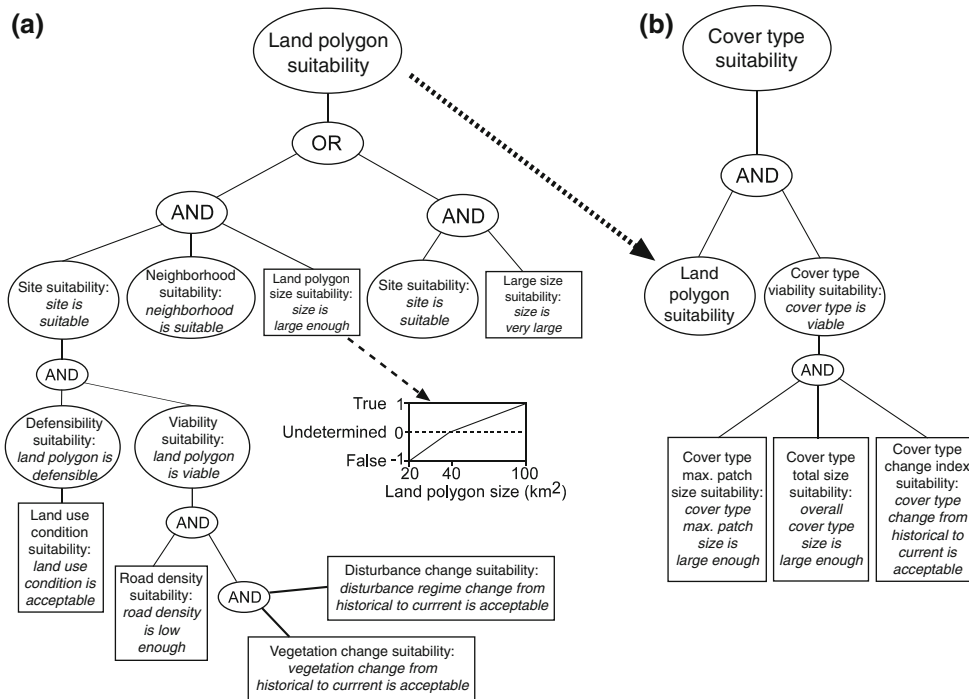


Fig. 2 Structure of knowledge base dependency networks (*enclosed in ovals*) terminating in data links (*enclosed in rectangles*), in which land polygon attribute values are evaluated with fuzzy logic functions to derive suitability ratings. Statements in italics in data link rectangles represent propositions regarding ecosystem state and processes tested by fuzzy logic functions. Dependency networks and data links are connected with AND and OR relational nodes. OR nodes evaluate to the maximum suitability rating derived from the antecedent networks connected to the OR node. AND node evaluation

is designed to produce a conservative estimate of truth in the presence of missing or partial negative evidence, according to the formula: $AND(t) = \min(t) + [average(t) - \min(t)] \times [\min(t) + 1]/2$ in which $AND(t)$ is the truth value of the AND node, $\min(t)$ is the minimum truth value of the AND node's antecedents, and $average(t)$ is a weighted average of the truth values of the AND node's antecedents. The predominance of AND nodes in the KBs therefore produces a conservative evaluation of suitability

layers, land use condition, road density, disturbance change index, vegetation change index, and land polygon size, provided input into the LP_{KB} through data links and were evaluated with LP_{KB} fuzzy logic functions (Table 1). The structure of a fuzzy logic function to evaluate the proposition that land polygon size is large enough for conservation purposes is illustrated in Fig. 2a. Sizes ≤ 20 km² received a suitability rating of -1 (completely false), sizes = 40 km² received a suitability rating of 0 (undetermined), and sizes ≥ 100 km² received a suitability rating of 1 (completely true). Linear functions determined the suitability rating between 20 and 40 km² (partial negative suitability) and between 40 and 100 km² (partial positive suitability). If the size was very large, suitability was considered to depend only on the land polygon itself, without consideration of its neighborhood.

The suitability rating for conditions in a land polygon was derived from two LP_{KB} dependency networks we termed defensibility (i.e., compatibility of land use with conservation activities) and viability (i.e., the likelihood that ecological conditions allow persistence of conservation targets) (Fig. 2a). A fuzzy logic function determined

the defensibility of land polygons for conservation by evaluating the proposition that land use condition on federal land in a land polygon was acceptable (Table 1). State, tribal, and private lands, for which no information about land use condition was available, were rated as unsuitable based on knowledge that past and in many cases current management was unlikely to be compatible with conservation goals (Quigley and others 2001). The viability of a land polygon for conservation included three fuzzy logic functions (Table 1). The fuzzy logic function applied to road density evaluated the proposition that road density was low enough for land polygon viability. The identical fuzzy logic functions for the indices of vegetation and disturbance change evaluated the proposition that change from historical to current conditions was acceptable for viability. Neighborhood suitability was evaluated with the same dependency networks (defensibility and viability) applied to the attributes of the land polygons that adjoined the focal polygon, except that road density of neighboring land polygons was not evaluated.

Suitability for the CT_{KB} incorporated overall land polygon suitability with a dependency network to determine the

Table 1 Fuzzy logic function threshold parameters for determining suitability ratings (truth values) from data layer values evaluated in LP_{KB} and CT_{KB}

Data layer	Proposition that fuzzy logic function evaluates	Fuzzy logic function threshold parameters		
		False −1	Undetermined 0	True +1
Land polygon knowledge base				
Land use condition	Land use condition (i.e., percent of land polygon with light to moderate human impact) on federal land is acceptable.	10	25	50
Road density	Road density (km/km ² in land polygon) is low enough.	2.69	0.9	0
Disturbance change	Disturbance regime index of change from historical to current (i.e., percent of land polygon with acceptable index values) is acceptable.	1	5	50
Vegetation change	Vegetation index of change from historical to current (i.e., percent of land polygon with acceptable index values) is acceptable.	1	5	50
Land polygon size	Land polygon size (area in km ²) is large enough.	20	40	100
Land polygon size	Land polygon size (area in km ²) is so large that neighborhood suitability need not be evaluated.	100	125	150
Cover type knowledge base				
Cover type maximum patch size	Cover type maximum patch size (area in km ²) is large enough.	4	6	8
Cover type total size	Cover type total size (area in km ²) is large enough.	8	10	15
Cover type change index	Cover type index of change from historical to current is acceptable.	2	1	0

viability of the cover type. Land polygon suitability ratings from the LP_{KB} provided input into the CT_{KB}, along with maximum cover type patch size, total cover type size expressed as area, and cover type change index, producing suitability ratings of land polygons for a particular cover type. Cover type viability was evaluated by applying three fuzzy logic functions to the propositions that maximum cover type patch size in a land polygon was large enough, total cover type size was large enough, and index of departure of current from historical vegetation conditions was acceptable (Fig. 2b; Table 1).

We conducted rank-order correlation of data layers using Kendall’s tau (Babiker and others 2005). Stepwise linear regression was used to relate LP_{KB} and CT_{KB} suitability to the suitability of components (dependency networks and data links) in the KB hierarchy structure.

Sensitivity to Fuzzy Logic Function Parameter Values

We conducted two levels of sensitivity analyses to determine the influence of fuzzy logic function parameters on suitability ratings. At the first level, moderate perturbations of parameter values were obtained by adding or subtracting 10% of the maximum nominal value (Table 1) describing each fuzzy logic function in the LP_{KB}. For example, for the fuzzy logic function describing land polygon size, 10% of the maximum

value (100 km²) was 10 km², producing low parameter values of 10, 30, and 90 km², and high parameter values of 30, 50, and 110 km². At the second level, a stronger test was provided by either dividing or multiplying the nominal parameter values by two. For each parameter sensitivity test, the LP_{KB} was reevaluated with the altered parameter values. At both levels, the significance of changes in suitability ratings with perturbations in parameter values was tested with repeated measures ANOVA (Rose 1983) using parameter perturbations as factors.

Sensitivity to Map Removal

We employed the scenario subsystem in EMDS to explore the sensitivity of suitability ratings to the removal of one or more input data layers (Lodwick and others 1990; Babiker and others 2005). Each map removal test was implemented by setting the appropriate truth value to zero (undetermined) in all land polygons for one or more data layers prior to calculating suitability. We examined the sensitivity of KB output to the removal of single data layers (e.g., removal of land use condition or road density), or combinations of data layers (e.g., removal of all components of the viability dependency network: road density, vegetation change, and disturbance regime change).

Results

Most rank-order correlations among data layers were significant (Table 2) due to the large number of land polygons analyzed, but a relatively high degree of data layer independence was indicated by the low tau values for most comparisons. We expected that a strong relationship would be found between cover type maximum patch size and cover type total size ($\tau = 0.874$). Moderately high correlations also occurred between vegetation change and cover type change index ($\tau = -0.498$) and between land polygon size and cover type total size ($\tau = 0.373$).

All suitability components (dependency networks and data links) were significant predictors of LP_{KB} suitability in stepwise regression (Table 3). The magnitude of the F values associated with the components reflected their position in the KB hierarchy, with upper level components (site, land polygon size, large size, and neighborhood suitability) exhibiting the highest F values, followed by intermediate level components (viability and defensibility suitability), and lower level components (vegetation change, disturbance change, and road density suitability). For the CT_{KB} , the highest level components, land polygon and cover type viability suitability, also had the highest F values (Table 3), followed by other components from both the CT_{KB} and LP_{KB} (cover type total size, land polygon size, road density, and vegetation change suitability).

Parameter Sensitivity

At the first level of parameter sensitivity tests, addition or subtraction of 10% from nominal values for individual fuzzy logic functions resulted in differences in suitability that averaged 2% or less (standard deviation <6.5%). Only the changes for parameters associated with the land polygon size function were significant using repeated measures ANOVA ($P < 0.001$). Increasing the perturbations of parameter values to division or multiplication by two produced changes of less than 4% (standard deviation

<12%). Significant changes were observed for functions associated with land use condition and land polygon size ($P < 0.001$). At both levels, suitability ratings for many land polygons experienced little or no change under parameter perturbations, especially for the large number of land polygons that had negative suitability ratings using nominal parameter values.

Map Removal Sensitivity

When all data layers were included as input into the LP_{KB} (i.e., the no removal case), a relatively small number of land polygons (576), occupying approximately 10% of the study area, had a suitability rating >0 (Table 4; Bourgeron and others 2003). Suitable land polygons (i.e., those with positive suitability ratings) were located primarily along the crest of the Cascade Range in Washington; the Rocky Mountains in western Montana, central Idaho, and western Wyoming; and portions of the Columbia Plateau in southeast Oregon and southern Idaho (Fig. 3a). Suitable land comprised predominantly federal ownership, including USFS ownership (54% of suitable land) located in the Rockies and Cascades, and BLM ownership (34%), largely in southeast Oregon and southwest Idaho. Only 4% of suitable land was privately owned.

Following removal of land use condition (i.e., assigning a value of zero or undetermined to the defensibility dependency network of the LP_{KB}), the number and area of land polygons that had positive suitability ratings increased over no removal (Table 4). The extent of suitable land increased in eastern Washington, northern and southeastern Oregon, and southern Idaho (Fig. 3b), with the differences occurring primarily on private (increase of approximately 32,500 km²) and BLM (increase of approximately 28,600 km²) land. These changes showed the strong contribution of the LP_{KB} defensibility dependency network to overall suitability. For some land polygons located on private land or intensively used public land, the defensibility ratings increased from negative values with no

Table 2 Kendall's rank correlation tau for data layers

Data layer	Land use condition	Road density	Disturbance change	Vegetation change	Land polygon size	Cover type maximum patch size	Cover type total size
Road density	-0.294 ^a						
Disturbance change	0.127 ^a	-0.159 ^a					
Vegetation change	0.132 ^a	-0.056 ^a	0.283 ^a				
Land polygon size	0.011NS	0.132 ^a	-0.022 ^a	0.005NS			
Cover type maximum patch size	-0.022 ^a	0.185 ^a	-0.073 ^a	0.133 ^a	0.227 ^a		
Cover type total size	-0.003 ^a	0.194 ^a	-0.064 ^a	0.098 ^a	0.373 ^a	0.874 ^a	
Cover type change index	-0.091 ^a	-0.175 ^a	0.247 ^a	-0.498 ^a	0.038 ^a	-0.124 ^a	-0.108 ^a

^a Significant at $P < 0.001$; NS: not significant

Table 3 Stepwise regression of land polygon and interior ponderosa pine KB suitability as functions of suitability of KB components (dependency networks and data links; see Fig. 2 for position of components in KB hierarchy structure)

Significant KB component	Df	F value	P value	Component type
Land polygon KB				
Site suitability	1	3312.9	<0.001	Dependency network
Land polygon size suitability	1	3232.5	<0.001	Data link
Large size suitability	1	277.5	<0.001	Data link
Neighborhood suitability	1	148.3	<0.001	Dependency network
Viability suitability	1	52.3	<0.001	Dependency network
Defensibility/land use condition suitability	1	24.7	<0.001	Data link
Vegetation change suitability	1	13.8	<0.001	Data link
Disturbance change suitability	1	5.9	0.015	Data link
Road density suitability	1	4.8	0.028	Data link
Interior ponderosa pine KB				
Land polygon suitability	1	3010.0	<0.001	Dependency network
Cover type viability suitability	1	395.7	<0.001	Data link
Cover type total size suitability	1	52.4	<0.001	Data link
Land polygon size suitability	1	48.6	<0.001	Data link
Road density suitability	1	7.7	0.006	Data link
Vegetation change suitability	1	6.3	0.012	Data link

Table 4 Number of land polygons and area for suitability following data layer removal from land polygon and interior ponderosa pine KBs

Data layer(s) removed	Number of polygons			Area (km ²)			Area (%)		
	Pos. suit.	Neg. suit.	0	Pos. suit.	Neg. suit.	0	Pos. suit.	Neg. suit.	0
Land polygon knowledge base									
None	576	16,649	2	53,666	505,693	76	9.59	90.39	0.01
Land use condition	999	16,226	2	120,592	438,743	100	21.56	78.43	0.02
All viability data layers ^a	862	16,364	1	86,726	472,506	203	15.50	84.46	0.04
Road density	944	16,283	0	91,503	467,932	0	16.36	83.64	0.00
Disturbance change	493	16,734	0	48,198	511,237	0	8.62	91.38	0.00
Vegetation change	491	16,736	0	48,064	511,371	0	8.59	91.41	0.00
Land use condition, road density	3,052	14,175	0	384,065	175,370	0	68.65	31.35	0.00
Land polygon size	4,408	12,814	5	86,580	472,022	833	15.48	84.37	0.15
Interior ponderosa pine knowledge base									
None	67	5,223	1	4,713	244,331	76	0.84	43.67	0.01
Land use condition	117	5,174	0	9,111	240,009	0	1.63	42.90	0.00
All viability data layers ^a	142	5,149	0	13,127	235,993	0	2.35	42.18	0.00
Road density	153	5,138	0	13,701	235,419	0	2.45	42.08	0.00
Disturbance change	61	5,230	0	4,326	244,794	0	0.77	43.76	0.00
Vegetation change	60	5,231	0	4,268	244,852	0	0.76	43.77	0.00
Land use condition, road density	684	4,606	1	72,392	176,690	38	12.94	31.58	0.01
Land polygon size	131	5,159	1	5,927	243,135	58	1.06	43.46	0.01
Cover type maximum patch size	69	5,221	1	4,850	244,194	76	0.87	43.65	0.01
Cover type total size	72	5,218	1	5,149	243,895	76	0.92	43.60	0.01
Cover type max. patch size, total size	169	5,121	1	12,636	236,408	76	2.26	42.26	0.01
Cover type change	72	5,218	1	4,941	244,103	76	0.88	43.63	0.01

Pos. suit., suitability rating >0; Neg. suit., suitability rating <0; ^a Road density, disturbance change, and vegetation change

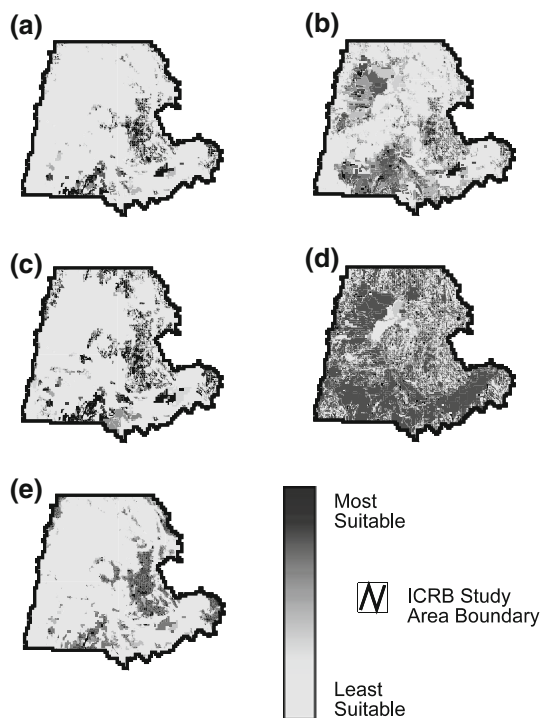


Fig. 3 Suitability ratings of land polygons in study area for land polygon knowledge base resulting from data layer removal, ranging from 1, most suitable (darkest gray), to -1, least suitable (lightest gray). **a** No removal; **b** Land use condition removed; **c** Road density removed; **d** Land use condition and road density removed; **e** Land polygon size removed

removal to zero with removal of land use condition, thereby increasing overall land polygon suitability.

The removal of road density produced an increase in suitable land over no removal (Table 4) which was not as high as that observed when land use condition was removed. Suitability increased primarily in the Cascades, portions of northern Washington, Idaho, and Montana, the Blue Mountains of southeastern Washington and northeastern Oregon, central Oregon, and southern Idaho (Fig. 3c). Most of the changes occurred on USFS land (increase of approximately 26,000 km²), in areas with defensible land use condition but high road densities, which precluded positive suitability ratings if road density was present. Removal of either of the other two viability data layers (disturbance and vegetation change index) produced only small decreases in suitable land over no removal (not shown). Removal of all three viability data layers produced results similar to removal of road density alone, demonstrating that road density had the greatest impact on the viability dependency network of the LP_{KB}.

When both land use condition and road density were removed, suitability increased greatly from no removal to encompass nearly 70% of the ICRB (Table 4). In this case, suitability depended only on disturbance and vegetation

change indices and land polygon size. Many land polygons met the LP_{KB} criteria for these attributes, and therefore, suitable land was widespread in the ICRB (Fig. 3d).

Removal of land polygon size produced suitable land polygon area similar to that observed when all viability data layers were removed (Table 4), but the number of suitable land polygons was larger than in any other removal test, because many small polygons became suitable in the absence of minimum size criteria. Most of the increase in suitability over no removal occurred on USFS land (increase of approximately 29,700 km²), reflecting the relatively high-elevation distribution of USFS land in the ICRB, with greater topographic relief and therefore many small-area biophysical environments (Fig. 3e).

We determined the suitability for conservation of land polygons for interior ponderosa pine, a widespread vegetation cover type in the ICRB, occupying 57,975 km² (10% of the ICRB) to evaluate removal sensitivity for a potential target of conservation activity. Interior ponderosa pine is representative of extensive community types that have high economic, recreation, and conservation values. Cover type suitability was assessed only for the 5,291 land polygons, occupying 249,120 km², which contained at least one interior ponderosa pine patch (minimum cover type patch size of 1 km²). These land polygons were concentrated along the western edge of the ICRB, in mountainous areas of western Montana and central Idaho, and in the Columbia Plateau in Washington and northern Oregon (gray shades in Fig. 4).

When no data layers were removed from input into the CT_{KB} for interior ponderosa pine, only 1.3% of land polygons, occupying 1.9% of the total area, had positive cover type suitability, reflecting the intensive use of such low elevation forested ecosystems (Table 4; Fig. 4a). Most land polygons rated as suitable by the LP_{KB} but unsuitable by the CT_{KB} had cover type maximum patch sizes and total sizes that were too small to meet the maximum patch size and total size criteria in the CT_{KB}; a smaller number of these land polygons had adequate cover type sizes but unacceptable cover type changes from historical to current conditions.

Following removal of land use condition from the CT_{KB}, the number and area of land polygons with positive suitability increased over no removal, predominantly on BLM, tribal, and private lands in eastern Washington at lower elevations (Fig. 4b). Removal of road density increased the number and area of suitable land polygons, producing a greater change than was observed with land use condition removal (Table 4; Fig. 4c). Removal of either the disturbance change index or vegetation change index produced little change (Table 4). The very strong effects of land use condition and road density on interior ponderosa pine suitability were demonstrated by their removal, in which

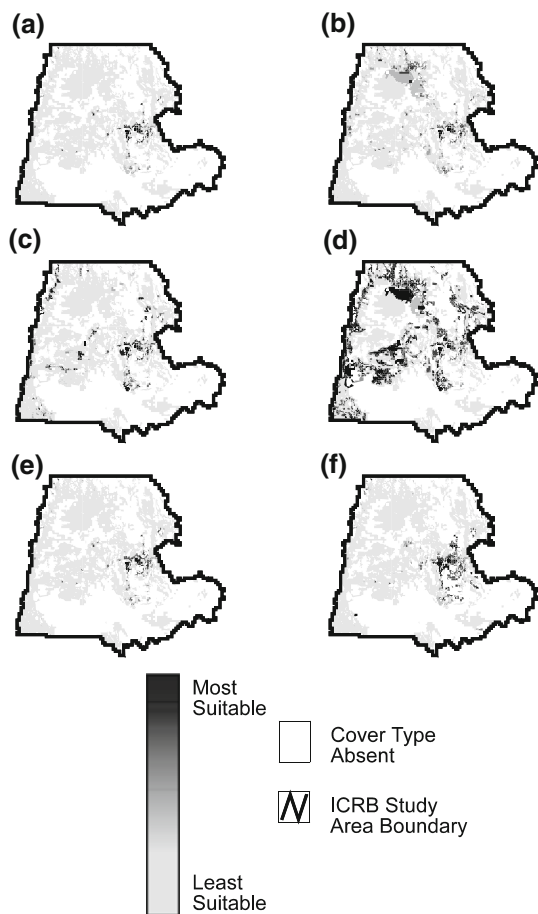


Fig. 4 Suitability ratings of land polygons in study area for interior ponderosa pine cover type knowledge base resulting from data layer removal. *Gray shades* represent suitability ratings for land polygons that contain at least one patch of the cover type, ranging from 1, most suitable (*darkest gray*) to -1 , least suitable (*lightest gray*). *White* represents land polygons not containing the cover type. **a** No removal; **b** Land use condition removed; **c** Road density removed; **d** Land use condition and road density removed; **e** Land polygon size removed; **f** Cover type maximum patch size and total size removed

there was a large increase in number and area of suitable land polygons over no removal (Table 4; Fig. 4d). Removal of land polygon size, but not cover type size, produced a moderate increase in area but a doubling of the number of suitable land polygons over no removal, because of the inclusion of small polygons as suitable (Table 4; Fig. 4e).

Removal of each of the components of cover type viability (cover type maximum patch size, cover type total size, and cover type change index) produced only slightly greater numbers and area of suitable land polygons than was observed with no removal (Table 4). When both size components were removed, so that cover type viability resulted only from cover type change index, an increase in suitability was observed (Table 4; Fig. 4f), as a result of the greater number of land polygons that met the criteria

for cover type change index suitability than met the size criteria.

Discussion

The relatively modest changes in area at both levels of parameter perturbations provided an indication that suitability was not extremely sensitive to our selection of parameter values and therefore constitute relatively robust measures for our application to conservation.

Removal of data layers from input into a KB that represents a formal conceptualization of suitability can substantially change both the amount and distribution of suitable land polygons for conservation in a region, as was shown for the removal of land use condition, road density, and land polygon size from the LP_{KB} (Table 4). However, many land polygons rated suitable with no removal also remained suitable following removal. This is reflected by the fairly consistent values in the column in Table 5 labeled ‘Pos. suit. remains pos.’ (i.e., area with positive suitability in the no removal case that remained positive after removal), and by the relatively small values in the column labeled ‘Pos. suit. becomes neg.’ (i.e., area with positive suitability in the no removal case that changed to negative after removal). Most of the changes occurred in land polygons that were rated unsuitable with no removal and that changed to a rating of suitable when one or data layers were removed (column labeled ‘Neg. suit. becomes pos.’ in Table 5).

The removal tests elucidated the roles played individually and in combination by the three most influential data layers, land use condition, road density, and land polygon size, in targeting particular aspects of conservation. The contribution of land use condition, as implemented in the defensibility component of the LP_{KB} , was to screen out land units with management activities assumed to be incompatible with conservation goals. Land use was shown to be important in the process of selecting candidate areas for conservation or restoration by Wessels and others (2000). Road density, the most influential component of the viability dependency network, was important in characterizing as unsuitable some higher elevation USFS sites that were otherwise rated highly with respect to their defensibility. This result adds to the already considerable amount of work on road effects, including impact on ecological conditions (Foreman and Alexander 1998; Jones and others 2000); as components of land suitability assessments (Stoms and others 2002; Pyke 2005); as a variable in an index of landscape health (Hemstrom and others 2001); and as a proxy variable to represent trends in ecological integrity (Quigley and others 2001).

Table 5 Categories of change in area (km²) for suitability from no removal case for land polygon and interior ponderosa pine KBs

Data layer(s) removed	Direction of change from no removal case			
	Pos. suit. remains pos.	Neg. suit. remains neg.	Neg. suit. becomes pos.	Pos. suit. becomes neg.
Land polygon KB				
Land use condition	47,075	432,129	73,517	6,538
All viability data layers ^a	51,534	470,340	35,150	2,132
Road density	52,973	467,205	38,488	693
Disturbance change	48,198	505,693	0	5,468
Vegetation change	48,064	505,693	0	5,602
Land use condition and road density	51,999	173,669	332,024	1,667
Land polygon size	46,801	465,914	39,745	6,066
Interior ponderosa pine KB				
Land use condition	4,242	239,462	4,869	471
All viability data layers ^a	4,557	235,837	8,494	156
Road density	4,713	235,419	8,912	0
Disturbance change	4,326	244,331	0	387
Vegetation change	4,268	244,331	0	445
Land use condition and road density	4,643	176,620	67,673	70
Land polygon size	4,598	243,002	1,329	57
Cover type maximum patch size	4,627	244,108	223	86
Cover type total size	4,668	243,850	481	45
Cover type maximum patch size and total size	4,668	236,363	7,968	45
Cover type change index	4,672	244,062	269	41

Pos. suit., suitability rating >0; Neg. suit., suitability rating 0; ^a Road density, disturbance change, and vegetation change

The effect of land polygon size was to restrict suitability to those land polygons we deemed of sufficiently large size for conservation purposes at a regional scale. Land unit size can have important effects in evaluating land suitability (Stoms and others 2002) and/or identifying potential conservation networks (Pressey and Logan 1998; Rouget 2003), with concomitant implications for representation of fine-scale conservation targets (Pressey and Logan 1998; Rodrigues and Gaston 2001; Rouget 2003); persistence of targets; management of large populations or species with large habitat requirements; and operation of ecological processes, including management of broad-scale disturbances (Schwartz 1999; Poiani and others 2000; DeVelice and Martin 2001).

The impact of particular data layers on suitability results in part from the manner in which the structure of the KB used to evaluate them is conceptualized and parameterized. Although we did not explicitly perform sensitivity analysis of KB structure, association of higher F values in stepwise regression with higher levels in the KB hierarchy indicated the importance of component position in the hierarchy.

Similarities in the results of LP_{KB} and CT_{KB} removal tests were expected because suitability ratings from the LP_{KB} were a component of the CT_{KB}. Nevertheless, for

single data layer removals, those with greatest influence (i.e., greatest change in suitability from the no removal case) differed in rank between the LP_{KB} and the interior ponderosa pine CT_{KB} (Table 4). Removal of land use condition produced greater change than removal of road density in the LP_{KB}; the reverse was true in the CT_{KB}. When land use condition was removed, many land polygons that were rated suitable in the LP_{KB} had unacceptable cover type change index, reducing the number and area of land polygons rated suitable in the CT_{KB}. This difference indicated that, to some extent, cover type change index substituted for land use condition in determining suitability. No corresponding reduction in suitability occurred with removal of road density, leading to a greater number and area of suitable land polygons for the CT_{KB}. KBs that differ from the LP_{KB} or CT_{KB} in the structuring of dependency networks and/or parameterization of fuzzy logic functions might be expected to exhibit different sensitivity to data layer removal (Reynolds and others 2003). This is illustrated by differences in the results of applying the same removal tests to the LP_{KB} and CT_{KB} (Table 4). In addition, regional characteristics, such as the distribution and spatial configuration of data attributes, also influence the results of map removals.

Identification of the attributes that contribute most strongly to suitability is important in considering potential changes to KB structure and parameterization, and ultimately to the conceptual representation of suitability. Such sensitivity analyses can also lead to priority-setting for refinement of land polygon attributes, such as ground checking data values, changing the scale of attributes, expanding or contracting the area of investigation, etc. (Reynolds 2001). For example, based on our results, it would be valuable to design a study to derive estimates of land use condition in the ICRB for ownerships other than USFS, BLM, and NPS.

The use of two types of KB (LP_{KB} and CT_{KB}) enabled us to combine information on the overall ecological condition of each land unit with information on the condition of each target feature of interest. We presented removal results for a single vegetation cover type, interior ponderosa pine. Similar results could be produced for any of the 35 ICRB naturally vegetated cover types for which we evaluated the CT_{KB} (Bourgeron and others unpublished), although caution is warranted when applying the models to cover types which may be difficult to map accurately at a regional scale, such as riparian vegetation and rare cover types. The sensitivity analyses reinforced the importance of including both biophysical and socio-economic attributes to determine the suitability of land units for conservation. Attributes should represent the impacts of human activities that alter land cover and other important aspects of habitat.

In practice, many potentially conflicting values are considered in selecting networks of conservation areas (Virolainen and others 1999). Network selection must balance efficiency in land area and cost with the viability and manageability of reserves (Pressey and Logan 1998). To satisfy the principles of reserve design, candidate sites should be drawn from those least disturbed by human activities and located so that management of surrounding areas is compatible with conservation (Bedward and others 1992). Methods are needed which explicitly evaluate as many relevant conservation criteria as possible, including the suitability of sites with respect their ecological conditions, and the influence of the presence or absence of land unit attributes on these criteria. KB models implemented in EMDS can provide such evaluations as part of a comprehensive approach to conservation network selection and can also be used to guide ecosystem management (Jensen and others 1996) or restoration activities (Reynolds and Hessburg 2005; Noss and others 2006). The incorporation of broad propositions in KBs to represent conservation suitability and subsequent sustainability can have value for national and regional assessments. For example, our evaluation of the proposition that a site is suitable synthesized diverse information obtained from evaluating multiple data links. In the future, this proposition could be reevaluated to

test whether land polygon conditions had significantly changed over time. The ability to monitor and spatially depict trends concerning broad ecosystem propositions (as developed in this study) may be advantageous for conducting ecosystem management and conservation. Furthermore, the KBs could be enlarged to assess potential conflicts when drawing multiple benefits from ecosystems (e.g., logging, wildlife management, conservation, and recreation) from the same area.

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