Use of State-and-Transition Simulation Modeling in National Forest Planning in the Pacific Northwest, U.S.A.

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Abstract

Effective national forest planning depends on scientifically sound analyses of land management alternatives relative to desired future conditions and environmental effects. The USDA Forest Service Pacific Northwest Region is currently using state-and-transition simulation models (STMs) to simulate changes in forest composition and structure for the revisions of five forest plans in Oregon and Washington. We illustrate the use of STMs to examine current and desired forest conditions, develop forest plan environmental impact statement (EIS) alternatives, and evaluate environmental effects, with examples from the Okanogan-Wenatchee National Forest (Washington, U.S.A.). Model parameters include ecosystem states and natural and human-caused disturbances, which were derived from empirical studies, published literature, and expert opinion. Forest growth rates were calibrated using Forest Vegetation Simulator (FVS) modeling of national forest inventory plot data and FVS post-processors, such as the Preside program. Preside was used to classify forest inventory plots into STM states, estimate mean residence times (within a state) and transition probabilities (between states), and summarize the alternative pathways between states. In some cases for the Okanogan-Wenatchee National Forest, Preside showed longer residence times for dense multi-story stands than assumed in previously developed STMs for the forest plan area. STMs are being used to simulate the effects of alternative combinations of forest treatments such as forest thinning, regeneration harvest, and prescribed burning. The effects of treatments on a suite of indicators and decision criteria, including forest structural states, departure from reference conditions, woody biomass yield, wildlife habitat, and fire severity and frequency, will be estimated using the output of STMs. STMs used in forest plan revisions have proved useful in testing assumptions, developing alternative restoration scenarios, and documenting current knowledge.

Keywords: Land use planning, state-and-transition model, alternative development, model calibration.

National Forest Management Planning in the United States

Management of national forests in the United States is guided by the strategic goals of the U.S. Department of Agriculture and USDA Forest Service, as well as laws, regulations, and agency policies. The Forest Service is responsible for managing the lands and resources of the National Forest System (NFS), which includes approximately 193 million acres in 44 states, Puerto Rico, and the Virgin Islands. The NFS is composed of 155 national forests, 20 national grasslands, and one national tallgrass prairie. Goals for managing NFS lands include (USDA FS 2007):

- Restore, sustain, and enhance the nation's forests and grasslands,
- Provide and sustain benefits to the American people,
- Conserve open space,
- Sustain and enhance outdoor recreation opportunities,
- Maintain basic management capabilities of the Forest Service,
- Engage urban America with Forest Service programs, and
- Provide science-based applications and tools for sustainable natural resources management.

The focus of National Forest System land management is continually evolving. Since the 1990s, the primary focus of NFS land management has shifted from optimization of commodity output toward the restoration of ecosystem function and resiliency.

The framework for NFS land management plans (Forest plans) was established by Congress in the National Forest Management Act (NFMA) of 1976 (16 U.S.C. § 1604).

Under NFMA, Forest plans:

1. Establish forest multiple-use goals and objectives;
2. Establish forest-wide standards and guidelines;
3. Establish management areas and direction applying to future activities;
4. Designate lands suitable and unsuitable for timber production;
5. Evaluate potential wilderness areas; and
6. Establish monitoring and evaluation requirements.

NFMA is implemented under an agency planning rule, which establishes administrative procedures for developing, revising, and amending forest plans (36 Code of Federal Regulations Part 219). Current forest plans and plan revisions for all national forests follow guidance from the 1982 Planning Rule (47 Federal Register 43037, Sept. 30, 1982). However, the Final Programmatic Environmental Impact Statement (EIS) for a new land management planning rule was released in January 2012;[1] future forest plan revisions will take place under this 2012 rule until a new rule is adopted. Forest planning must also adhere to the requirements of the National Environmental Policy Act (NEPA) of 1969 (42 U.S.C. § 4321), which set up procedural requirements for all federal government agencies to prepare environmental assessments (EAs) and EISs, which disclose the environmental effects of proposed federal agency actions.

Forest plans establish direction so that all future decisions on the forest will consider physical, biological, economic, and other sciences, and assure coordination of multiple-uses and a sustainable yield of products and services. Coupled with laws and regulations, forest plans create a management system for future decisionmaking. Projects and activities are, proposed, analyzed and carried out within the framework of the plan.

Currently, Forest plans consider the roles and capabilities of NFS lands within a complex matrix of climate change, increased forest densities, extended drought, uncharacteristic insect epidemics, intense wildfires, expansion of residential development into forest lands, and rapidly changing socioeconomic settings. Given the mix of ecosystem processes, management objectives, and an uncertain future regarding NFS lands, plus the need to meet NEPA requirements (e.g., to disclose the effects of Forest Service management in EAs and EISs), National Forest planners depend on scientifically sound modeling tools to analyze the effects of alternative management scenarios.

Forest plans are developed by first drafting a proposed plan that attempts to address known challenges, public concerns, and new information. This proposed plan is released for public comment. After analyzing comments on the proposed plan, alternatives to the proposal are included in a draft environmental impact statement (DEIS). Generally, the DEIS: (1) compares alternative ways of managing national forest lands; and (2) outlines the physical, biological, social, and economic effects of each alternative. Alternatives include a "no change" (or "no action") proposal, which represents a continuation of current forest plan direction. After analysis of public comment on the DEIS, a final environmental impact statement (FEIS) and Record of Decision (ROD) are released along with a final forest plan which becomes management direction for the next 10 to 15 years.

Table 1 summarizes the key national forest planning considerations and their relationships to ecological state-and-transition modeling (STM). Given the 2012 Planning Rule, science must be taken into account, appropriately interpreted, and applied when planning models are developed. Incomplete or unavailable information, scientific uncertainty, and risk are evaluated and disclosed as a part of model and forest plan documentation. Published research,

[1] The Final Programmatic EIS for the 2012 Forest Service planning rule is available at: http://www.fs.usda.gov/detail/planningrule/home/?cid=stelprdb5349164.

Table 1—Key National Forest Planning considerations and their relationship to ecosystem modeling

Forest planning consideration	State-and-transition modeling task related to national forest planning
Desired conditions	Define ecosystem states and transitions that are relevant to current, future, and desired conditions.
	Simulate long-term reference conditions to serve as baselines.
	Define relationships of key issues to desired ecosystem states and/or transitions (e.g., wildlife habitat, smoke production, watershed health).
Objectives	Simulate management actions and outcomes that will move the forest toward desired conditions. This is done by management area and/or forest-wide.
Standards and Guidelines	Use transition targets or adjust transitions probabilities to simulate effects of standards and guidelines.
	Define states that are important to track relative to standards and guidelines (e.g., threatened and endangered species habitat).
Draft Proposed Action (PA) and alternatives to the PA	Build PA and alternative scenarios based on desired conditions, natural processes, temporal variability, and varying management strategies and extents.
Analysis of effects of the PA and alternatives	Simulate alternative outcomes for key indicators and decision criteria.
	Simulate cumulative effects of the PA and alternatives for ecosystem and social values across treatment types and land jurisdictions.
Monitor, adapt and amend plan	Model parameters serve to document assumptions.
	Adjust model probabilities, temporal and transition multipliers, initial conditions, and other parameters through time as conditions change.
Best available science	Appropriately use empirical data whenever possible.
	Implement quality control on all models.

empirical studies, expert opinion, or combinations of each are used to define model states, transition probabilities between states, and temporal cycles of disturbance.

Forest Plan Modeling in the Pacific Northwest

The Pacific Northwest (PNW) Region of the USDA Forest Service includes 16 national forests. Five national forests are currently revising their Forest Plans (fig. 1).

Two landscape level modeling applications are supported in the PNW Region for forest planning: the linear programming model Spectrum (USDA FS 1995) and the state-and-transition simulation model VDDT/Path (ApexRMS and ESSA Technologies Ltd. 2012; ESSA Technologies Ltd. 2007). The original planning efforts in the 1980s and early 1990s aimed to meet goals and objectives to optimize or maximize net public benefit from various forest outputs. The first round of forest plans were developed using FORPLAN (the predecessor to Spectrum; Johnson et al. 1986, Kent et al. 1991). FORPLAN was used to choose the best mix of management options to meet specified goals and objectives given resource connstraints.

Now, into a second round of planning, objectives for national forest management have changed along with social values and knowledge. These changes have also led to a shift in approach away from linear programming toward STM. National forest management goals currently emphasize restoring and maintaining ecosystem health, biodiversity, and resilience, while contributing to economic and social sustainability (USDA FS 2007). A linear programming approach generally has less applicability in addressing these types of goals. Further, forest planning staff now commonly use GIS to spatially analyze key issues, such as wildlife viability and habitat distribution, invasive species, and fire behavior. VDDT/Path is a state-and-transition modeling framework used in the PNW and elsewhere for examining the role of various disturbance agents and management actions in changing vegetation composition and structure. With STMs, users create and

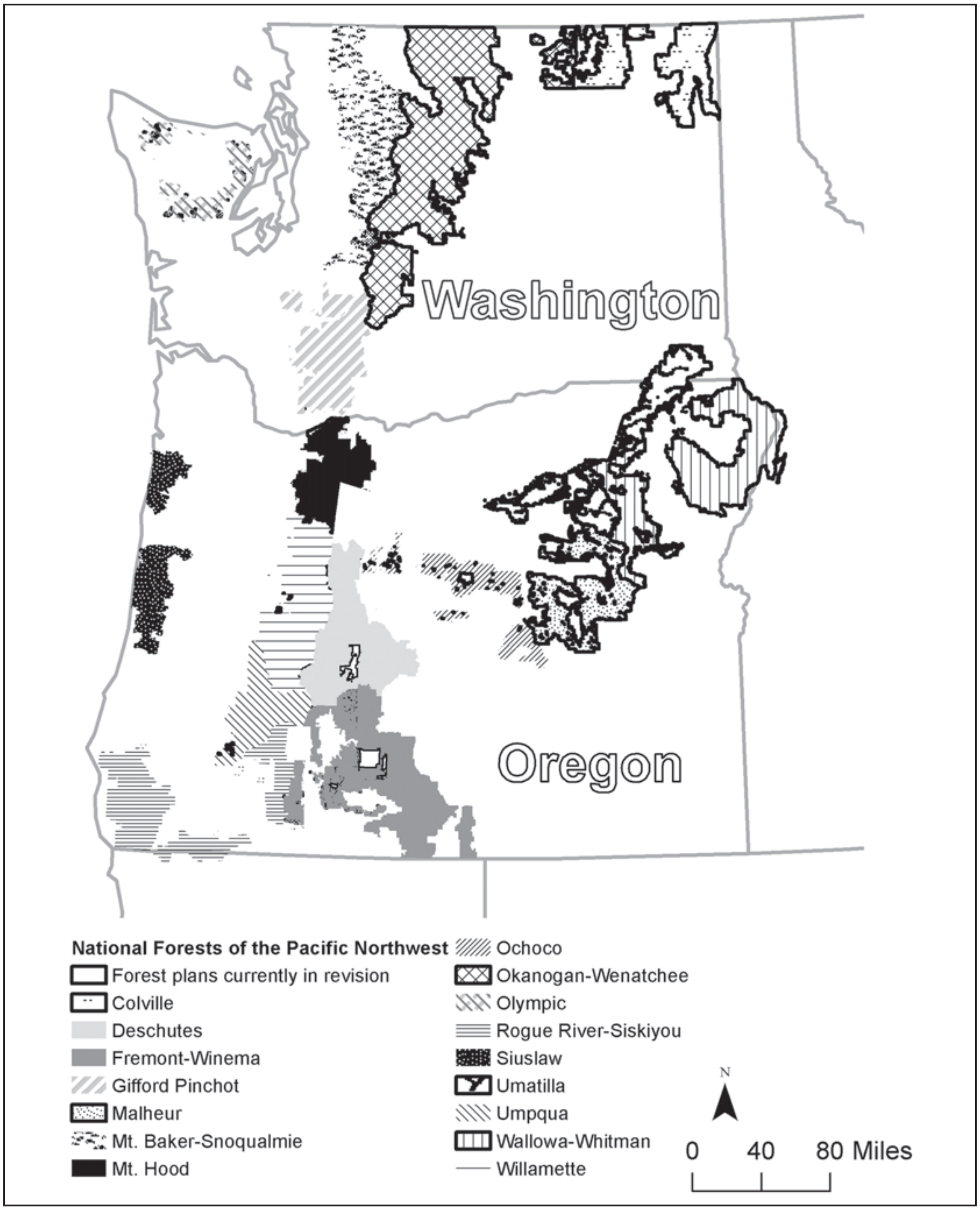


Figure 1—National Forests in the Pacific Northwest Region, USA, including five forests that are currently revising forest plans.

test quantitative assumptions about vegetation dynamics, and simulate their effects on ecosystems into the future at the landscape level. Unlike linear programming models, STMs can address the interaction of many complex natural and human factors (e.g., tree harvests, fire, insects, pathogens, mammals, weather, growth, competition) and their combined effects over long periods, but they do not directly optimize a solution given ecosystem functions and management objectives. Principally, the VDDT/Path STM is:

- Flexible
- In the public domain

- Relatively user friendly
- Able to model both deterministic and probabilistic processes
- A non-equilibrium model, which characterizes Ecosystems as constantly changing as a result of disturbance and other processes
- Compatible with the Tool for Exploratory Landscape Scenario Analysis (TELSA) spatial model (Kurz et al. 2000)
- Technically supported at the USFS PNW Regional and National levels

All five national forest plan revision efforts in the PNW Region are using STMs as their primary landscape level vegetation modeling framework in conjuntion with regiona/local spatial and non-spatial data. The plan revision team in northeast Washington for the Okanogan-Wenatchee and Colville National Forests is using STMs compiled, standardized, and enhanced by the Integrated Landscape Assessment Project (ILAP[2]). ILAP has produced VDDT/Path STMs and associated GIS data seamlessly for all broad vegetation types across the PNW Region (Oregon and Washington), regardless of land ownership (Hemstrom et al. 2012). Three national forests in the Blue Mountains are revising their plans using models that were precursors to ILAP, in combination with locally derived existing and potential vegetation spatial data.

Throughout this paper, examples of concepts will be presented from the Okanogan-Wenatchee National Forest Plan revision effort that is currently underway. The Okanogan-Wenatchee National Forest encompasses more than 4-million acres in Washington State and stretches from the Canadian border to about 180 miles south, and from the Cascade Crest east into the Okanogan highlands. The forest is very diverse—from high, glaciated alpine peaks along the Cascade Crest, through valleys of old growth forest, to dry shrub-steppe at its eastern edge. Annual precipitation varies widely from more than 70 inches along the crest to less than 10 inches at its eastern edge.

The Okanogan and Wenatchee National Forests first developed their forest plans in 1989 and 1990, respectively. The forests were administratively combined into one forest in 2000. The plan revision process began in 2003 but was delayed by the development of a new U.S. Forest Service Planning Rule and subsequent litigation action between 2005 and 2008. The Okanogan-Wenatchee National Forest faces at least the following challenges, which are being considered as they revise their forest plan for the next 10–15 years:

- Climate is already a significant stressor in the Columbia River Basin and eastern Cascade Range and if predictions are correct, the land area affected by wildfire could double by 2040. Vegetation communities will also change, likely in unpredictable ways (CIG 2009).
- Climate change, increasing pollution, spreading invasive plant and animal species, demand for natural resources, and human activities threaten to destabilize ecosystems.
- Fragmentation of wildlife habitat resulting from use patterns on lands adjacent to national forests, management activities, and increased demand of NFS lands is affecting the ability to manage for federally protected species, such as the northern spotted owl, Canada lynx, grizzly bear, and gray wolf.
- In the past ten or more years, there have been extensive outbreaks of, or increases in insects and disease (e.g., mountain pine beetle, western spruce budworm, balsam woolly adelgid, white pine blister rust), in some cases resulting in widespread tree mortality over large landscapes.

[2] ILAP is a two-year project working on the watershed-level prioritization of land management actions based on fuel conditions, wildlife and aquatic habitats, economic values, and projected climate change across all lands in Arizona, New Mexico, Oregon, and Washington. The project creates a variety of analytical and graphical tools—including VDDT/Path models—that generate tables, graphs, and maps that land managers and planners can use to integrate and prioritize management activities. ILAP is a partnership between the U.S. Forest Service and Oregon State University. See http://oregonstate.edu/inr/ilap/ and Hemstrom et al. (2012) for more information.

- Uncharacteristic wildfires are inherently dangerous and difficult to suppress. Associated costs are rising.

The Forests released a draft proposed plan for public comment in June 2011. At this point in time, the plan revision team is developing themes for management alternatives that will eventually be analyzed in a draft environmental impact statement. Hence, applications of STM to-date have been limited to setting up model structures, transitions, and initial conditions, and developing a reference condition scenario. Future efforts will result in the development of more complex model scenarios and outputs than are described in this paper.

Ecological Models

Currently, ecological modeling for forest plan revisions in the PNW Region start with ILAP state-and-transition models and data, which are consistent with national and regional vegetation mapping and classification standards. Individual Forest Plan revision teams adjust these regionally-compiled models to meet their needs, such as adding state classes, adjusting potential vegetation type (PVT) boundaries, using local vegetation data in lieu of regional data sets, condensing the number of model classes into fewer states or PVTs, or other adjustments. Figure 2 provides a generalized overview of key relationships between STMs and spatial and non-spatial data within the context of national forest planning.

Potential vegetation types—
A potential vegetation type encompasses a group of plant associations that are characterized by a particular development pattern due to environment conditions and disturbance regimes (Henderson et al. 2011). Each VDDT/Path model represents one PVT within a specific ecoregion. For the Okanogan-Wenatchee forest plan revision, the forested landscape is stratified into five potential vegetation type groups[3] that are each depicted by one or more PVT models, including dry forest (dry pine, dry mixed conifer PVTs), mesic forest (moist mixed conifer, cool-moist forest), cold-moist forest (Pacific silver fir), cold-dry forest (mountain hemlock), and alpine forest including subalpine parkland).

The Integrated Landscape Assessment Project has created spatial GIS data for PVTs across the Pacific Northwest Region, including all land ownerships (fig. 3). These PVT maps display the spatial distribution of each state-and-transition model. They were created by either cross walking existing plant association group maps (created from 2004 to 2008 using a non-linear regression technique) to ILAP PVTs, or using a Random Forest Nearest Neighbor imputation process to map PVT distributions (completed in 2010). Potential vegetation type maps being used by the Okanogan-Wenatchee forest plan revision were created by cross walking a plant association group map created by nonlinear regression in 2004 to ILAP PVTs.

State-and-transition model structure—
Within each STM, states are defined by standardized combinations of cover type and structure (tree size, canopy density, and canopy layering). ILAP forested vegetation model state class specifications include at least the following:

- Dominant cover type (one, two, three, or mixed species dominance)
- Seven tree diameter classes (<1”, 1–5”, 5–10”, 10–15”, 15–20”, 20–30”, >30”)
- Four tree density (canopy cover) classes (<10 percent, 10–40 percent, 40–60 percent, 60 + percent)
- Two tree layer classes (single storied, or multiple storied)

The Okanogan-Wenatchee National Forest Plan revision is largely using state-and-transition models created by ILAP but has added or deleted a few model states based on local observations and empirical data availability. In some cases, there are close to 50 vegetation states for some ILAP PVT models. For the Okanogan-Wenatchee plan revision, giant tree size classes (30” + diameter) were added to a number of ILAP models. Also natural successional pathways were adjusted in the mountain hemlock model to capture the

[3] Okanogan-Wenatchee revision efforts are currently focused on constructing forest and woodland VDDT/Path models. Non-forested ecosystems make up a relatively smaller portion of the National Forest.

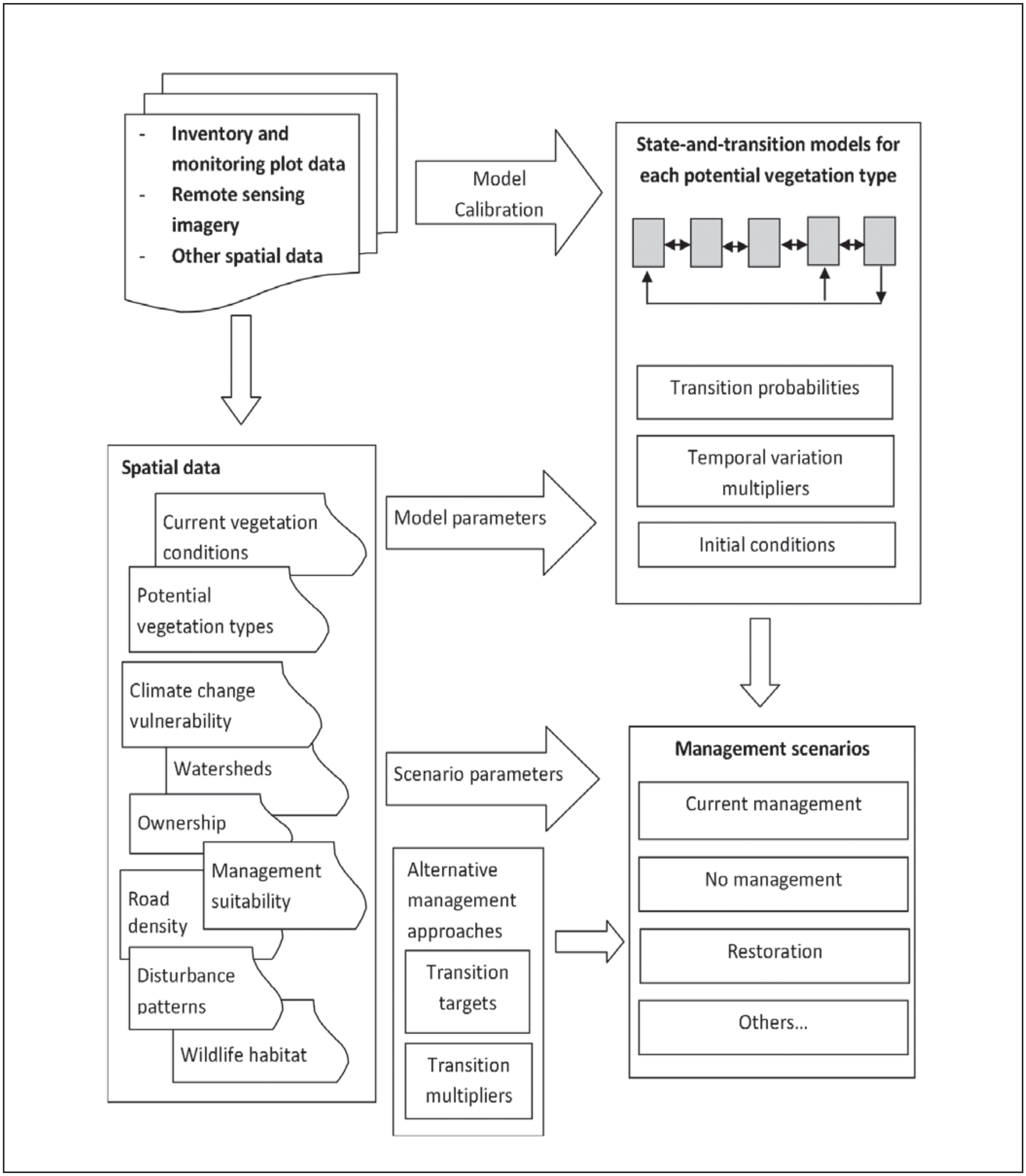


Figure 2—Overview of relationships between state-and-transition models, and spatial and non-spatial data within the context of national forest planning.

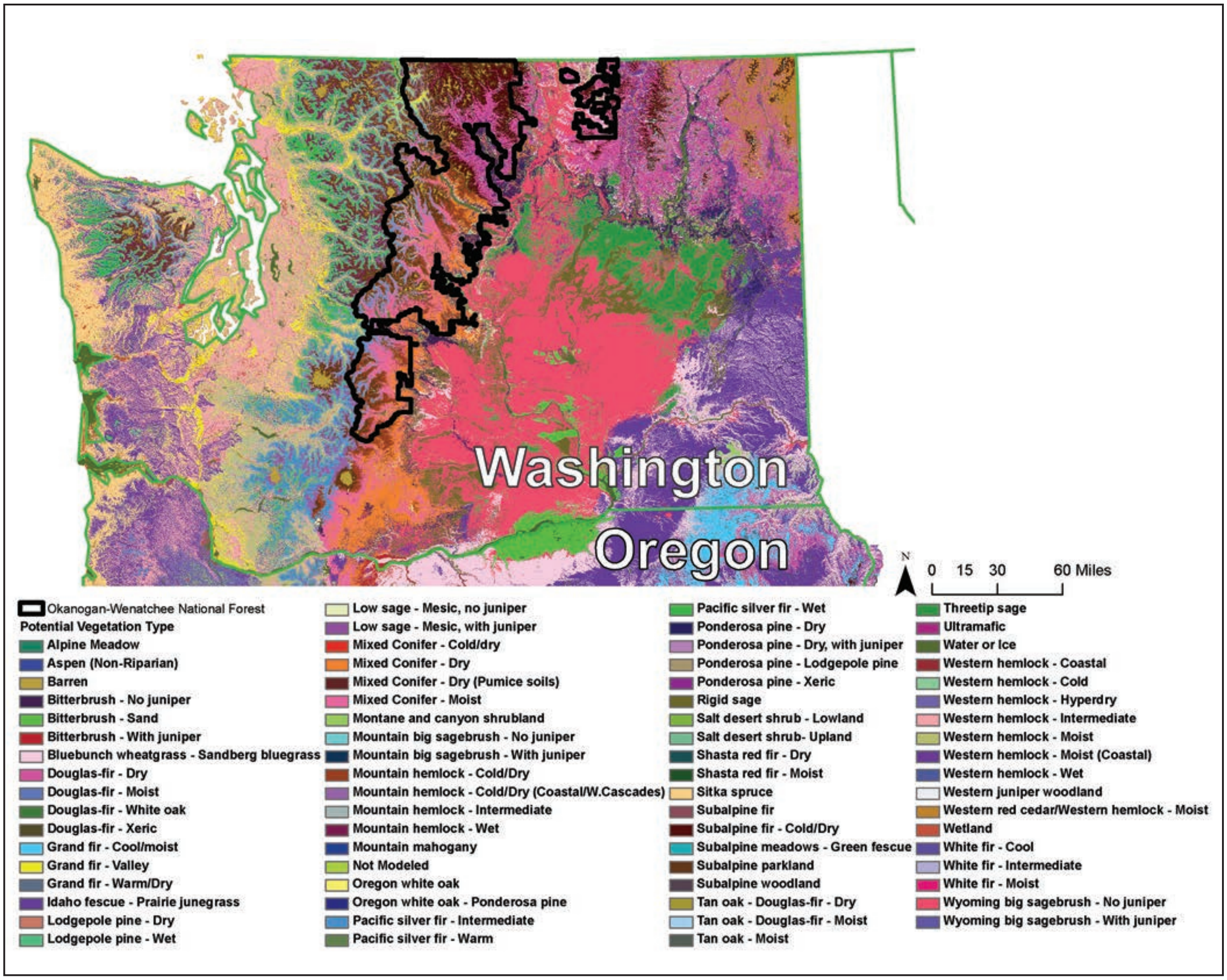
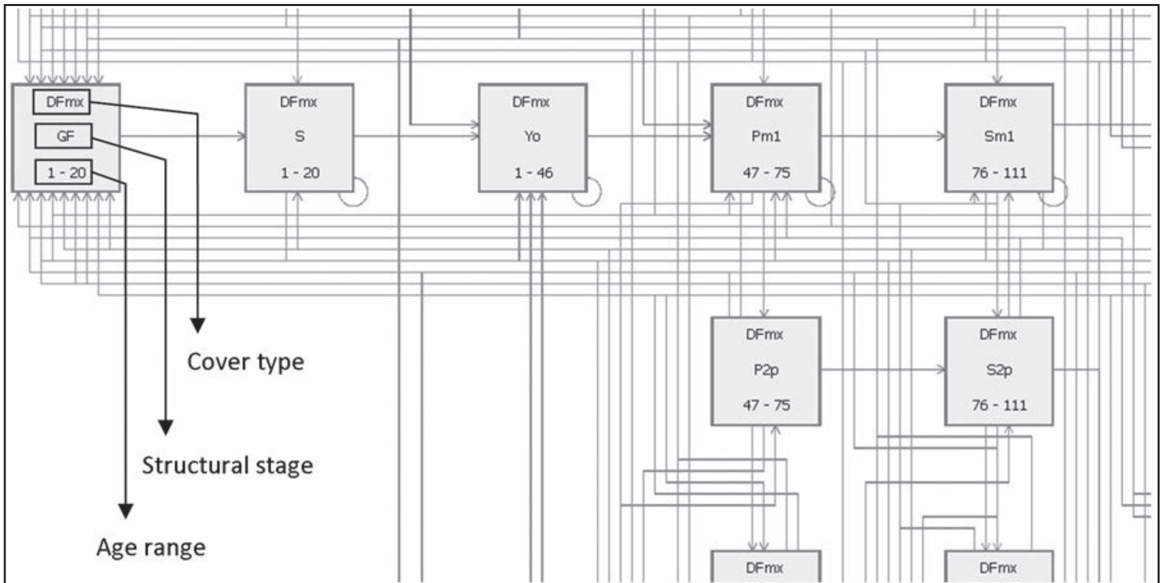


Figure 3—Potential vegetation types of Washington and the Okanogan-Wenatchee National Forest as mapped by the Integrated Landscape Assessment Project (Hemstrom et al. 2021).

observed dynamics between vegetation states dominated by lodgepole pine cover, and bark beetle/fire disturbances, which frequently prevent forests from developing toward later seral stages. Consequently, to simplify analysis and interpretation, and create compatibility with existing data on historical reference conditions, forested structural states were combined into seven structural groups for most analyses. These seven classes were derived from the Interior Columbia Basin Ecosystem Management Project (Hessburg et al. 1999), and include: (a) Stand Initiation, (b) Stem Exclusion Open Canopy, (c) Stem Exclusion Closed Canopy, (d) Understory Re-initiation, (e) Young Forest Multi-Strata, (f) Old Forest Single Strata, and (g) Old Forest Multi-Strata.

Figure 4 illustrates a small portion of the mesic (cool-moist) forest STM being used for the Okanogan-Wenatchee National Forest plan revision. This mesic forest model contains 34 vegetation states ranging from post-disturbance grass/forb conditions to closed canopy, multi-layer giant tree conditions. Transitions between states result from tree growth (increase in tree size and/or stand density) or disturbances (i.e., fire, insects, disease, severe weather, or management actions). Generally, growth transitions were



State class codes. *Cover type*: DFmx = Douglas-fir/mixed species cover type. *Structural stages*: GF = grass/forb; S = shrubs; Yo = Seedling/sapling open density; Pm1 = pole, medium density, single story; Sm1 = small tree, medium density, single story; P2p = pole, multi=story, post-disturbance; S2p = small tree, multi-story, post-disturbance.

Figure 4—A portion of the mesic forest STM model being used for the Okanogan-Wenatchee National Forest plan revision. The complete mesic (cool-moist) forest model includes 34 state classes and 207 probabilistic transitions. Tables 2a and 2b display examples of transitions between state classes.

calibrated by running forest inventory plot data through the Forest Vegetation Simulator (FVS) (Dixon 2002). This process is explained in more detail below in the section titled "Empirical calibration of vegetation succession rates." Fire transition probabilities were derived from Monitoring Trends in Burn Severity mapping data (Eidenshink et al. 2007).

Existing vegetation type map and initial model conditions—

The PNW Region has a spatial database of existing vegetation that was produced by the USFS PNW Research Station and Oregon State University, in close collaboration with the Western Wildland Environmental Threat Assessment Center (WWETAC), Interagency Mapping and Assessment Project (IMAP—a precursor to the ILAP project), Northwest Forest Plan Effectiveness Monitoring program, Remote Sensing Applications Center (RSAC), and the Forest Inventory and Analysis (FIA) program at the PNW Research Station. Existing vegetation mapping was integrated with ongoing sample-based forest inventories conducted by FIA at the PNW Research Station and Current Vegetation Survey (CVS) of the USFS PNW Region and Bureau of Land Management (BLM) lands in western Oregon. Gradient imputation (Gradient Nearest Neighbor, or GNN; Ohmann and Gregory 2002) was used to map vegetation composition and structure for areas of forest and woodland. GNN uses multivariate gradient modeling to incorporate data from FIA field plots with satellite imagery and mapped environmental data. A suite of fine-scale plot variables is imputed to each pixel in a digital map, and regional maps can be constructed for many of the same vegetation attributes available for FIA plots. Nonforest areas were mapped by ILAP scientists using a similar GNN imputation method. All GNN map products are grid-based at 30-m spatial resolution.

For the Okanogan-Wenatchee forest plan revision, these GNN existing vegetation maps were combined with the PVT layer, an ownership/land jurisdiction layer, and a management emphasis layer to determine initial forest conditions by PVT and management emphasis. Spatial land ownership data is used to delineate lands that fall under USDA Forest Service management jurisdiction and as such under Forest Plan revision direction. The spatial boundaries of non-NFS lands within the general planning area (e.g., other federal, state, private lands) are used to delineate areas that do not fall under forest plan direction, but may be important in analyses of cumulative effects of proposed management actions across all lands in the general planning area. The management emphasis layer for the Okanogan-Wenatchee plan revision divides NFS lands into "Wilderness," "Timber Suitable," and "Other" categories, each of which represent lands with similar forest management constraints and hence similar management transition probabilities. Initial conditions are the starting point for modeling alternative future scenarios representing forest plan revision EIS alternatives. The ownership/land jurisdiction classes used in the Okanogan-Wenatchee Plan revision are defined primarily by NFS versus other lands. The management emphasis layer is defined by the management emphasis being used for the forest plan revision, such as wilderness, timber suitable lands, and "other" management areas. It is expected that probabilities for management activities will generally differ between areas with differing management emphases.

Probabilistic transitions—
Natural and anthropogenic disturbances are characterized in STMs by deterministic and probabilistic transitions. A standardized suite of probabilistic transition types is used across the USFS PNW Region to maintain the ability to combine model parameters and ensure ease of model interpretation across geographical areas. Tables 2a and 2b show deterministic transition probabilities (primary successional pathways), and examples of probabilistic transition probabilities of the mesic (cool-moist) forest STM being used for the Okanogan-Wenatchee National Forest plan revision, respectively. Table 3 lists all probabilistic transition types currently being used in STMs for forest planning in the USFS PNW Region. Probabilistic transitions between states result from tree growth, natural disturbances, and anthropogenic management actions. In general, VDDT/Path STMs are attributed with average annual probabilities of transition. Transition multipliers are used to increase or decrease average transition probabilities by transition type across all states.

The Okanogan-Wenatchee National forest plan revision is using the probabilistic transition types created by ILAP, with corrections to some of the types of management treatments assigned to each state and adjustment of some natural disturbance probabilities (i.e. wildfire, insects and disease) to better reflect local situations. The forest plan revision effort is also using ILAP's Monte Carlo temporal multipliers, which were developed from existing data and expert knowledge about temporal patterns in the frequency and intensity of fire[4] and insect disturbances.

Compatibility with other models—
The National Forest Management Act (NFMA) requires that land management plans provide for diversity of plant and animal communities based on the suitability and capability of the land area while meeting overall multiple-use objectives. For terrestrial wildlife species, diversity is assessed through the use of a regional assessment procedure (Suring et al. 2011), which includes the identification of source habitat[5] and modeling of viability relative to reference conditions. The structure of STMs in the PNW Region are designed, to the extent possible, to be compatible with these terrestrial species viability assessment models, at least for upland forests. First, the classes of potential vegetation types used to stratify national forests for forest planning are amenable to analysis of potential wildlife habitat for terrestrial species viability assessments. Second, structural states (e.g., tree size class and density) within forest planning vegetation models are generally compatible with the definition of the structural components of wildlife species source habitat. Third, the reference point used to assess ecosystem health, design forest plan objectives, as well as assess terrestrial species viability is partly determined by the "historical or natural range of variability".

[4] ILAP uses data from the Monitoring Trends in Burn Severity (MTBS) database to develop temporal variation sequences and multipliers for wildfire disturbances.
[5] Source habitat includes vegetation states that contribute to stationary or positive wildlife population growth (Wisdom et al. 2000).

Table 2a—Deterministic transitions (primary successional pathways) of the mesic (cool-moist) forest STM being used for the Okanogan-Wenatchee National Forest plan revision. The mesic forest model contains 34 vegetation states ranging from postdisturbance grass/forb conditions to closed canopy, multi-layer, giant tree conditions

From class (all states have a Douglas-fir/mixed tree cover type)	Start age (years)	End age (years)	To class (all states have a Douglas-fir/mixed tree cover type)
Grass/forb	1	20	Shrubs
Grass/forb post disturbance	1	20	Shrubs post disturbance
Shrubs	1	20	Seedling/sapling open cover
Shrubs post disturbance	1	20	Seedling/sapling open cover
Seedling/sapling medium cover	1	46	Pole closed cover single story
Seedling/sapling open cover	1	46	Pole medium cover single story
Seedling/sapling post disturbance	1	46	Pole medium cover single story
Pole single story post disturbance	47	75	Small tree single story post disturbance
Pole multi-story post disturbance	47	75	Small tree multi-story post disturbance
Pole closed cover single story	47	75	Small tree closed cover single story
Pole closed cover multi-story	47	75	Small tree closed cover multi-story
Pole medium cover single story	47	75	Small tree medium cover single story
Pole medium cover multi-story	47	75	Small tree medium cover multi-story
Small tree single story post disturbance	76	111	Medium tree medium cover single story
Small tree multi-story post disturbance	76	111	Medium tree medium cover multi-story
Small tree closed cover single story	76	111	Medium tree closed cover single story
Small tree closed cover multi-story	76	111	Medium tree closed cover multi-story
Small tree medium cover single story	76	111	Medium tree medium cover single story
Small tree medium cover multi-story	76	111	Medium tree medium cover multi-story
Medium tree single story post disturbance	112	167	Medium tree medium cover single story
Medium tree closed cover single story	112	167	Large tree closed cover single story
Medium tree closed cover multi-story	112	167	Large tree closed cover multi-story
Medium tree medium cover single story	112	167	Large tree medium cover single story
Medium tree medium cover multi-story	112	167	Large tree medium cover multi-story
Large tree single story post disturbance	168	300	Large tree medium cover single story
Large tree closed cover single story	168	300	Giant tree closed cover single story
Large tree closed cover multi-story	168	300	Giant tree closed cover multi-story
Large tree medium cover single story	168	300	Giant tree medium cover single story
Large tree medium cover multi-story	168	300	Giant tree medium cover multi-story
Giant tree single story post disturbance	301	500	Giant tree single story post disturbance
Giant tree closed cover single story	301	500	Giant tree closed cover single story
Giant tree closed cover multi-story	301	500	Giant tree closed cover multi-story
Giant tree medium cover single story	301	500	Giant tree medium cover single story
Giant tree medium cover multi-story	301	500	Giant tree medium cover multi-story

For more information on the use and limitations of the use HRV in establishing desired conditions, see the section below titled “Modeling Alternative Management Scenarios and their Environmental Consequences.”

Empirical calibration of vegetation succession rates— Growth projections of forest inventory data using the Forest Vegetation Simulator (FVS) (Dixon 2002) provide empirically based information for validating model state age ranges and successional transition rates. Relatively large amounts of plot data from regional forest inventories are available for most modeled states in the PNW Region’s forested STMs. For the Okanogan-Wenatchee plan revision, a computer program called Preside (Vandendriesche 2009) was used to classify data from over 3,200 U.S.

Table 2b—A sample of probabilistic transitions of the mesic (cool-moist) forest STM being used for the Okanogan-Wenatchee National Forest plan revision. Probabilistic transitions between states result from tree growth, natural disturbances, and anthropogenic management actions

From state class[a]	To state class[a]	Transition type[b]	Annual probability	Age shift (years)[c]	Time since transitions (years)[d]
Giant tree single story post disturbance	Grass/forb	Stand-replacement wildfire	0.0040	0	0
Giant tree closed cover single story	Giant tree closed cover single story	Non lethal wildfire	0.0008	5	0
Giant tree closed cover single story	Large tree single story post disturbance	Spruce budworm outbreak	0.0100	0	0
Grass/forb	Shrubs	Stand-replacement wildfire	0.0027	0	0
Grass/forb	Seedling/sapling open cover	Natural regeneration, mid-seral species	0.0075	0	0
Giant tree medium cover single story	Giant tree medium cover multi-story	Understory development	0.0400	1	20
Large tree single story post disturbance	Grass/forb	Stand replacement wildfire	0.0012	0	0
Large tree single story post disturbance	Large tree single story post disturbance	Non lethal wildfire	0.0015	5	0
Large tree single story post disturbance	Large tree medium cover multi-story	Understory development	0.0400	1	20
Large tree closed cover single story	Large tree single story post disturbance	Spruce budworm outbreak	0.0100	0	0
Medium tree single story post disturbance	Grass/forb	Stand-replacement wildfire	0.0012	0	0
Medium tree single story post disturbance	Medium tree single story post disturbance	Non lethal wildfire	0.0015	5	0
Medium tree closed cover multi-story	Medium tree closed cover single story	Non lethal wildfire	0.0011	5	0
Medium tree medium cover single story	Grass/forb post disturbance	Stand-replacement wildfire	0.0012	0	0
Pole single story post disturbance	Pole multi-story post disturbance	Understory development	0.0400	1	20
Pole multi-story post disturbance	Grass/forb	Stand-replacement wildfire	0.0015	0	0
Pole multi-story post disturbance	Pole single story post disturbance	Non lethal wildfire	0.0012	5	0
Shrubs	Seedling/sapling open cover	Natural regeneration, mid-seral species	0.0038	0	0
Shrubs post disturbance	Shrubs post disturbance	Non lethal wildfire	0.0015	5	0
Small tree multi-story post disturbance	Shrubs post disturbance	Non lethal wildfire	0.0012	5	0
Small tree multi-story post disturbance	Small tree closed cover multi-story	Understory development	0.0100	0	20
Small tree closed cover single story	Shrubs post disturbance	Spruce budworm outbreak	0.0100	0	0
Small tree single story post disturbance	Seedling/sapling post disturbance	Natural regeneration, mid-seral species	0.0038	0	0

Table 2b—A sample of probabilistic transitions of the mesic (cool-moist) forest STM being used for the Okanogan-Wenatchee National Forest plan revision. Probabilistic transitions between states result from tree growth, natural disturbances, and anthropogenic management actions (continued)

From State Class[a]	To State Class[a]	Transition Type[b]	Annual Probabilistic	Age Shift (years)[c]	Time Since Transitions (years)[d]
Seedling/Sapling medium cover	Grass/Forb	Stand replacement wildfire	0.0020	0	0
Seedling/Sapling post disturbance	Seedling/Sapling post disturbance	Non-lethal wildfire	0.0015	1	0

[a] All states of this mesic forest model have a Douglas-fir/mixed tree cover type.
[b] The mesic forest model contains 207 transitions between 34 vegetation states. Only a sample of natural disturbance probabilities is displayed here. Anthropogenic management actions not shown here include various intensities of harvest, thinning, salvage, tree planting, and prescribed fire (see table 3).
[c] For transitions that accelerate forest development, "Age shift" refers to the number of years added to the age of the state class as a result of the transition.
[d] For transitions that are dependent on a certain number of years without prior disturbance, "Time since transition" refers to the number of years that a state must be "disturbance free" for the transition to occur.

Table 3—Natural and anthropogenic types of probabilistic transitions used in Forest Planning in the USDA Forest Service Pacific Northwest Region

Natural transition types	Anthropogenic transition types
Wildland fire (non-lethal, mixed severity, and stand replacement)	Prescribed fire (non lethal, mixed severity, and stand replacement)
Dwarf mistletoe	Partial harvest salvage
Canopy growth	Pre-commercial thin
Western pine beetle	Selection harvest
Mountain pine beetle	Group selection harvest
Spruce budworm	Regeneration harvest
Douglas-fir beetle	Salvage
High severity wind	Planting
Understory development	Livestock grazing
Natural regeneration	Partial harvest (15 types, depending on current tree size and density)
Alternative successional pathway	
Root disease	

Forest Service forest inventory and monitoring plots[6] into vegetation classes (i.e., cover type, size class, canopy cover, canopy layers) for subsequent FVS projection of the plot data into the future. The Preside program calculates the average time plots from a particular vegetation state stay in that state and the probability of movement to other model states.

The general sequence of steps being used to integrate FVS projections into STMs is:

1. Prepare the inventory data for projection by FVS.
2. Adjust FVS default parameters for growth, mortality, and regeneration for each PVT model.
3. Develop natural growth projections to estimate rates of forest succession.
4. Process FVS output through the Preside program and accumulate the results into a matrix summarizing mean residence times within states and transition probabilities between states.
5. Compare empirically derived transition rates (from FVS) to STM parameters and adjust the STM where necessary.

[6] More information on forest inventory and analysis data for the USFS PNW region is available at: http://fia.fs.fed.us/library/fact-sheets/default.asp.

Table 4—Inventory plot distribution by potential vegetation type for FVS calibration of STM models used in the Okanogan-Wenatchee forest plan revision

		Number of inventory plots at start of FVS simulation by tree size class						
Potentia vegetation type	Total number of inventory plots used in FVS simulations	Grass/ forb (<1 in.)	Young (1-5 in.)	Pole (5-10 in.)	Small (10-15 in.)	Medium (15-20 in.)	Large (20-30 in.)	Giant (>30 in.)
Dry forest	1,467	169	5	105	548	504	132	4
Mesic forest	911	24	13	92	368	287	120	7
Cold-moist forest	207	4	4	29	69	54	37	10
Cold-dry forest	622	45	8	144	309	80	36	0
Alpine forest	71	9	0	14	26	22	0	0
Total plots	3,278	251	30	384	1,320	947	325	21

Table 4 summarizes the number of inventory plots used by tree size class to calibrate STMs for the Okanogan-Wenatchee forest plan revision. Preside analyses showed only a few discrepancies in growth transition rates for some vegetation states between FVS and the ILAP models. For example, in some cases Preside showed longer residence times for dense multi-story stands than related parameters in the ILAP models so growth rates for these states were consequently adjusted.

While not yet accomplished for the Okanogan-Wenatchee forest plan revision, FVS can also be used to validate or estimate transition pathways and/or probabilities for management, insects and disease, fire, or other natural or human-caused disturbances. It can also be used to report model attributes such as woody biomass volume or smoke emissions from fire. Additionally, climatic effects have recently been integrated into FVS to produce a new model called Climate–FVS, which provides a tool to allow climate change impacts to be incorporated in forest and project plans (Crookston et al. 2010).

Modeling Alternative Management Scenarios and their Environmental Consequences

Forest plan alternatives are developed in-part by evaluating and current ecosystem and socioeconomic conditions, and designing alternative suites of management actions to achieve desired conditions. State-and-transition models are the primary framework used in the PNW Region for designing and testing Forest planning alternatives and analyzing some of their environmental effects.

For the Okanogan-Wenatchee National Forest plan revision, desired conditions are derived primarily from information on historical ranges of variation in vegetation structure (Hessburg et al. 1999; Landres et al. 1999). Hessburg et al. (1999) used sample-based aerial photointerpretation on the eastern slope of the Cascade Mountains in Washington State to build spatially continuous historical (1938–1956) vegetation maps for 48 randomly selected sub-watersheds. These data were used to build desired conditions used in the forest plan revision. While attempts to strictly recreate conditions of the past are often not desirable or feasible (e.g., due to climate change, non-native species invasion, soil erosion, social intolerance of fire frequencies at levels representative of Native American burning (Kay 2007), and future climatic changes may in-time reduce the relevancy of historical references, the HRV remains an objective reference for at least the short-term management of natural resources (Keane et al. 2009). The Okanogan-Wenatchee Forest Plan revision team is currently comparing likely climate change projections and “future ranges of variation” in ecosystem structure and function against HRV to improve forest plan development and implementation.

Objectives for vegetation management in the draft Okanogan-Wenatchee proposed plan were developed by comparing current and desired vegetation and fire regime conditions, and testing alternative suites of management practices (e.g., tree harvest, forest thinning, prescribed fire) to support a variety of resource objectives ranging from creating diverse wildlife habitats to maintaining scenic values while providing forest products. For example, relative to desired conditions, dry mixed conifer forests are generally deficit in stand initiation, stem exclusion/closed canopy, and old forest single story structures (Hessburg et al., 1999). Overall, proposed plan direction is intended to make ecosystems more resilient to disturbance driven by climate change, reduce impacts of insects and diseases, and produce quality forest commodities.

The acceptability of these alternative management scenarios are also based on their feasibility within current budget assumptions and ability to ensure public safety. Development of these alternative suites of management practices—scenarios—begins with a STM that is parameterized with current annual disease, fire, and weather transition probabilities. Alternative sets of transition targets and transition multipliers are then iteratively used to test options—which integrate natural processes and management activities—for moving the forested landscape from current (initial) conditions toward desired goals. During scenario modeling, 10 to 30 Monte Carlo simulations are run to capture stochastic variability.

Comparisons of the environmental consequences of forest plan alternatives help support the selection of the final forest plan. For example, figure 5 illustrates the outcomes of two possible management scenarios for dry mixed conifer forest lands suitable for timber production on the Okanogan-Wenatchee National Forest. The "No Management" scenario excludes all management actions except fire suppression and allows all other natural disturbances to operate freely. The "Restoration" scenario represents one possible suite of regenerating stand densities harvest, thinning, and prescribed fire actions designed to move dry forest toward desired conditions. Forest harvest and thinning at a rate of 1-2 percent of timber suitable lands represents a level of activity consistent with historical budgets. As figure 5 demonstrates, over the 10-15 year planning horizon this restoration scenario moves dry mixed-conifer forests toward desired conditions (e.g., greater amounts of old forest single story; less dense, multistory conditions).

Table 5—Common monitoring indicators calculated from STM model output that are used in forest planning in the USDA Forest Service Pacific Northwest Region

Stand replacement fire hazard	Wildlife habitat quality
Fire regime condition class	Timber volume
Wildlife habitat abundance	Biomass
Vegetation density class	Revenue
Successional stage	Cost
Single versus multi-layered	Smoke production
Forest structural groups	

However, this scenario also reveals that changes in management approach across large landscapes may take decades to effectively change ecosystem structure and composition due to the length of time needed for forest development, and constraints that limit the extent or intensity of management actions (e.g., budget, air quality regulations). Some of the environmental consequences of alternatives can also be estimated by calculating indicators that are a function of the model's predicted area over time for state classes and transitions. Table 5 displays some common indicators used in forest planning in the PNW Region. Attributes such as forest structural groups, suitable wildlife habitat, or biomass volume can be assigned to one or more state classes, or calculated from model outputs.

Conclusions

The USFS PNW Region has extensive experience applying STMs and has an expanding model library. These models represent the integration of the best available science, albeit from a variety of sources including published research, peer-reviewed literature, unpublished papers, and expert judgment. Scenario planning in general, and STMs specifically often incorporate a variety of quantitative and qualitative information and consideration of this diverse information in a systemic way frequently leads to better decisions (Peterson et al. 2003). On the other hand, no matter what the underlying data source, models carry with them a certain degree of error and uncertainty. Sources of error in STMs include, but are not limited to:

- data or knowledge gaps
- omitting states not currently present but which could occur on the landscape

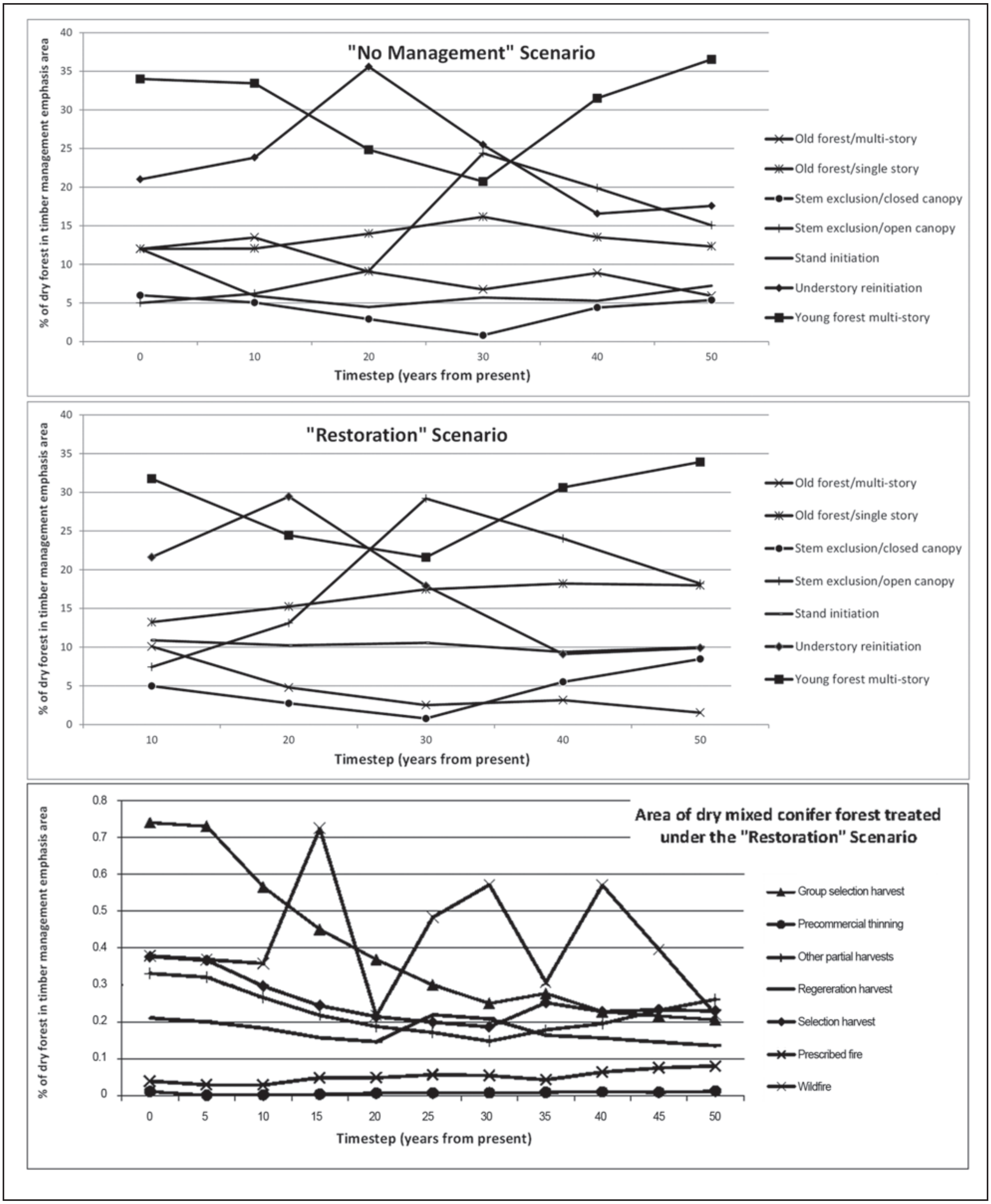


Figure 5—Outcomes of 50-year STM simulations of two potential management scenarios for dry mixed conifer forest on lands suitable for timber production on the Okanogan-Wenatchee National Forest. Also shown is a graph of treatments used in the "restoration" scenario.

- application of transition probabilities from similar, but not identical processes or systems
- inappropriately broad application of data from localized sources
- using mean probability values for processes with wide or bimodal variability
- failure to incorporate temporal variation in disturbance processes
- failure to capture spatially controlled processes
- failure to capture the effects of past land use on ecosystem structure and function

While the use of expert knowledge can introduce additional sources of model uncertainty, published literature alone rarely provides the detailed, site-specific information necessary to fully parameterize STMs. When empirical data is available, it is usually limited in extent and rarely includes an analysis of appropriate application scales or spatial heterogeneity (Bestelmeyer et al. 2011). Experts and practitioners are often the only source of information about ecosystem structure, function, and dynamics, especially at local scales (Drescher et al., 2008).

Local resource management experts, including forest, fire, and insect and pathogen ecologists, have qualitatively reviewed STM parameters and modeled outcomes for the Okanogan-Wenatchee forest plan revision. These experts and managers generally concur that the models are fair representations of the landscape-level forest structure, composition and function for the purposes of broad forest planning. However, non-spatial STMs generally simplify spatial heterogeneity, particularly at resolutions finer than the analysis area (Bestelmeyer et al. 2011), and these limitations should be considered during the planning process and subsequent implementation. For example, riparian systems are generally under-represented in the suite of STMs currently available for national forest planning, and as such are often assumed to behave similarly to adjacent uplands during broad landscape analyses. Development of models for unique ecosystems, spatial modeling of systems and processes dependent on spatial constraints, and continual integration of lessons learned from forest plan and climate monitoring can be used to improve the accuracy of STM parameters through time.

State-and-transition models are being used successfully to integrate resources for developing forest plan alternatives and analyzing the relative effects of those alternatives. These models can also be used to test assumptions within the complex matrix of climate change, increased forest densities, extended drought, uncharacteristic insect epidemics and fires, expansion of residential development into wild lands, and uncertainty in our understanding of ecosystem structure and function. The USFS PNW region's library of STMs provide an opportunity to link landscape and forest-level analyses to broadscale analyses, while also establishing a framework for adaptive feedback between levels of analysis. This capacity is particularly important relative to the analysis of regional issues, such as conservation of old forest dependent species, effects of road density on habitat integrity, commodity production, and effectiveness of alternative ecosystem restoration strategies. Broader applications of STMs by other landowners, such as other federal agencies and state departments of natural resources, and development of consistent models across large geographic extents (such as ILAP's suite of STMs for the PNW and Southwestern regions) are creating opportunities for integration of science and planning across larger geographic extents. Greater collaboration can help integrate multiple sources of scientific information, and improve our collective ability to effectively manage natural resources.

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