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A new approach to evaluate forest structure restoration needs across Oregon and Washington, USA

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ABSTRACT

Widespread habitat degradation and uncharacteristic fire, insect, and disease outbreaks in forests across the western United States have led to highly publicized calls to increase the pace and scale of forest restoration. Despite these calls, we frequently lack a comprehensive understanding of forest restoration needs. In this study we demonstrate a new approach for evaluating where, how much, and what types of restoration are needed to move present day landscape scale forest structure towards a Natural Range of Variability (NRV) across eastern Washington, eastern Oregon, and southwestern Oregon. Our approach builds on the conceptual framework of the LANDFIRE and Fire Regime Condition Class programs. Washington–Oregon specific datasets are used to assess the need for changes to current forest structure resulting from disturbance and/or succession at watershed and regional scales.

Across our analysis region we found that changes in current structure would be needed on an estimated 4.7 million+ ha (40% of all coniferous forests) in order to restore forest structure approximating NRV at the landscape scale. Both the overall level and the type of restoration need varied greatly between forested biophysical settings. Regional restoration needs were dominated by the estimated 3.8+ million ha in need of thinning and/or low severity fire in forests that were historically maintained by frequent low or mixed severity fire (historical Fire Regime Group I and III biophysical settings). However, disturbance alone cannot restore NRV forest structure. We found that time to transition into later development structural classes through successional processes was required on approximately 3.2 million ha (over 25% of all coniferous forests). On an estimated 2.3 million ha we identified that disturbance followed by succession was required to restore NRV forest structure.

The results of this study are intended to facilitate the ability of local land managers to incorporate regional scale, multi-ownership context into local forest management and restoration. Meeting the region-wide restoration needs identified in this study will require a substantial increase in the pace and scale of restoration treatments and coordination amongst governments, agencies, and landowners.

1. Introduction

Ecological restoration has become a dominant paradigm for the management of many public forests across the United States (USDA Forest Service, 2012a,b). Ecological restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2004). Within western states, this present focus on restoration is largely in response to the widespread degradation of terrestrial and aquatic habitats and uncharacteristic fire, insect, and disease outbreaks resulting from a century or more of wildfire suppression, intensive harvesting, grazing, and mining (Brown et al., 2004; Franklin et al., 2008; Hessburg and Agee, 2003; Hessburg et al., 2005; North et al., 2009; Peterson et al., 2005; Schoennagel et al., 2004). Since 2010 $20 to

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$40 million has been appropriated annually for the ecological restoration of federal forests through the Collaborative Landscape Restoration Program (CFLRP; H.R. 5263, fs.fed.us/restoration/CFLRP). In addition to CFLRP, the USDA Forest Service has undertaken a number of initiatives in recent years to increase the pace and scale of forest restoration including but not limited to implementing a new forest planning rule (USDA Forest Service, 2012a), the Watershed Condition Framework (USDA Forest Service, 2011a), and a bark beetle strategy (USDA Forest Service, 2011b). Similarly, state governments in Oregon, Washington and elsewhere are promoting both the ecological and economic benefits of forest restoration. For example, the Oregon Federal Forest Health Package (SB 5521 passed by the Oregon Legislature in 2013) is providing nearly $2.9 million for technical assistance and scientific support needed to increase the pace and scale of collaboratively developed management efforts and to pilot a new business model that contributes funding directly to help increase the pace and scale of implementing restoration work on national forests.

Despite highly publicized calls to increase the pace and scale of forest restoration (Rasmussen et al., 2012; USDA Forest Service, 2012b) we lack a comprehensive understanding of forest restoration needs. In many, but not all, of the interior Pacific Northwest forest ecosystems previous studies have documented patterns of departure from historical conditions (e.g., Everett et al., 2000; Hagmann et al., 2013; Haugo et al., 2010; Hessburg et al., 2005, 2000b; Heyerdahl et al., 2014; Perry et al., 2011; Wright and Agee, 2004). However these studies are not able to provide a systematic evaluation of where, how much, and what types of treatments are needed to restore forest structure at regional scales (100,000s–1,000,000s of ha). Until recently most restoration planning and implementation has occurred at scales of watersheds or smaller (⩽5000 ha). Although there has been a gradual increase in the size of proposed projects, small project areas are still often used. Because the overarching objectives of forest restoration are frequently to influence ecological processes such as disturbance regimes and habitat connectivity operating at very large spatial scales (10,000's–100,000's of ha), a broader spatial perspective is required to evaluate the overall magnitude of ecological and planning needs. Without an understanding of regional scale restoration needs it is difficult to accurately quantify the magnitude of restoration funding needs for state and national entities or to set the context for prioritization of limited land management resources. It is also difficult to determine the cumulative, regional scale impact of current restoration efforts and evaluate whether these efforts are "making a difference". Consequently, evaluation of restoration needs requires a perspective larger than individual watersheds or even individual national forests, and that considers forested lands across all ownerships within a region.

In this study we demonstrate a new approach for evaluating where, how much, and what types of treatments are currently needed to restore a Natural Range of Variability (NRV) in forest structure across eastern Washington, eastern Oregon, and southwestern Oregon. NRV is defined as a frequency distribution of ecosystem characteristics, including the appropriate spatial and temporal scales for those distributions and a reference period, typically prior to European settlement. These ecosystem characteristics may encompass a wide suite of terrestrial and aquatic considerations (Keane et al., 2009; Landres et al., 1999; Morgan et al., 1994; USDA Forest Service, 2012a); here we focus on forest structure.

We acknowledge the limitations of focusing on forest structure as an indicator of ecosystem health, and the NRV as the reference condition. Many biotic and abiotic components must be considered for comprehensive restoration of forest ecosystems, including forest structure. Nevertheless, forest structure presents a tractable coarse filter to which many other aspects of biodiversity (e.g., terrestrial wildlife habitat, riparian and aquatic habitat, herbaceous diversity and productivity, and fire, insect, and disease frequency and severity) respond (Agee, 1993; Hessburg et al., 1999; Johnson and O'Neil, 2001; Peterson et al., 2005). Ideally, we would also evaluate future range of variability (FRV) reference conditions that describe the expected response of forest ecosystems to climate change (Gartner et al., 2008; Keane et al., 2009). FRV is an emerging concept, but FRV reference models are not yet consistently available at a regional scale. While the specific impacts of climate change are uncertain, restoring to a NRV is assumed to increase forests' resilience and adaptive capacity (Agee, 2003; Hessburg et al., 1999; Keane et al., 2009; Millar et al., 2007; Stephens et al., 2013; Stine et al., in press). Finally, NRV does not necessarily represent desired conditions for federal forests, which reflect social and economic concerns as well as ecological ones. Nevertheless, NRV represents a strong foundation for developing desired conditions because it represents the ecological capability of the landscape (USDA Forest Service, 2012a).

2. Methods

2.1. Study area

We assessed forest vegetation restoration needs for the approximately 11,619,000 ha of forest across eastern Washington and eastern and southwestern Oregon, USA (Fig. 1). This geography generally includes the extent of historically frequent fire forests within the USDA Forest Service's Pacific Northwest Region. These forests cover very broad climatic, edaphic, and topographic gradients with widely varying natural disturbance regimes. They range from *Tsuga mertensiana forests* and parklands along the crest of the Cascade Range with a mean annual precipitation of 1600–2800 mm per year and historical fire return intervals of several centuries to dry *Pinus ponderosa* forests in southeast Oregon with mean annual precipitation of 355–760 mm per year and historical fire return intervals of less than 10 years (Agee, 1993; Franklin and Dyrness, 1973). Our challenge was to develop an approach that can be applied across this vast extent encompassing large environmental gradients with data that are consistent and meaningful.

2.2. Core concepts and data sources

We built upon the conceptual framework of the LANDFIRE and Fire Regime Condition Class (FRCC) programs (Barrett et al., 2010; Rollins, 2009) and incorporated Washington–Oregon specific datasets. Our assessment of forest vegetation restoration need is based on four primary data inputs: (1) a classification and map of forested biophysical settings, (2) NRV reference conditions for each biophysical setting, (3) a delineation of "landscape units" for each biophysical setting, and (4) a map of present day forest vegetation structure.

2.2.1. Mapping forested biophysical settings

Biophysical settings are potential vegetation units associated with characteristic land capabilities and disturbance regimes (Barrett et al., 2010). Many different forested biophysical settings are found across Washington and Oregon based on vegetation, soils, climate, topography, and historic disturbance regimes (Keane et al., 2007; Pratt et al., 2006; Rollins, 2009). They provide the framework for describing fire regimes. We mapped biophysical settings across Washington and Oregon using the 30 m pixel Integrated Landscape Assessment Projects' Potential Vegetation Type (PVT) dataset (Halofsky et al., in press), which compiled previous potential forest vegetation classification and mapping efforts including Simpson (2007) and Henderson et al. (2011). We also incorporated subsequent refinements to PVT mapping in

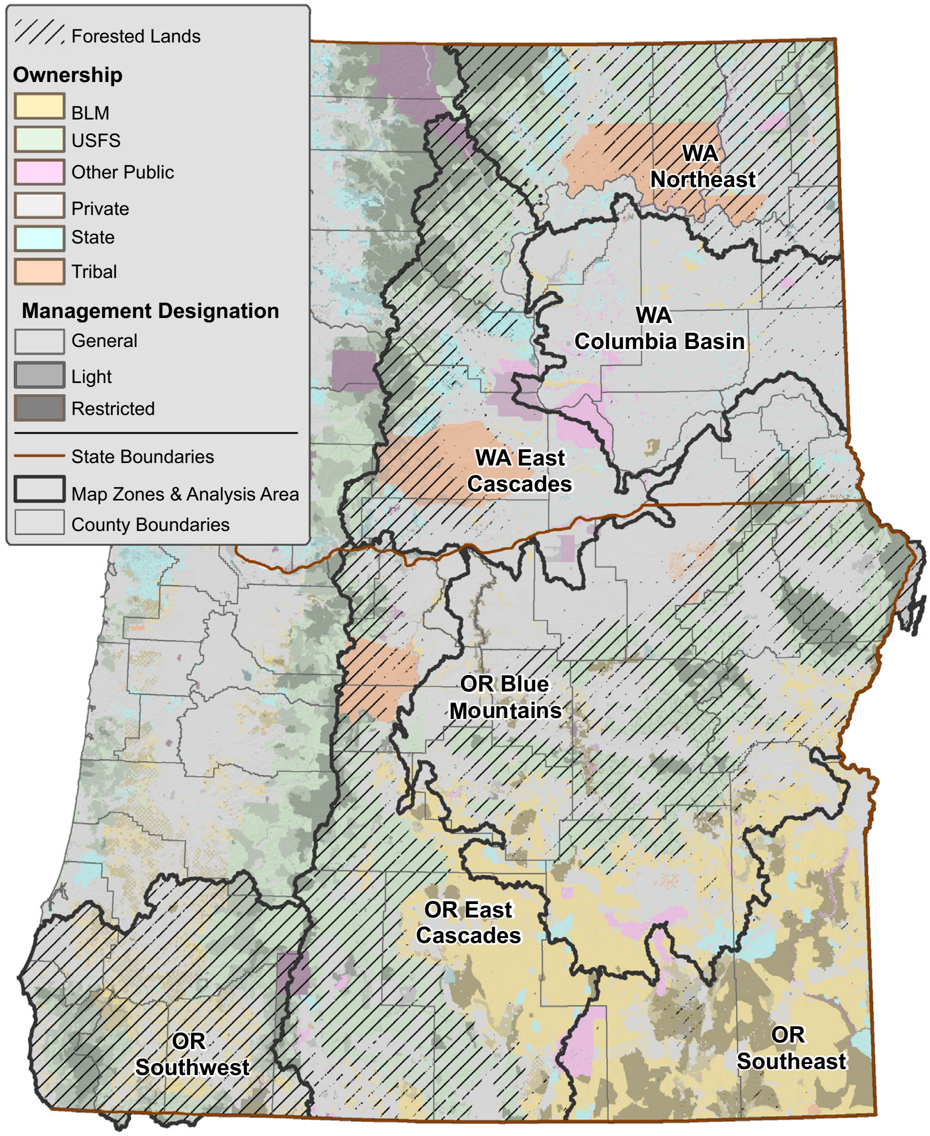

Fig. 1. Map Zones, forest ownership and forest extent in eastern Washington and eastern and southwestern Oregon.

southwestern Oregon (E. Henderson, Oregon State University, unpublished data).

A biophysical setting model from either the LANDFIRE Rapid Assessment or the later LANDFIRE National program (Rollins, 2009; Ryan and Opperman, 2013) was assigned to each PVT mapping unit (Appendix A.1). Assignments were made by staff in the US Forest Service Pacific Northwest Region Ecology Program based upon the geographic, environmental, and biological characteristics of the biophysical setting models and the PVT mapping units. We defined forests across our study area as those described as a "forest" or "forest and woodland" land cover class in the biophysical setting model. National Forest System lands are typically considered "forest" if they have >10% tree canopy cover, and this generally coincides with forest, and forest and woodland land cover classes (USDA Forest Service, 2004).

2.2.2. Natural range of variability reference conditions

Each biophysical setting model is composed of a suite of 3–5 successional/structural stages (s-classes). These classes typically include: (A) Early Development, (B) Mid-Development Closed Canopy, (C) Mid-Development Open Canopy, (D) Late Development Open Canopy, and (E) Late Development Closed Canopy. The definition of each s-class in terms of species composition, stand structure, and stand age is unique for each biophysical setting (Appendix A.2). The percentage of a biophysical setting in each s-class will differ depending on disturbance frequencies and/or intensities. The LANDFIRE and FRCC conceptual framework assumes that, given natural processes, a biophysical setting will have a characteristic range of variation in the proportion in each s-class and that an effective indicator of "ecological condition" for a given landscape is the relative abundance of each s-class within biophysical settings (Barrett et al., 2010; Keane et al., 2011).

NRV reference models describe how the relative distribution of s-classes for a biophysical setting were shaped by succession and the frequency and severity of disturbances prior to European settlement and provide a comparison to present-day forest conditions (Keane et al., 2009; Landres et al., 1999). LANDFIRE biophysical setting models are used to develop NRV estimates through the use of state-and-transition models incorporating pre-European settlement rates of succession and disturbance. Rates were determined through an intensive literature and expert review process (Keane et al., 2002, 2007; Pratt et al., 2006; Rollins, 2009).

The distribution of s-classes for each biophysical setting which results from running state-and-transition models for many time-steps (Appendix A.3) does not represent a specific historical date, but instead approximates characteristic conditions that result from natural biological and physical processes operating on a landscape over a relatively long time period. NRV is frequently represented by a single value, the mean relative abundance of each s-class from a collection of Monte Carlo state-and-transition model simulations (e.g., Low et al., 2010; Shlisky et al., 2005; Weisz et al., 2009). However, we extended this method by developing and using ranges for each s-class resulting from the stochastic variation around the mean within the state-and-transition models. The main source of this stochastic variation was the random draw to determine whether or not a transition occurred at each time step. We ran 10 simulations for each biophysical setting state-and-transition model over 1000 cells and 1000 annual time steps (Provencher et al., 2008; Forbis, 2006). Simulations were started with an equal proportion in each s-class and it took 200–400 years for the initial trends to stabilize. We calculated the range for each s-class as ±2 standard deviations from the mean abundance from the last 500 time steps (Provencher et al., 2008). Simulations were modeled using the Vegetation Dynamics Development Tool (ESSA Technologies, 2007).

2.2.3. Landscape units

Following the LANDFIRE and FRCC conceptual framework, we defined discrete landscape units to compare present-day forests to modeled NRV reference conditions (Barrett et al., 2010; Pratt et al., 2006). Landscape units varied in size based upon their associated historical fire regimes (Hann and Bunnell, 2001; Hardy et al., 2001) as described in each biophysical setting model (Appendix A.2). To be meaningful, landscape units must be large enough to fully contain the extent of historical disturbance events and scale of other ecological dynamics, but small enough to allow detection of present day disturbance events or management activities (Keane et al., 2009; Landres et al., 1999). In a simulation study focusing on landscapes in northern Utah, USA, Karau and Keane (2007) report an optimal landscape size of ~11,500 ha for assessing vegetation dynamics within low and mixed severity fire regime biophysical settings. Historically high severity fire regime systems require much larger landscapes to evaluate vegetation dynamics. Within the Oregon Coast Range, Wimberly et al. (2000) recommend landscapes of 300,000 ha or larger to compare modeled historic and current levels of late-successional stands within forests with a high severity fire regime.

In comparison to these previous studies, we used slightly larger landscape units to ensure appropriate estimates of restoration need. Restoration needs within historical Fire Regime Group I (FRG I; Table 1) biophysical settings were calculated within watersheds (10-digit/5th level hydrologic units; average ~46,000 ha). Within historical Fire Regime Group III (FRG III; Table 1) biophysical settings we used subbasins (8-digit/4th level hydrologic units; average ~285,000 ha). For these two scales, we used watershed and subbasin delineations from the US Geological Survey Watershed Boundary Dataset (Simley and Carswell, 2009; http://nhd.usgs.gov). Finally, restoration need within historical Fire Regime Groups IV and V (FRG IV & V; Table 1) biophysical settings was assessed within "map zones" (Fig. 1; average ~3.5 million ha) modified from the Integrated Landscape Assessment Project "Model Regions" (Halofsky et al., in press). We created "map zones" by setting the boundaries of the ILAP Model Regions to subbasin boundaries in order to maintain consistent nesting of our landscape units.

Table 1
Historic fire regime groups from Barrett et al. (2010).

Fire regime group	Frequency	Description
I	0–35 years	Generally low severity fires replacing less than 25% of dominant overstory; can include mixed-severity fires that replace up to 75% of the overstory
II[a]	0–35 years	High-severity fires replacing greater than 75% of the dominant overstory vegetation
III	35–200 years	Generally mixed-severity, can also include low-severity fires
IV	35–200 years	High-severity fires
V	200+ years	Generally replacement-severity, can include any severity type in this frequency range

[a] There are no forested biophysical settings classified as Fire Regime Group II within our analysis regions.

2.2.4. Present-day forest structure and composition

We characterized present-day forest vegetation with the gradient nearest neighbor imputation (GNN; Ohmann and Gregory, 2002) datasets produced by the US Forest Service Pacific Northwest Research Station and Oregon State University Landscape Ecology, Modeling, Mapping, and Analysis research group (www.fsl.orst.edu/lemma). The 30 m pixel GNN datasets derive from a process integrating regional inventory field plots, environmental gradients, and Landsat imagery. Within Oregon and Washington the GNN datasets have become a common regional-scale measurement of present-day forest conditions (Moeur et al., 2011). Due to the Landsat imagery used to produce the GNN datasets "present-day" is year 2006 within southwest Oregon, eastern Oregon Cascades, and eastern Washington Cascades and year 2000 in all other map zones (Fig. 1).

To compare present-day forest vegetation to the NRV reference conditions, we mapped the current distribution of s-classes for each biophysical setting using GNN data. S-class mapping was based upon tree canopy cover and tree size thresholds provided for each s-class in the biophysical setting model descriptions (Appendix A.2). Quadratic mean diameter has been used in previous applications of the GNN data to classify forest size class (Moeur et al., 2011). However, simply using the GNN dataset's reported quadratic mean diameter to represent forest stand size class has been found to over represent the abundance of large and extra-large size class stands in eastern Oregon and Washington forests (M. Hemstrom and K. Mellen-McLean personal observations). Consequently, we used total canopy cover accounting for canopy overlap, and a combination of canopy cover and trees per acre by size class to classify GNN data into successional stages. We first applied a customized decision process developed to assign one of the 7 regional forest stand size classes (USDA Forest Service, 2004) to each pixel based on the GNN plot-related attributes of trees per acre by diameter class and canopy cover by diameter class (Appendix A.4). We then assigned biophysical setting s-classes by size class and total canopy cover. The first two steps of the size class decision process sets a density threshold for the number of trees >50.8 cm or >76.2 cm diameter breast height in order for a pixel to be classified as large or extra-large, respectively. These threshold values vary by biophysical setting from approximately 20–50 trees per hectare and were determined by US Forest Service Pacific Northwest Region Ecology Program specialists. We evaluated our "GNN size class decision process" using stand exam and forest inventory and analysis plot data from the Mahleur National Forest. Estimated abundance of large and very large size classes using our "GNN size class decision process" were very close to levels based stand exam and plot data (76,897 ha. versus 74,244 ha respectively; M. Hemstrom unpublished data). In contrast, simply applying the GNN dataset's quadratic mean diameter measure grossly overestimates the abundance of large and very large size classes (234,327 ha; M. Hemstrom unpublished data) compared to stand exam and plot data. All size class and s-class assignments were made using custom Python scripts (Python Software Foundation) within ArcMap 10.1 (Environmental Systems Resources Institute, 2013).

2.3. Forest restoration needs analysis

We assessed forest restoration needs based on the present-day relative abundance of s-classes compared to NRV reference conditions. Within each biophysical setting and landscape unit (stratum), we determined which s-classes were overrepresented and which were underrepresented, then how many hectares would need to transition to a different s-class in order to move the present-day distribution of all s-classes to within the NRV reference distribution (mean ± 2 SD). We categorized these specific transitions between s-classes as resulting from implementation of "disturbance only", "succession only", or "disturbance then succession" restoration categories based upon the identity of the excess and deficit classes (Fig. 2). Our analysis considered the following possible restoration categories and the resulting transitions between s-classes.

2.3.1. Disturbance only

- **Thinning/low severity fire**: Transitions between mid and late development closed canopy to open canopy s-classes through the removal of small and medium sized trees. May be accomplished through fire or mechanical treatment.
- **Opening/high severity fire**: Transition from any mid or late development s-class to "Early Development" through removal of the major proportion of medium and large trees, generally to create a clearing. May be accomplished through fire or mechanical treatment.
- **Overstory Thinning**: Transition from late development to mid development open canopy s-class through removal of overstory cohort trees and retention of smaller understory cohort trees. This transition is likely to be accomplished through mechanical treatment, insects, or disease.

2.3.2. Disturbance then succession

- **Thinning/low fire + grow with fire**: This is a two-step transition that first requires fire or mechanical treatment to transition from mid development closed canopy to mid development open canopy followed by growth with fire to transition to a late development open canopy s-class.
- **Other disturbance + growth**: Transition to mid development closed canopy from any other mid or late development s-class. The specific pathway of this uncommon transition varies by biophysical setting, but includes both disturbance and growth for all biophysical settings.

2.3.3. Succession only

- **Growth with fire**: Transitions from "Early Development" to "Mid Development Open Canopy" or from "Mid Development Open Canopy" to "Late Development Open Canopy" in Fire Regime Group I or III biophysical settings. These transitions are considered succession only as fire disturbance is not immediate required to alter the successional trajectory.
- **Growth without fire**: All other transitions from earlier to later development s-classes, typically maintaining or resulting in a closed canopy

We defined all possible transitions between s-classes within each biophysical setting (Fig. 2) described in terms of the unique characteristics of each biophysical setting's state-and-transition model and s-class descriptions. All transition definitions for a biophysical setting are captured in that setting's "rules table" (Table 2, Appendix A.5). When a transition between s-classes required more than one discrete step based upon that biophysical setting's state-transition model, we defined both a "primary" and a "secondary" transition (Fig. 2 and Table 2).

The restoration needs calculations were conducted in a stepwise fashion for each strata. For each strata, we first calculated the excess or deficit abundance of each s-class when compared to that biophysical settings' NRV reference condition. In order to incorporate the full range of conditions represented by NRV, excesses are calculated from the upper edge (mean + 2 SD) of the biophysical setting's NRV while deficits are calculated from the lower edge (mean – 2 SD; Fig. 3). Using the upper and lower edges of NRV provides a more conservative estimate of restoration need based upon the variability a biophysical setting may experience over time. Based upon the first transition (e.g. row 1) in that biophysical setting's rules table (Table 2) we determined if there was an over-abundance of hectares in the "excess" s-class and an under abundance in the "deficit"

Excess S-Class (Currently over-represented compared to reference condition)	Deficit S-Class (Currently under-represented compared to reference condition): Early Devl.	Mid Closed	Mid Open	Late Open	Late Closed
Early Devl.		Grow without fire	Grow with fire	Grow with fire	Grow without fire
Mid Closed	Opening / high fire		Thin / low fire	Thin / low fire + grow with fire	Grow without fire
Mid Open	Opening / high fire	Other disturbance + growth		Grow with fire	Grow without fire
Late Open	Opening / high fire	Other disturbance + growth	Overstory thinning		Grow without fire
Late Closed	Opening / high fire	Other disturbance + growth	Overstory thinning	Thin / low fire	

= Disturbance Only
= Succession Only
= Disturbance then Succession

Fig. 2. Default transitions used in calculations of forest structure restoration need. If there is an excess in the vertical s-class and a deficit in the horizontal s-class for particular strata (biophysical setting × landscape unit), then each intersecting cell represents the hypothetical transition needed to restore forest structure to the Natural Range of Variability (NRV). See Appendix A.3 for NRV reference conditions for each biophysical setting and Appendix A.5 for specific restoration transition definitions for each biophysical setting.

s-class. If no, we skipped that transition step. If yes, we "moved" hectares from the excess to the deficit s-class, such that the deficit s-class does not become overabundant and the excess s-class does not become under abundant relative to the NRV reference condition. These "moved" hectares were then considered "restoration hectares" and were added to the tally for that particular transition category. We then recalculated the excess or deficit abundance of each s-class following the hypothetical redistribution of acres between s-class in the previous step. Based upon the second transition in that biophysical setting's rules table (row 2) we determined if there was an overabundance in the "excess" s-class and a under abundance in the "deficit" s-class. If yes, we "moved" hectares following the same procedure as for the first priority transition and added them to the tally of restoration hectares. If no, we skipped this transition step. This process was then repeated for all transition steps for all 1729 strata. Calculations were conducted using a custom Python script (Python Software Foundation) within ArcMap 10.1 (Environmental Systems Resources Institute, 2013).

We determined the order of operation for each biophysical setting's rules table based on the following logic. First we considered disturbance transitions that were analogous to the predominant historical disturbances within that setting (e.g., thin/low fire for FRG I biophysical settings). Second we considered other disturbance transitions that were less common based on the biophysical setting's historical disturbance regime. Third we considered successional transitions analogous to that setting's historical growth dynamics. Fourth we considered other multi-step disturbance treatments, and fifth we considered multi-step successional treatments. To assess the potential bias introduced by the order of transitions we compared the number of all disturbance and all successional restoration hectares per biophysical setting and landscape unit combination calculated with the specified order of operation (Appendix A.5) versus a randomized order of operation. The absolute difference (mean ± 1 SD) in all disturbance and in all succession restoration hectares was inconsequential (1.8 ± 3.5% and 2.3 ± 4.8% of total hectares respectively per biophysical setting and landscape unit, $n = 1729$).

2.4. Forest ownership and management

Understanding how restoration needs differ amongst forest ownerships and management designations is essential to an integrated landscape scale approach to ecological restoration across ownerships. We intersected our assessment of forest restoration need with forest ownership and management allocations spatial data compiled by Halofsky et al. (in press). We considered six ownership categories (US Forest Service, US Bureau of Land Management, State, Other Public, Tribal, Private), and three levels of forest management intensity (Restricted, Limited, General). Restricted management includes forests where mechanical treatments are typically not allowed, such as Wilderness Areas, National Parks, Inventory Roadless Areas, and Research Natural Areas. Limited management includes forests in which mechanical treatments may be allowed with certain limitations, such as late successional reserves. General management refers to lands where mechanical treatments are allowed.

We used an "equal distribution" approach to determine restoration need by forest ownership and management designation at the level of map zones. Our restoration need calculations provide the percentage of total hectares for each present day sub-strata (landscape unit × biophysical setting × s-class) currently "in need" of disturbance and/or successional restoration. We also determined for each present day sub-strata the number of hectares within each ownership × management designation category. We then made the assumption that the overall percentage of a sub-strata in need of each restoration need transition applied equally across ownership × management designation categories. Consequently, we calculated the number of hectares in need of each restoration need transition for each ownership × management designation × sub-strata. Finally, we summed these values to total active and growth restoration need per ownership and management designation category per map zone. We recognize in some areas with mixed federal and private lands (e.g., checkerboard ownership configurations), a more generalized and variable allocation of restoration needs by landowners could emerge.

3. Results

3.1. Regional-wide trends in forest restoration need

We found that approximately 41% (4,742,000 ha) of all coniferous forest in eastern Washington and eastern and southwestern Oregon was in need of a transition to a different s-class in order to restore forest structure to a NRV reference condition (Table 3,

Table 2
Default restoration transitions "rule table" for biophysical settings with historic low or mixed severity fire regimes. Table describes the primary and secondary actions needed to transition from the excess to the deficit s-class. See Appendix A.5 for a complete list of rules tables for each biophysical setting.

Order	Excess S-Class	Deficit S-Class	Primary Actions	Secondary Actions	Category
1	Mid closed	Mid open	Thin/low fire		Disturbance Only
2	Late closed	Late open	Thin/low fire		Disturbance Only
3	Mid closed	Late open	Thin/low fire	Grow with fire	Disturbance then Succession
4	Late open	Mid open	Overstory thinning		Disturbance Only
5	Late closed	Mid open	Overstory thinning		Disturbance Only
6	Mid closed	Early	Opening/high fire		Disturbance Only
7	Mid open	Early	Opening/high fire		Disturbance Only
8	Late open	Early	Opening/high fire		Disturbance Only
9	Late closed	Early	Opening/high fire		Disturbance Only
10	Early	Mid open	Grow w/fire		Succession Only
11	Mid open	Late open	Grow w/fire		Succession Only
12	Early	Mid closed	Grow w/o fire		Succession Only
13	Mid closed	Late closed	Grow w/o fire		Succession Only
14	Mid open	Late closed	Grow w/o fire		Succession Only
15	Late open	Late closed	Grow w/o fire		Succession Only
16	Mid open	Mid closed	Other disturbance	Growth	Disturbance then Succession
17	Late open	Mid closed	Other disturbance	Growth	Disturbance then Succession
18	Late closed	Mid closed	Other disturbance	Growth	Disturbance then Succession.
19	Early	Late open	Grow with fire	Grow with fire	Succession Only
20	Early	Late closed	Grow without fire	Grow without fire	Succession Only

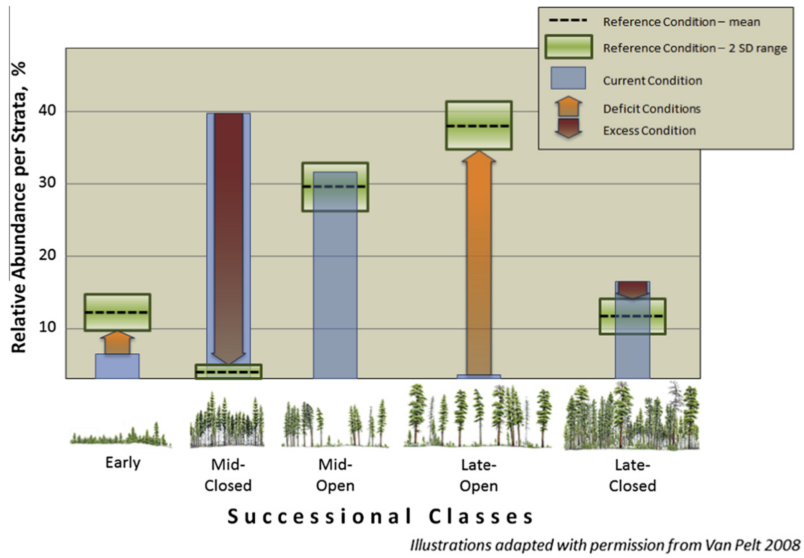

Fig. 3. Example of how the comparison of excess and deficit s-classes to natural range of variability reference conditions (NRV) are determined for a strata (biophysical setting × landscape unit). This example depicts the Dry Douglas-fir biophysical setting within the Oregon Blue Mountains – Upper Tucannon watershed (HUC 1706010706). See Appendix A.3 for NRV reference conditions for each biophysical setting. Forest illustrations adapted with permission (Van Pelt, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figs. 4 and 5). Across these regions Disturbance then Succession was the most common restoration need category (20% of all forests, 5,678,000 ha) followed by Disturbance Only (14%, 3,920,000 ha) and Succession Only (7%, 2,120,000 ha; Table 3). On the largest individual ownership, the US Forest Service, approximately 38% (2,412,000 ha) of coniferous forests was in need of transition to a different s-class. Only (16%) of the overall restoration needs and 14% of the Disturbance Only plus Disturbance then Succession restoration needs on US Forest Service lands were within Restricted management areas. Across all US Forest Service Forests, the Disturbance Only and Disturbance then Succession categories were roughly equivalent at 15% and 17% of all national forests respectively (Table 3). Overall restoration need was higher on Bureau of Land Management, State, and Private forests (52%, 45%, and 45% of forests per respective ownership) with Disturbance then Succession, the most common restoration need category on these ownerships (Table 3).

Both the overall level and the type of restoration need varied greatly between forested biophysical settings. Specific restoration need transitions are illustrated in Fig. 2. Historical FRG 1 forests were both the most abundant (5,627,000 ha) and had the greatest overall restoration needs (2,857,000 ha, 51% of all FRG I forests, Table 4). Restoration needs within FRG I forests were dominated by the "thinning/low severity fire followed by growth" transition in the mid-development closed canopy s-class (1,695,000 ha, Table 4). We also found a substantial need for "thinning/low severity fire only" in the mid development closed canopy and late development closed canopy s-classes (390,000 and 261,000 ha respectively, Table 4). Forests historically characterized as FRG III were slightly less abundant (4,947,000 ha) and had lower overall restoration needs (33% of all FRG III forests; Table 4). "thinning/low severity fire followed by growth" in the mid-development closed canopy s-class was again the most commonly needed restoration transition (420,000 ha; Table 3). Other commonly needed transitions were "opening/high severity fire" in mid-development closed canopy s-classes (215,000 ha) and "thinning/low fire only" in late development closed canopy s-classes (223,000 ha). Historical FRG IV & V forests were the least common (1,045,000 ha) and had the lowest overall restoration needs (23% of all FRG IV & V forests, Table 4). Within FRG IV & V forests restoration needs were evenly divided between the Disturbance Only and Succession Only categories in the early and mid-development s-classes (Table 4).

3.2. Comparisons of forest restoration need among map zones

Across eastern Washington and eastern and southwestern Oregon we found the highest proportion of restoration need in the Oregon Southwest (1,321,000 ha, 51% of all forests) and

Table 3
Forest structure restoration needs by ownership for eastern Washington and eastern and southwestern Oregon. See Appendix B.2 for detailed summaries of restoration need by forest ownership–management and Map Zones.

Forest owner	Total	Disturbance only[a]		Disturbance then succession[b]		Succession only[c]	
	ha.	ha.	%	ha.	%	ha.	%
US Forest service	6,381,000	960,000	15	1,074,000	17	378,000	6
Bureau of land management	705,000	98,000	14	197,000	28	73,000	10
State	390,000	57,000	15	90,000	23	28,000	7
Other public	141,000	23,000	16	11,000	8	11,000	8
Tribal	697,000	70,000	10	143,000	20	41,000	6
Private	3,305,000	378,000	11	783,000	24	326,000	10
Total	11,619,000	1,586,000	14	2,298,000	20	858,000	7

[a] Includes the thin/low fire, opening/high fire and overstory thinning transitions.
[b] Includes the thin/low fire + growth and other disturbance + growth transitions.
[c] Includes the grow with fire and the grow without fire transitions.

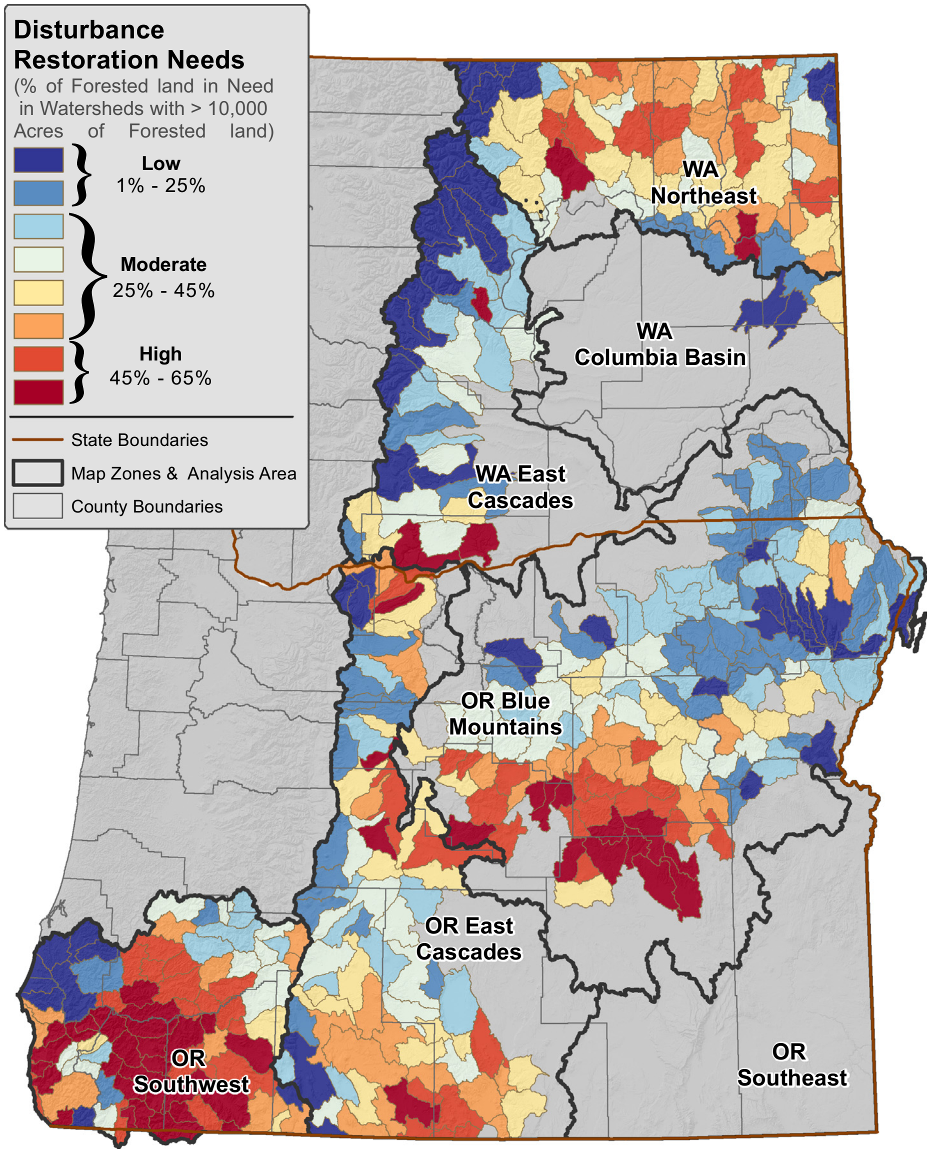

Fig. 4. All disturbance restoration needs as a percentage of forests within 10-digit/5th level hydrologic unit watersheds. Includes the thin/low fire, opening/high fire, overstory thin, thin/low fire + growth, and other disturbance + growth transitions. Within Map Zone labels WA = Washington and OR = Oregon. See Appendix B.4 for restoration need summaries per watershed.

Washington Northeast (955,000 ha, 46% of all forests) map zones (Table 5, Figs. 4 and 5). In contrast to other zones, the majority of overall Disturbance restoration needs (Disturbance Only plus Disturbance then Succession) in Oregon Southwest and Washington Northeast occurred off US Forest Service lands (Fig. 6) and were concentrated in the historically low severity fire regime forests (Fig. 7). Additionally, in both map zones the overall Succession restoration needs (Succession Only plus Disturbance then Succession) were nearly as great as the overall Mechanical/Fire restoration needs (39% vs. 33% and 23% vs. 25% of all forests in the map zone respectively; Table 5).

Compared with these map zones, the overall proportions of restoration need were slightly lower within the Oregon Blue Mountains (1,095,000 ha, 38% of all forests) and Oregon East Cascades (866,000 ha, 36% of all forests; Table 5). Restoration needs within the Oregon Blue Mountains were dominated by the Disturbance then Succession category (696,000 ha, 24% of all forests) while the Oregon East Cascades have equivalent levels of the Disturbance Only and Disturbance then Succession categories (382,000 ha, 16% and 401,000 ha, 17% respectively, Table 5). Within both zones the majority of overall Disturbance needs are on US Forest Service lands (648,000 ha, 69% and 519,000 ha, 66% respectively; Fig. 6) and were found across the FRG I and III biophysical settings (Fig. 7). This is in contrast to the Oregon Southwest and Washington Northeast zones, where sum total of needs were greatest outside the national forests.

We found the lowest overall levels of restoration need within the Washington East Cascades (476,000 ha, 30% of all forests). Similar to the Oregon East Cascades, the Washington East Cascades had equivalent levels of the Disturbance and the Disturbance then Succession (each approximately 190,000 ha/12% of all forests; Table 5). US Forest Service lands contributed only 40% (152,000 ha) of overall Disturbance restoration needs (Fig. 6), and were concentrated in the historically FRG I forests (Fig. 7).

The Oregon Southeast and Washington Columbia Basin map zones were dominated by non-forested ecosystems. Although levels of overall restoration need as a percentage of total forested area are similar to other map zones (Oregon Southeast 44%, Washington

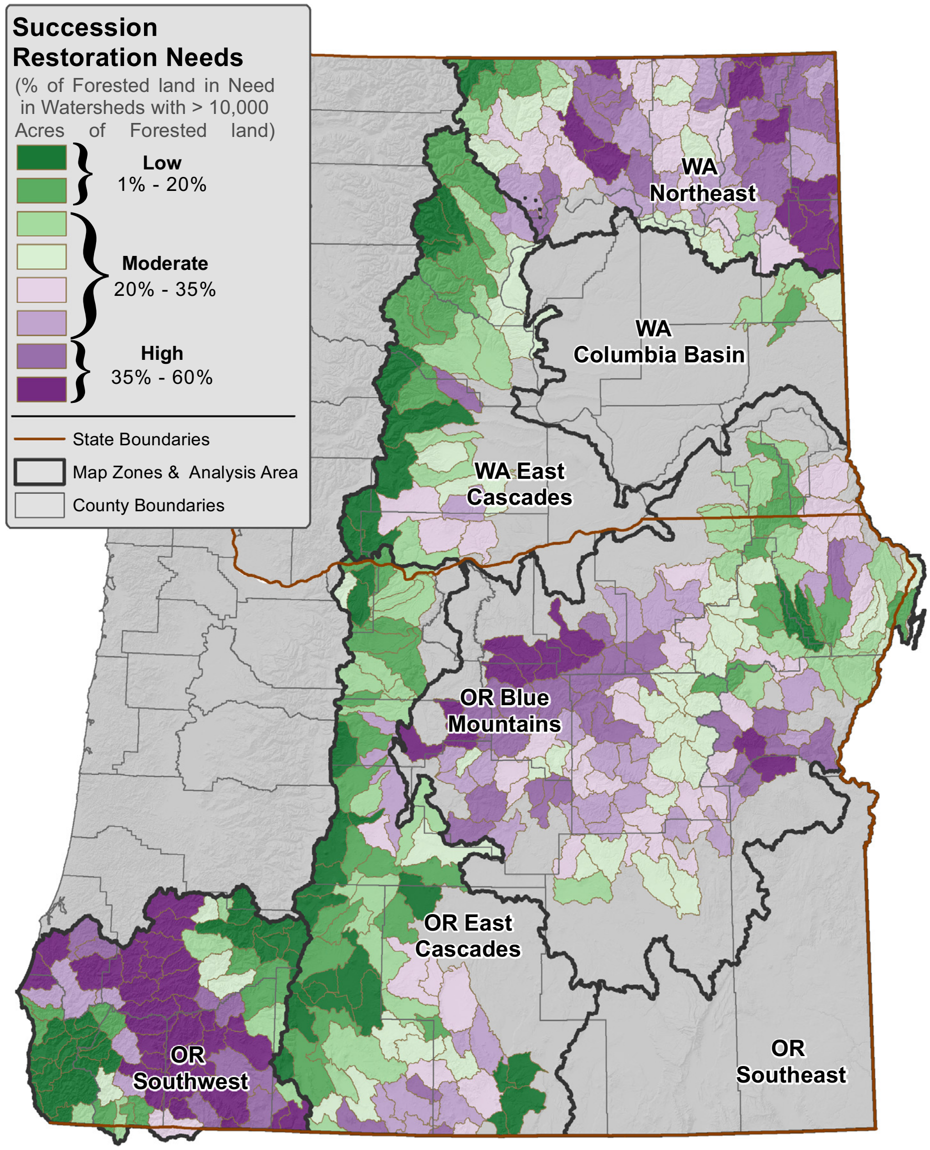

Fig. 5. All succession restoration needs as a percentage of forests within 10-digit/5th level hydrologic unit watersheds. Includes the thin/low fire + growth, other disturbance + growth, grow with fire, and grow without fire transitions. Within Map Zone labels WA = Washington and OR = Oregon. See Appendix B.4 for restoration need summaries per watershed.

Columbia Basin 37%), they contribute little to the regional-wide restoration needs (Table 5).

4. Discussion

4.1. Interpreting regional restoration needs

We found that forest structural restoration needs across eastern Washington and eastern and southwestern Oregon were dominated by the need for thinning and/or low severity fire transitions within forests historically characterized by low and mixed severity fire regimes (FRG I and III biophysical settings; Table 4). These basic findings reflect the commonly understood impacts of wildfire suppression and past management on historically fire-dependent forest ecosystems across western North America (Noss et al., 2006). However, we found substantial variation in restoration need per watershed (5th field hydrologic units) across our region with results ranging from less than 5% to greater than 80% of all forests within individual watersheds in need of disturbance transitions. The variation we observed in restoration needs was driven in large part by the distribution of forest biophysical settings, but also by patterns of forest ownership and management. We found the highest levels of restoration need at both map zone and watershed scales in locations dominated by FRG I biophysical settings and with forest ownerships that likely focused primarily on timber production, resulting in a preponderance of early and mid-development closed canopy successional classes.

Within the vast majority of the watersheds we evaluated, disturbance alone cannot restore NRV forest structure. Deficits in late development forest structure were clearly evident; succession into later development s-classes was required in over half (66%) of the total restoration needs across the region. However, the predominant late development successional classes and the successional pathways to these classes vary amongst biophysical settings and may require repeated disturbances. The map zones with the highest proportion of overall disturbance needs (Oregon Southwest and Washington Northeast) also had the highest successional restoration

Table 4
Forest structure restoration need transitions by forested biophysical setting historical fire regime group's successional classes for eastern Washington and eastern and southwestern Oregon. See Appendix B.3 for detailed summaries of restoration need by forest biophysical settings and Map Zones.

S-Class	Total forest	Disturbance only			Disturbance then succession		Succession only	
		Thin/low fire	Opening/high fire	Overstory thinning	Thin/low fire + Grow	Other Disturbance + Grow	Grow with fire	Grow without fire
	ha.	ha.	ha.	ha.	ha.	ha.	ha.	ha.
FRG I – All S-Classes								
Early	625,000	0	0	0	0	0	59,000	17,000
Mid Closed	2,797,000	390,000	132,000	0	1,695,000	0	0	160,000
Mid Open	1,303,000	0	21,000	0	0	0	46,000	40,000
Late Open	144,000	0	0	0	0	0	0	0
Late Closed	758,000	261,000	10,000	27,000	0	0	0	0
FRG III – All S-Classes								
Early	586,000	0	8000[a]	0	0	0	60,000	11,000
Mid Closed	2,007,000	77,000	215,000	0	420,000	0	0	166,000
Mid Open	1,126,000	0	58,000	0	0	174,000	55,000	125,000
Late Open	136,000	0	0	0	0	0	0	0
Late Closed	1,092,000	223,000	12,000	33,000	0	1000	0	0
FRG IV & V – All S-Classes								
Early	129,000	0	0	0	0	0	4000	31,000
Mid Closed	387,000	42,000	43,000	0	0	7,000	0	54,000
Mid Open	125,000	0	0	0	0	0	0	29,000
Late Open	53,000	0	0	9000	0	0	0	0
Late Closed	353,000	0	2000	24,000	0	0	0	0
All forests total	11,619,000	993,000	500,000	94,000	2,116,000	182,000	225,000	633,000

[a] Transition between two different early successional classes within the subalpine parkland biophysical setting.

needs (Figs. 4 and 5). In most locations, restoration programs must focus on both the application of mechanical treatments and fire while also conserving and promoting old trees and late development forest structures (Franklin and Johnson, 2012; Franklin et al., 2013; Stine et al., in press).

The historical dynamics and present day management of historical mixed severity fire regime forests has received particular attention recently by the science and management communities (e.g., Halofsky et al., 2011; Perry et al., 2011; Stine et al., in press). The complex nature of mixed severity fire regimes and long history of management for many of these forests were reflected in the variety of specific restoration transitions needs that we identified for FRG III biophysical settings (Table 3). Stine et al. (in press) argue that due to greater productivity, restoration needs within historical mixed severity fire regime forests may be even greater than historical low severity fire regime forests. While we identified a greater proportion of total forested area in need of restoration within historical FRG I forests, FRG III forests may certainly be prioritized in local restoration programs due to higher site productivity and concurrent higher fuel levels, and greater risk of high severity fire and insect/disease mortality (*see* Section 4.2).

Similarly, the historic role of high severity fire and the importance of complex early seral habitats in western forested landscapes have also received significant recent attention by the science and management communities (Hutto, 2008; Swanson et al., 2011). As a proportion of overall restoration needs, the opening/high severity fire transition was most common in historically mixed and high severity fire regime forests (e.g., FRG III, IV, & V biophysical settings). All disturbance restoration need transitions in this paper, and particularly the opening/high severity fire transition, should be interpreted with respect to historical spatial patterns at patch and landscape scales. Stand level reconstructions of frequent fire forests in western North America emphasize high levels of fine scale spatial heterogeneity in the form of individual trees, tree clumps, and openings within forest stands (Churchill et al., 2013; Larson and Churchill, 2012). At landscape scales, reconstructions of historical patch sizes from the eastern Washington Cascades reveal distributions following a negative power law, with many small (⩽10s ha) and few very large patches (1000s ha+; Hessburg et al., 2007, 2000a; Perry et al., 2011). Consequently, the majority of opening/high severity transitions that we report, particularly within historical low severity fire regime forests (e.g., FRG I biophysical settings), are likely to be represented as smaller within-stand openings. Within FRG III, IV, and V biophysical settings, the opening/high severity fire transitions may also represent larger patches of early seral habitat.

4.2. Management implications

In recent years there have been numerous calls by local, state, and federal governments, agencies, and stakeholder groups to increase the pace and scale of forest restoration treatments across Oregon and Washington (State of Oregon, 2011; The Nature Conservancy, 2012; USDA Forest Service, 2013). We have identified approximately 1.7 million ha presently in need of disturbance (including disturbance then succession) to restore forest structure NRV on US Forest Service lands outside of wilderness and inventoried roadless areas (e.g., "USFS-Restricted", Appendix Table B.2). Within our analysis area the US Forest Service averaged approximately 12,000 ha per year of hazardous fuels treatments between 2004 and 2013 and had a total of nearly 19,000 ha of forest vegetation improvements in 2013 (US Forest Service Pacific Northwest Region; unpublished data). Assuming that these treatments are additive and address disturbance restoration needs identified in this study, at these treatment rates it will take over 50 years to meet the identified disturbance restoration needs on these US Forest Service lands. These assumptions are not likely to be true for all of the recorded treatments. Furthermore, this rough comparison does not take into account the extremely important influences of wildfire, managed or otherwise, and other unplanned disturbance events or the natural growth and succession of forests. The US Forest Service Pacific Northwest Region is increasing the rate of restoration treatments, notably in the Blue Mountains. For example, acres treated in the Pacific Northwest Region increased 22% from Fiscal Year 2012 to Fiscal Year 2013 (US Forest Service Pacific Northwest Region; unpublished data). Our results indicate that such an increase in treatment rate on federal forests is warranted. However, region-wide restoration needs cannot be met through focus on unreserved US Forest Service lands alone. Coordination amongst governments, agencies, and landowners and application

Table 5
Forest structure restoration need transitions by Map Zone for eastern Washington and eastern and southwestern Oregon. See Appendix B.4 for detailed summaries of restoration need by watershed.

Map zones	Total forest	Disturbance only			Disturbance then succession		Succession only	
		Thin/low fire	Opening/high fire	Overstory thinning	Thin/low fire + Grow	Other disturbance + Grow	Grow with fire	Grow without fire
	ha.	ha.	ha.	ha.	ha.	ha.	ha.	ha.
Oregon Blue Mtns.	2,907,000	91,000	149,000	1,000	554,000	142,000	74,000	84,000
Oregon East Cascades	2,379,000	267,000	101,000	14,000	370,000	31,000	37,000	46,000
Oregon Southeast	17,000	0	0	0	3000	0	4000	1000
Oregon Southwest	2,616,000	352,000	79,000	67,000	534,000	1,000	24,000	263,000
Oregon Totals[a]	**7,919,000**	**711,000**	**329,000**	**82,000**	**1,462,000**	**175,000**	**138,000**	**394,000**
Washington Columbia Basin	54,000	7000	1000	0	5000	0	6000	1000
Washington East Cascades	1,575,000	125,000	49,000	12,000	188,000	6000	52,000	44,000
Washington Northeast	2,071,000	150,000	120,000	0	462,000	1000	29,000	194,000
Washington totals	**3,700,000**	**282,000**	**171,000**	**12,000**	**654,000**	**7000**	**87,000**	**239,000**

[a] Includes the portions of the Oregon Blue Mountains map zone within Washington State political boundaries.

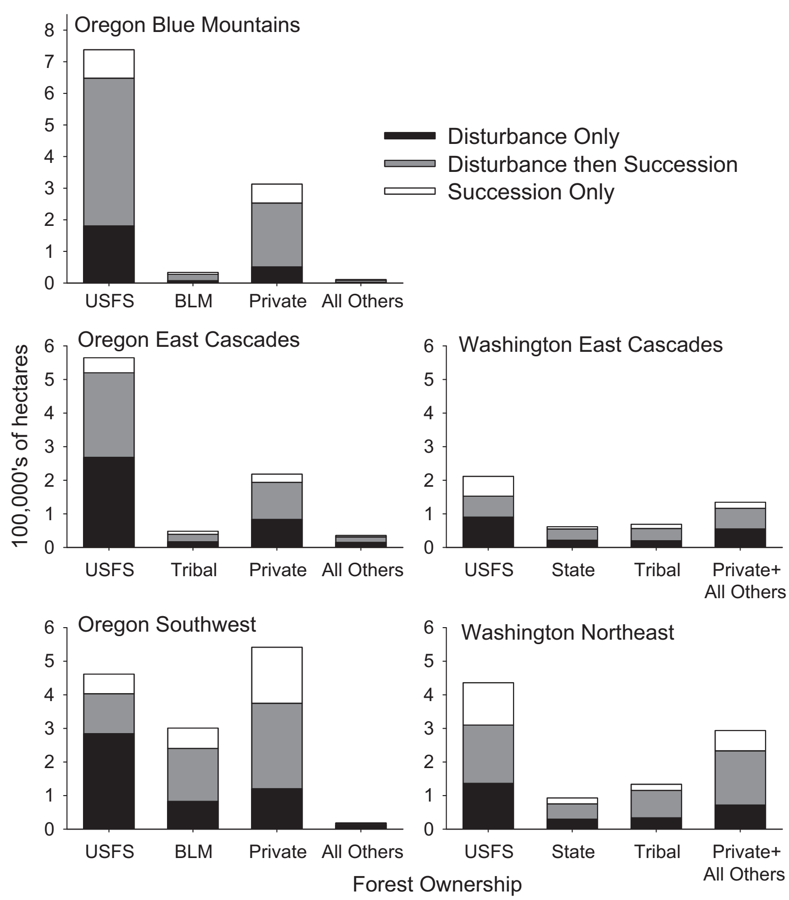

Fig. 6. Forest structure restoration needs by forest ownership per Map Zone for eastern Washington and eastern and southwestern Oregon. USFS = US Forest Service. BLM = US Bureau of Land Management. "Disturbance Only" includes the thin/low fire, opening/high fire and overstory thinning transitions. "Disturbance then Succession" includes the thin/low fire + growth and other disturbance + growth transitions. "Succession only" includes the grow with fire and grow without fire transitions. See Appendix B.2 for detailed summaries of restoration need by forest ownership–management and Map Zones.

of the entire "toolbox" (e.g., mechanical treatments, prescribed fire, managed wildfire, protection) will be required.

A primary motivation behind this study is to facilitate the ability of local land managers to incorporate regional scale, multi-ownership context into local forest management and restoration. This assessment, however, is not a replacement for the evaluation of local landscapes (1000s–10,000s of ha) and development of local landscape prescriptions. With that understanding, the results from this study may inform local landscape evaluations and development of local landscape restoration prescriptions (e.g., Hessburg et al., 2013). For example, our results provide managers with the ability to place local treatments within regional context based on relative restoration needs by biophysical settings and s-classes (Appendix B.3). Land managers may also use our results to estimate and compare overall treatment need amongst potential project areas through our watershed level summaries (Appendix B.4). However, local landscape evaluations are still required to develop on the ground restoration treatments. Ideally, these local

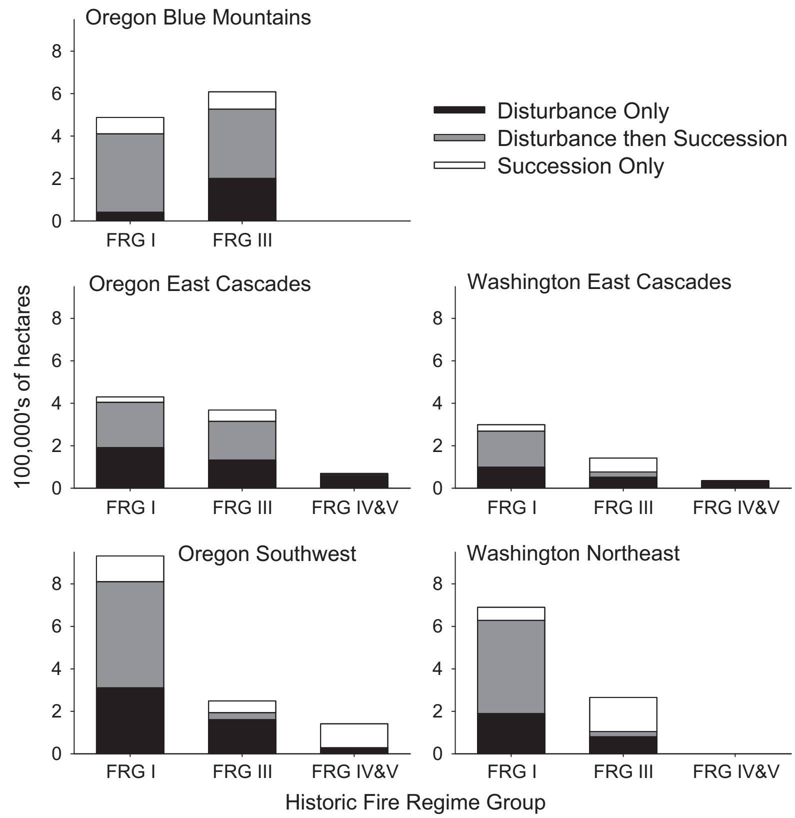

Fig. 7. Forest structure restoration need by forested biophysical setting historic fire regime groups (FRG; Table 1) per Map Zone for eastern Washington and eastern and southwestern Oregon. "Disturbance Only" includes the thin/low fire, opening/high fire and overstory thinning transitions. "Disturbance then Succession" includes the thin/low fire + growth and other disturbance + growth transitions. "Succession only" includes the grow with fire and grow without fire transitions. See Appendix B.3 for detailed summaries of restoration need by forest biophysical settings and Map Zones.

evaluations also incorporate important factors not included in our analysis such as tree species composition, forest patch size, shape, and configuration, aquatic ecosystem conditions, and specific habitat requirements. Additionally, local adjustments to the state-and-transitions models, such as changing disturbance probabilities to reflect the impact of climate, insects, disease and other natural cycles (sensu Forbis, 2006), could help refine the NRV estimates presented here. Consequently, local landscape evaluations require measurements of forest structure and composition at finer spatial resolutions (e.g., lidar, high resolution aerial photography) than are presently available for our regional scale analysis.

Forest restoration programs must consider not only patterns of vegetation and habitat, but also ecological processes such disturbance, hydrology, and migration. Our evaluation of forest restoration needs considers only half of the Fire Regime Condition Class assessment; forest structure but not contemporary fire/disturbance history (Barrett et al., 2010). However, a fundamental principle of landscape ecology is the linkage between ecological patterns and processes (Turner et al., 2001). Restoration of pattern in forested landscapes, from local to regional scales, facilitates the restoration of ecological processes. Consequently, the restoration needs identified in this study help to set the stage for the restoration of ecological processes. Finally, as better data on historical disturbance becomes available, more refined estimates of ecological departure, and associated indications for treatment, may be possible.

4.3. Appropriate uses of restoration needs results

We expect that both the results of this analysis and the conceptual framework we have introduced will be useful in providing regional context for local restoration treatments, conducting regional scale prioritizations, and assessing the scope and scale of current restoration programs. However, such uses require an understanding of the data and assumptions upon which this analysis was built. The restoration transitions we report are broad characterizations; they do not represent specific sivicultural prescriptions and are limited by both the accuracy and resolution of the current forest structure and potential vegetation type mapping we used, and by the simplified classification of each biophysical setting into five s-classes. Similarly, there are many aspects of ecological restoration, including but not limited to tree species composition and aquatic ecosystems, which our narrow focus on forest structure did not consider. Given these limitations, our results should not be interpreted below the resolution of individual watersheds (5th field hydrologic units, average ~46,000 ha).

In addition, the restoration transitions we report in this study do not directly correspond to the concepts of "active restoration" and "passive restoration" which are referenced in other discussions of forest restoration (e.g., Morrison and Lindell, 2011). Active restoration typically refers to direct intervention or manipulation, such as mechanically thinning a forest stand, whereas passive restoration typically refers to no action, such as letting a natural fire ignition burn. Yet both of these scenarios, mechanical treatment and letting a natural ignition burn, may be included in our disturbance transitions. Whether active or passive restoration means are used within a specific location to achieve identified disturbance restoration needs depends upon forest ownership and management allocation for that location. We recognize that there are many significant differences in the ecological outcomes of mechanical treatments versus prescribed fire versus wildfire (Schwilk et al., 2009). Furthermore, fire is frequently required following mechanical treatment in order to meet ecological and/or forest fuels objectives (Schwilk et al., 2009). However, we consider that either mechanism is capable of achieving the coarse s-class transitions that we report in this study.

As our understanding of historical and future ecosystem dynamics, classification and mapping of biophysical settings, and measurement of current conditions across Oregon and Washington improves, new data may be incorporated into our conceptual approach to revise the results presented here. Our conceptual approach is also applicable to other regions. The basic concepts of our approach may be applied anywhere that the foundational inputs of biophysical setting classification and mapping, reference conditions, landscape units, and mapping of current conditions is available. There is great value having a consistent approach to evaluating where, how much, and what kinds of forest restoration are needed across regional scales.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.09.014.

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