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Trends in forest structure restoration need over three decades with increasing wildfire activity in the interior Pacific Northwest US

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A B S T R A C T

Wildfire is a keystone ecological process in many forests worldwide, but fire exclusion and suppression have driven profound shifts in forest structure (e.g., increased density, canopy cover, biomass) that have contributed to increases in large, high-severity fire in many seasonally dry forests and woodlands of the western United States. Comparisons between contemporary and historic range of variability (HRV) in forest structure can quantify the amount and types of restoration that shift landscapes toward structural conditions that have historically fostered resilience to fire. However, landscapes are dynamic over time and conditions reflect the net effects of planned actions (e.g., fuel reduction treatments) and unplanned actions (e.g., wildfire). How wildfire activity may shift landscapes toward or away from the HRV and correspondingly affect the need for restoration, has not been widely tested. Here, we quantify long-term (1986–2017), and continuous (annual resolution) trends of forest restoration need and ask how wildfire activity during this period has affected restoration need trends at three nested spatial extents: across the eastern Washington (USA) ecoregion, among fire regimes within this ecoregion, and between watersheds of a frequent/low-severity fire regime that experienced contrasting amounts of wildfire. At the broadest scale, restoration need did not change substantially during the study period, with approximately 35 % of forest area in need of disturbance restoration—despite 16.6 % of the total forested area (593,000 ha) burning from 1986 to 2016. At intermediate spatial extents (among fire regimes), forests characterized by historically frequent/low-severity fire experienced the greatest decrease in disturbance restoration need following recent fire activity. Although > 50 % of forests within this fire-regime remained in need of disturbance restoration at the end of the study period, we found a strong correspondence between forested area burned and decreased restoration need in this fire regime; relationships were equivocal or non-existent in other fire regimes. At the finest spatial scale (watersheds dominated by historically frequent/low-severity fire-regime forests), we found sharp contrasts between areas that experienced high fire activity in recent years and those that did not. At this scale, recent large fires have decreased disturbance restoration need by > 25 %. Our findings suggest that recent large wildfires have reduced the amount of forest in need of restoration, but have done so modestly and primarily at local or sub-regional extents. Overall, our approach can be applied to understanding how wildfires or other disturbances contribute to affecting forest structure and management targets in other ecosystems through time and space.

Abbreviations: DNR, Department of Natural Resources; FIA, Forest Inventory and Analysis; FRG, Fire regime group; FRI, Fire return interval; FRV, Future range of variability; FVS, Forest Vegetation Simulator; GNN, Gradient Nearest Neighbor; HRV, historical range of variability; HUC, Hydrologic unit code; ILAP, Integrated Landscape Assessment Project; MTBS, Monitoring Trends in Burn Severity; RdNBR, Relative differenced Normalized Burn Ratio; USGS, United States Geological Survey; WCB, Washington Columbia Basin; WEC, Washington East Cascades; WNE, Washington Northeast.

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1. Introduction

In fire-dependent forests, wildfire is a critical disturbance process that drives and maintains forest structure (i.e., the size and spatial arrangement of trees) and function (e.g., Pausas and Keeley, 2019), though many forests worldwide face pressing management challenges as the climate warms (Hessburg et al., 2019). For example, in many dry, historically fire-frequent forests, fire exclusion and suppression have profoundly altered forest structure and composition, creating dense, spatially homogenous forests (Hessburg et al., 2000; Hessburg et al., 2005; Naficy et al., 2010) that are vulnerable to uncharacteristically severe wildfire, drought, and insect outbreaks (Fornwalt et al., 2016; Stephens et al., 2018; Parks and Abatzoglou, 2020; Hagmann et al., 2021). Climate warming and drying can further erode forest resilience to future wildfire by promoting weather conditions conducive to high intensity burning (Abatzoglou and Williams, 2016; Abatzoglou et al., 2021) and adding additional stressors to post-fire recovery processes (Harvey et al., 2016a; Stevens-Rumann et al., 2018; Davis et al., 2019). Forest resilience can be defined as the ability of a forest to tolerate a disturbance without transitioning to an alternative state (e.g., a non-forest; Walker et al., 2004) and is a primary focus of contemporary forest management. Challenges associated with managing dry forests have led to calls for increasing the pace and scale of fuel reduction treatments that restore landscapes to conditions more resilient to fire (Prichard et al., 2021), exemplified by policies and programs such as the Collaborative Forest Landscape Restoration Program in the US. (e.g., Schultz et al., 2012) and initiatives being led by states (e.g., Addington et al., 2018; WA DNR, 2020; Forest Management Task Force, 2021). Assessments of landscape structure that capture the dynamic interplay of disturbance and vegetation patterns can support and inform such management efforts (Agee and Skinner, 2005; Hessburg et al., 2015).

A commonly used target condition and template of resilience in landscape restoration efforts is the historical range of variability (HRV) of forest structure (e.g., Churchill et al., 2013). The HRV describes the spatial and temporal variation of an ecological condition (Landres et al., 1999; Hessburg et al., 2019), and with forests, HRV can be quantified by the central tendency and range of forest structure conditions (e.g., tree size, density, canopy cover, biomass) expected across a landscape over a given time period. In much of the western US, forest-structure HRV is characterized by conditions before European contact and colonization, when structural patterns were aligned with fire regimes driven by lightning ignitions and Indigenous cultural burning (Kimmerer and Lake, 2001; Long et al., 2021). Contemporary forests where fire regimes have been minimally disrupted since European colonization can also provide estimates of forest structure HRV (e.g., Murphy et al., 2021; North et al., 2021). In historically fire-frequent forests, forest structure HRV consists primarily of low stand densities with considerable patch and landscape heterogeneity, and are thought to confer resilience to future fire by reducing the probability of large, high-severity wildfires (Hessburg et al., 2015; Murphy et al., 2021). In many landscape assessments, contemporary forest structure conditions are compared to the HRV to describe ecological departure from reference conditions, guide the selection of treatments (e.g., mechanical fuel treatments or prescribed fire) to move conditions towards the HRV, and quantify the magnitude of restoration need (e.g., Haugo et al., 2015, DeMeo et al., 2018).

Landscape assessments are commonly conducted as a snapshot of conditions at one point in time, and may not reflect dynamics as landscapes interact with disturbances continually through time. Though uncommon to date, assessments of long-term trends in restoration need can provide useful information about the trajectory and pace of restoration while also assessing the efficacy of management actions and/or natural disturbances in addressing restoration need. Such an application is particularly useful in exploring the role that natural disturbances such as wildfire can play in achieving forest restoration targets. For example, mechanical fuel reduction treatments or pile burning can require substantial time to plan and implement and are not feasible on a large portion of landscapes (North et al., 2015). As such, with increasing frequency, managed wildfire is used as an opportunistic restoration tool (e.g., Barros et al., 2018; Huffman et al., 2020; North et al., 2021; Churchill et al., 2022). With wildfire activity and severity increasing across the western US under a warming and drying climate (Abatzoglou and Williams, 2016), understanding the role and extent of contemporary wildfires in addressing or exacerbating restoration need can guide land management decisions (Stephens et al., 2021; Larson et al., 2022).

Dry inland forests of eastern Washington (USA) provide a useful setting to examine the role of wildfire in addressing restoration need over time. Assessments of restoration need in 2006 (Haugo et al., 2015) and 2012 (DeMeo et al., 2018) concluded that dry forests were highly departed from the HRV, with approximately 30 % of forested land in eastern Washington needing some type of disturbance restoration treatment (i.e., fuel treatments and/or prescribed fire). In response, the Washington Department of Natural Resources (WA DNR) enacted the 20-Year Forest Health Strategic Plan with a goal of treating 500,000 ha of forest by 2037 (WA DNR, 2017). However, wildfire activity has also increased in recent decades, with large fire years in eastern Washington in 2006, 2014, 2015, and 2021 (Reilly et al., 2017, WA DNR, 2022). Despite the increase in recent wildfire activity, the region remains in a substantial fire deficit relative to historical levels, particularly in terms of the amount of low to moderate severity fire (Haugo et al., 2019). Individual fire events can shift forest structure toward or away from the HRV (Churchill et al., 2022), but how such trends unfold continuously through time across multiple spatial scales is poorly understood.

Here, we used the framework developed by Haugo et al. (2015) and DeMeo et al. (2018) to quantify long-term (1986–2017) and inter-annual trends in restoration need in forests of eastern Washington. Our objectives were to: (1) explore how recent wildfire activity has affected restoration need trends at the ecoregion scale across eastern Washington, (2) compare trends and the role of fire in affecting trends among forests of varying natural historical fire regimes (e.g., low-severity and frequent fire regimes vs high-severity and infrequent fire regimes), and (3) compare two subregions dominated by historically low-severity and frequent fire regimes as a case study of how the localized effects of wildfire drive trends in restoration need.

2. Methods

2.1. Study area

The study area includes all forested land east of the Cascade crest within the Washington Northeast (WNE), Washington East Cascades (WEC), and Washington Columbia Basin (WCB) map zones from the original Haugo et al. (2015) and DeMeo et al. (2018) assessments (Fig. 1). These forested lands total 3.58 million ha and broadly encompass dry mixed-conifer and ponderosa pine forests at lower elevations, moist mixed-conifer at moderate elevations, and subalpine fir and Engelmann spruce forests at higher elevations.

Approximately 52 % of the study area is occupied by forests belonging to fire regime group (FRG) I (Barrett et al., 2010), which is characterized by low severity fire with an average fire return interval (FRI) of 0 to 35 years (Table 1). FRG I forests include dry mixed-conifer (46 % of study area), mesic ponderosa pine (5.9 %), and white oak/ponderosa pine forests (0.1 %; Table 2). Twenty-nine percent of the study area is occupied by FRG III forests, which have mixed-severity fire regimes with an average FRI of 35 to 100 + years (Table 1). FRG III forests include moist mixed-conifer (11.8 % of study area), northern Rocky Mountain mixed-conifer (7.7 %), subalpine woodland (6.1 %), and low elevation Pacific silver fir (3.8 %; Table 2). Approximately 10 % of the study area is occupied by FRG IV forests, which are characterized by high severity fire with an average FRI of 35 to 100 + years (Table 1). FRG IV forests include spruce/fir (9.9 % of study area) and subalpine fir forests (0.2 %; Table 2). The remaining 9 % of the study area is occupied

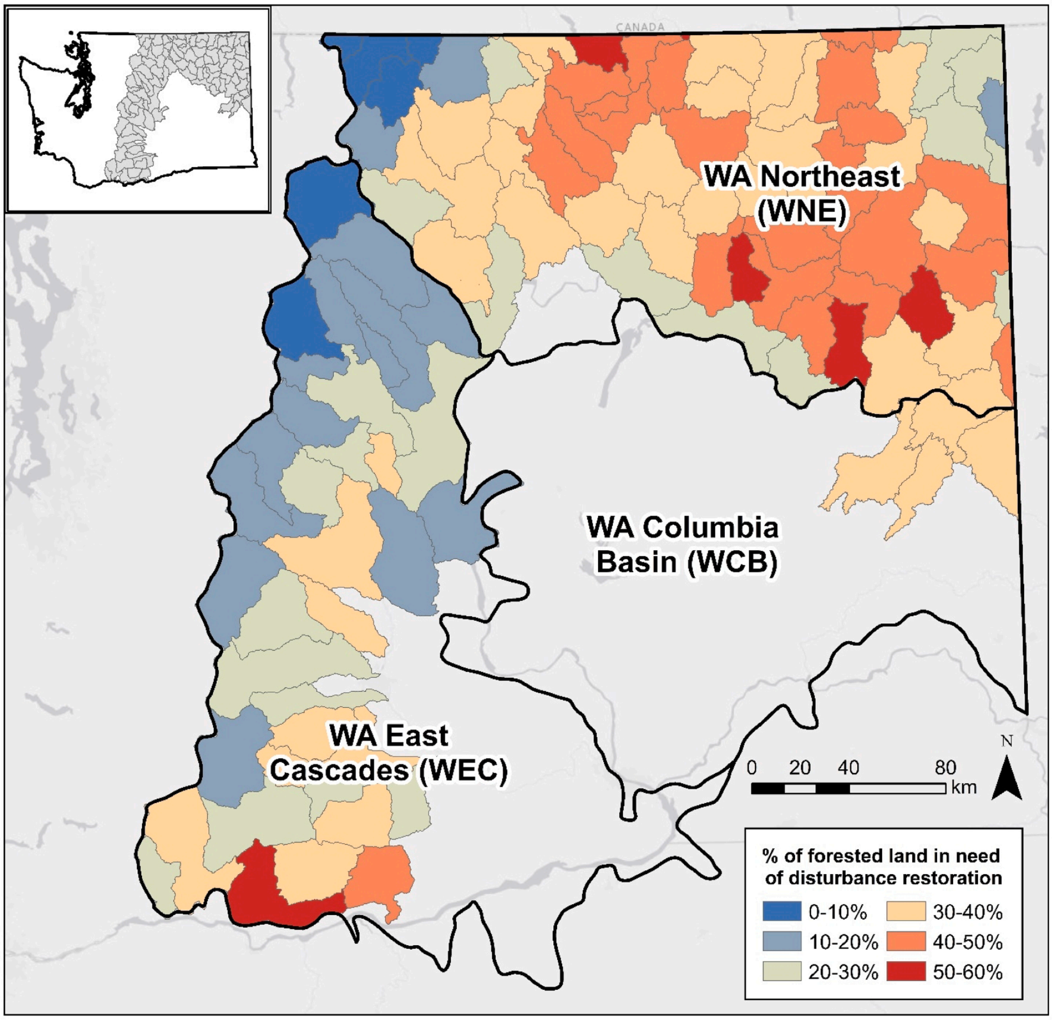

Fig. 1. Status of disturbance-related need (2017)- Status of total disturbance-related need by HUC10 watershed in 2017. Disturbance need in strata was allocated to HUC10 watersheds based on the amount of area each stratum occupied within a watershed (e.g., if 10% of a stratum fell within a watershed, then 10% of its total disturbance need was allocated to that watershed). See Haugo et al. (2015) and DeMeo et al. (2018) for similar maps from 2006 and 2012.

Table 1
Fire regime group (FRG) characteristics, landscape level and scale at which they were analyzed, the percentage of the study area (eastern Washington forests) they occupy, and number of strata they contain (out of 365).

FRG	Fire Return Interval (years)	Fire Severity	Landscape Level/ Scale	Layers Used	Percentage of Study Area (%)	Number of Strata
I	0–35	low	Watershed	10-digit/5th level USGS HUC*	51.9	293
III	35–100+	mixed	Sub-basin	8-digit/4th level USGS HUC	29.4	66
IV	35–100+	high	Map zone	ILAP** eco-regions cut to USGS sub-basin boundaries	10.1	3
V	200+	high	Map zone	ILAP eco-regions cut to USGS sub-basin boundaries	8.5	3

* USGS HUC = United States Geological Survey Hydrologic Unit Code (https://water.usgs.gov/GIS/huc.html).
** ILAP = Integrated Landscape Assessment Project (https://inr.oregonstate.edu/ilap).

by FRG V forests, which are characterized by high severity regimes with an average FRI exceeding 200 years (Table 1). FRG V forests are primarily xeric Pacific mountain hemlock (8.5 % of study area; Table 2).

2.2. Restoration needs Assessment

To calculate annual ecological departure of forest structure conditions from 1986 to 2017, we used four steps as outlined in Haugo et al. (2015): (1) dividing the landscape into meaningful strata based on LANDFIRE biophysical settings and their associated FRGs (https://www.landfire.gov/index.php), (2) mapping current forest structure conditions, (3) calculating ecological departure by comparing current forest structure conditions to reference conditions (HRV) within strata, and (4) determining the amount and type of restoration needed to guide conditions towards reference conditions within strata. Below we provide a brief summary of each step involved in this assessment of ecological departure of forest structure, which acts as a coarse-filter metric of landscape resilience and sustainability. For a complete methods description see Haugo et al. (2015) and DeMeo et al. (2018).

In this analysis, we used the strata produced by the original Haugo

Table 2
Biophysical settings, their associated fire regime group, and the percentage of the study area (eastern Washington forests) they occupy.

Biophysical Setting	Fire Regime Group	Percentage of Study Area (%)
Dry mixed-conifer	I	46.0
Moist mixed-conifer	III	11.8
Spruce/fir	IV	10.0
Xeric Pacific mountain hemlock	III	8.5
Northern Rocky Mountain mixed-conifer	V	7.7
Subalpine woodland	III	6.1
Mesic ponderosa pine	I	5.9
Low elevation Pacific silver fir	III	3.8
Subalpine fir	IV	0.2
White oak/ponderosa pine	I	0.1

et al. (2015) and DeMeo et al. (2018) assessments. Strata were delineated based on LANDFIRE biophysical settings, defined as a potential vegetation unit associated with a natural disturbance regime pre-European colonization. In contrast to existing (current) vegetation, potential vegetation at this broad scale reflects the capacity of a location to generate biomass, support ecosystems, and foster ecological processes such as fire regimes. Biophysical settings were assigned at one of three spatially nested landscape levels depending on the characteristics of the FRG: FRG I was analyzed at the watershed scale (10-digit/5th level hydrological unit), FRG III at the sub-basin scale (8-digit/4th level hydrological unit), and FRG IV and V at the map zone scale (Integrated Landscape Assessment Project eco-regions delineated at USGS sub-basin boundaries; Table 1). Different landscape levels were used to ensure biophysical settings were analyzed at ecologically relevant spatial scales. LANDFIRE biophysical settings were mapped spatially by cross-walking them to the 2012 Integrated Landscape Assessment Project (ILAP; https://inr.oregonstate.edu/ilap) potential vegetation type (PVT) rasters. Within the study area, there were 10 biophysical settings (Table 2) and 365 strata (i.e., unique combinations of biophysical setting and landscape level).

Current forest structure conditions were mapped annually from 1986 to 2017 using gradient nearest neighbor (GNN) datasets from the Landscape Ecology, Modeling, Mapping and Analysis (LEMMA) lab at Oregon State University (https://lemma.forestry.oregonstate.edu/data) (Bell et al., 2021). Three GNN-derived forest structure attributes (canopy cover, trees per acre, and quadratic mean diameter per diameter class; Table A.1) were used to develop rule-based criteria with which each 30-meter resolution pixel was classified as one of 5 structural/successional classes—early development, mid-development closed canopy, mid-development open canopy, late-development open canopy, and late-development closed canopy. These rule-based criteria varied by biophysical setting to reflect differences in characteristic size, density, and canopy cover of early, mid-, and late-development forests under varying ecological contexts – for example, the characteristic forest structure attributes of late-development forests may differ between a subalpine fir and ponderosa pine biophysical setting. For more detailed information on how structural/successional classes are assigned, see Haugo et al. (2015). The currently accepted GNN method was applied to all years, though note that the data from 2006 and 2012 are not directly comparable to those used in previous restoration need assessments (Haugo et al., 2015; DeMeo et al., 2018) due to iterative changes in the GNN methodology.

To calculate ecological departure, the relative abundance of each structural/successional class within a stratum in a given year was compared to reference conditions (i.e., HRV in forest structure) to determine if current conditions were above, below, or within the HRV and by what magnitude using a simple similarity matrix. Highly departed strata indicate that forest structure conditions (i.e., the relative abundance of each structural/successional class) differ substantially from reference conditions. For comparison to earlier studies, we used published reference conditions for the HRV that were quantified by LANDFIRE state and transition models for each biophysical setting and represent the average relative abundance of each structural/successional class plus or minus 2 standard deviations (mean +/- 2SD) from the last 500 time steps across model runs (10 model runs for each biophysical setting, over 1000 cells and 1000 annual time steps). We recognize that there are alternative approaches to characterizing the HRV, however we relied on reference conditions used in the original Haugo et al. (2015) framework to allow for comparisons with earlier assessments for the region. Current forest structure conditions were compared to the nearest edge of the HRV range (mean +/- 2SD), providing a conservative estimate of restoration need. For example, if a structural/successional class was below the HRV, it was compared to the minimum value of the HRV range (i.e., mean – 2SD); if a structural/successional class was above the HRV, it was compared to the maximum value of the HRV (mean + 2SD). See Haugo et al. (2015) for more details.

To determine the amount and type of restoration treatments required to guide structural/successional class conditions towards the HRV, outputs from the ecological departure analysis were passed through a ruleset table outlining every potential structural/successional class transition. Each structural/successional class transition was assigned one of three restoration need treatments: disturbance only (i.e., mechanical thinning and/or prescribed fire), growth only (i.e., allowing forests the time to grow), and disturbance followed by growth (note: the "growth" treatment type is analogous to "succession" in the Haugo et al. (2015) and DeMeo et al. (2018) papers). For example, in ponderosa pine biophysical settings transitions from closed-canopy to open-canopy forest or the creation of early development forest were assigned disturbance only treatments. Restoration need treatments associated with a specific structural/successional class transition varied by biophysical settings and their unique ecological contexts. If a structural/successional class transition in the ruleset table moved forest structure conditions towards the HRV, the minimum amount of area needed to move conditions within the HRV was tallied under the corresponding treatment type. The departure status of the donating and receiving structural/successional classes was updated, then passed to the next transition in the ruleset. If a transition in the ruleset did not move conditions towards the HRV, it was skipped. The final outputs from the restoration need assessment provide a summary of how much area within each stratum require treatment. However, the outputs do not specify exactly which pixels within a stratum should be treated. Thus, they are spatially explicit at the scale of the stratum but not at finer scales. More detailed descriptions and supplementary material are provided in Haugo et al. (2015). These methods were repeated each year from 1986 to 2017. To assess broad trends, restoration need was summed up across strata to the desired scale (e.g., across eastern Washington forests, by FRG, or within subregion case-study areas).

2.3. Comparing restoration need trends to wildfire activity

To determine forested area burned within strata, annual burn severity rasters from 1986 to 2016 were combined with a strata raster (i.e., a raster classifying the 365 unique strata). We did not include annual area burned in 2017 as we did not have structural data after this year and therefore could not attribute any change in restoration need to wildfire activity in this year. Annual burn severity rasters were acquired from Monitoring Trends in Burn Severity (MTBS; https://www.mtbs.gov/) and re-classified as unburned, low, moderate, high severity, and no data using Haugo et al. (2019) RdNBR thresholds for percent basal area loss. No data pixels represent areas where RdNBR values were<1 (i.e., pixels that increased in greenness from pre to post fire in the satellite imagery) and were assumed to be unburned. Low, moderate, and high severity pixels were summed within strata to represent total area burned. We conducted a sensitivity analysis to assess the effect of including or excluding no data pixels; this decision did not change the qualitative interpretations of the analysis (see appendix; Fig. A.1). Total forested area burned was summed across strata to the desired spatial extents (i.e., across eastern Washington forests, by FRG, or within subregion case-study areas).

Fires can result in delayed tree mortality that is not immediately detected in the GNN structural/successional class rasters. Furthermore, satellite imagery used as covariates to derive GNN datasets represent conditions at some point in the growing season and could represent either pre-fire or post-fire conditions within a given year, making it difficult to attribute change in restoration need to wildfire activity between 2 consecutive years. To reduce issues associated with detection lag in GNN derived datasets, comparisons between area burned and changes in restoration need were conducted within aggregated 5-year time intervals for each stratum, from 1986 to 2017 (Table A.2; note, this period is not evenly divided by 5, so the first interval is larger (1986 to 1992) but also experienced minimal wildfire activity). A sensitivity analysis was performed using time intervals from 2 to 10 years (see appendix; Fig. A.2). Five years was selected as the time interval of focus, as it was long enough to reduce the effects associated with detection lag and short enough to examine punctuated and clustered years of fire activity. Annual forested area burned was summed across the 5-year time intervals, excluding the last year in the interval (e.g., for the time interval from 2007 to 2012, annual area burned was summed for years 2007, 2008, 2009, 2010, and 2011) and compared to the difference in total disturbance need between the first and last year of the 5-year interval (e.g., total disturbance need in 2007 subtracted from total disturbance need in 2012; Table A.2).

To test whether wildfire decreased disturbance need within FRGs, we compared the observed versus expected area of overlap between declining disturbance need and forested area burned within FRGs across strata within 5-year time intervals. Assuming no relationship between forested area burned and declining disturbance need, the amount of their overlap within an FRG would reflect the amount of overlap due to random chance. However, if wildfire contributed to a reduction in disturbance needs, we would expect greater amounts of overlap between declining disturbance need and area burned than expected under random chance (i.e., disturbance need is declining more-so in areas where wildfire is occurring).

Comparisons between observed and expected area of overlap between forested area burned and changes in disturbance need were calculated at the scale of strata then summed across FRGs. To calculate the observed area of overlap within each FRG, we summed the amount of area burned within strata that experienced a reduction in disturbance need across FRGs for each 5-year interval (e.g., area burned within FRG I strata that experienced a decline in disturbance need were summed). Area burned within strata that increased in disturbance need were not included in the observed overlap calculations. To determine the expected area of overlap within each FRG under random chance, we multiplied the proportion of forested area burned within the FRG by the forested area that experienced a decrease in disturbance need in the FRG. The proportion of forested area burned in the expected area of overlap calculation included any forested area burned, regardless of whether it fell within strata that increased or decreased in disturbance need. Differences between these two values were interpreted as evidence of an effect of wildfire on reducing disturbance restoration need. This approach of comparing observed versus expected values in a spatial overlay has been applied in similar studies (e.g., Hart et al., 2015).

2.3.1. Case study: FRG I subregions with and without wildfire

To compare how wildfire affected restoration need over time at finer spatial scales, we conducted a case study. We focused on FRG I forests within two subregions, each consisting of several watersheds (Table A.3). The first subregion was composed of 5 watersheds in the North Cascades of Washington that experienced relatively large fire years in 2006, 2014, and 2015, the largest of which included the Tripod complex (2006), Carlton complex (2014), Okanogan Complex (2015), and the Black Canyon fire (2015). The second subregion was comparable but had experienced minimal wildfire, insect outbreak, or logging. We used satellite imagery, aerial detection surveys (ADS; https://www.fs.usda.gov/detail/r6/forest-grasslandhealth/insects-diseases/?cid=stelprdb5286951), and insect outbreak maps (Meddens et al., pers comms) to select 5 watersheds northeast of the first subregion.

In both subregions, we assessed the long-term trends (1986–2017) in restoration need and structural/successional class proportions relative to forested area burned. To better understand whether wildfire is addressing disturbance need, we also compared specific structural/successional class transitions between the two subregions from 2011 to 2017. We chose this interval as it includes declining disturbance restoration need within the wildfire subregion and the greatest total area burned. To create the transition matrices, we combined the structural/successional class rasters from 2011 and 2017 in ArcMap (https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources) using the “Combine” tool. Outputs from the combine tool summarize the amount (i.e., number of pixels) and specific types of structural/successional class transitions (i.e., pathways) that occurred between 2011 and 2017, including no change (i.e., pixels that remained in the same structural/successional class from 2011 to 2017). We focused all calculations on FRG I strata, excluding other FRGs within the subregion.

3. Results

3.1. Broad-scale (eastern WA) restoration need trends

At the broadest spatial extent (all forested area in eastern Washington), restoration need trends remained steady from 1986 to 2017 (Fig. 2a). Restoration need averaged 16.5 %, 18.6 %, and 7.5 % of total forested area for disturbance only, disturbance followed by growth, and growth only, respectively (Fig. 2a). Disturbance followed by growth and growth-only changed minimally over the 32-year period (<0.5 % change; Fig. 2a). In comparison, the need for disturbance only restoration increased from 16.1 % in 1986 to 17.5 % in 1999, declined to 15.9 % in 2007, changed minimally from 2007 to 2011, and declined again to 14.3 % in 2017 (Fig. 2a). The periods in which disturbance only need declined corresponded with periods of increased wildfire activity (Fig. 2b; 5.4 % and 8.8 % of total forested area burned from 1999 to 2007 and 2011 to 2017, respectively). A total of 593,000 ha of forested area burned from 1986 to 2016 across the ecoregion (42.8 % high severity, 44.1 % moderate severity, and 13.1 % low severity). Among fire regimes, the greatest proportion of cumulative area burned as high severity was for FRG IV (61.6 %) followed by FRG V (53 %), FRG III (43.8 %), and FRG I (33.7 %; Table 4). Burn severity distributions for each FRG are discussed in greater detail below in section 3.2.

In 2017, approximately 33 % of all forested land required some type of disturbance (disturbance only or disturbance followed by growth) and 7.4 % required growth only (Fig. 2a). Disturbance restoration need was greatest within the WNE map zone and the southern portion of the WEC map zone (Fig. 1).

3.2. Restoration need trends among fire regime groups

Forests within FRG I were the most departed from reference conditions and required the greatest overall restoration need relative to other FRGs (Fig. 3a). The average restoration need in FRG I was 20.2 %, 33.7 %, and 3.6 % for disturbance only, disturbance followed by growth, and growth only restoration, respectively (Fig. 3a; Table 3). Total disturbance need peaked between 1996 and 1999 at 55.7 % and declined to 52.8 % in 2007 and to 50.2 % between 2011 and 2017, similar to trends at the spatial extent of eastern Washington (Fig. 3a). From 1986 to 2016, 17 % of FRG I forests (317,000 ha) experienced wildfire (33.7 % high severity, 50.5 % moderate severity, and 15.8 % low severity; Table 4).

Change in total disturbance need within FRG I strata ranged from −6,900 ha (decrease in need) to + 2,300 ha (increase in need) within 5-

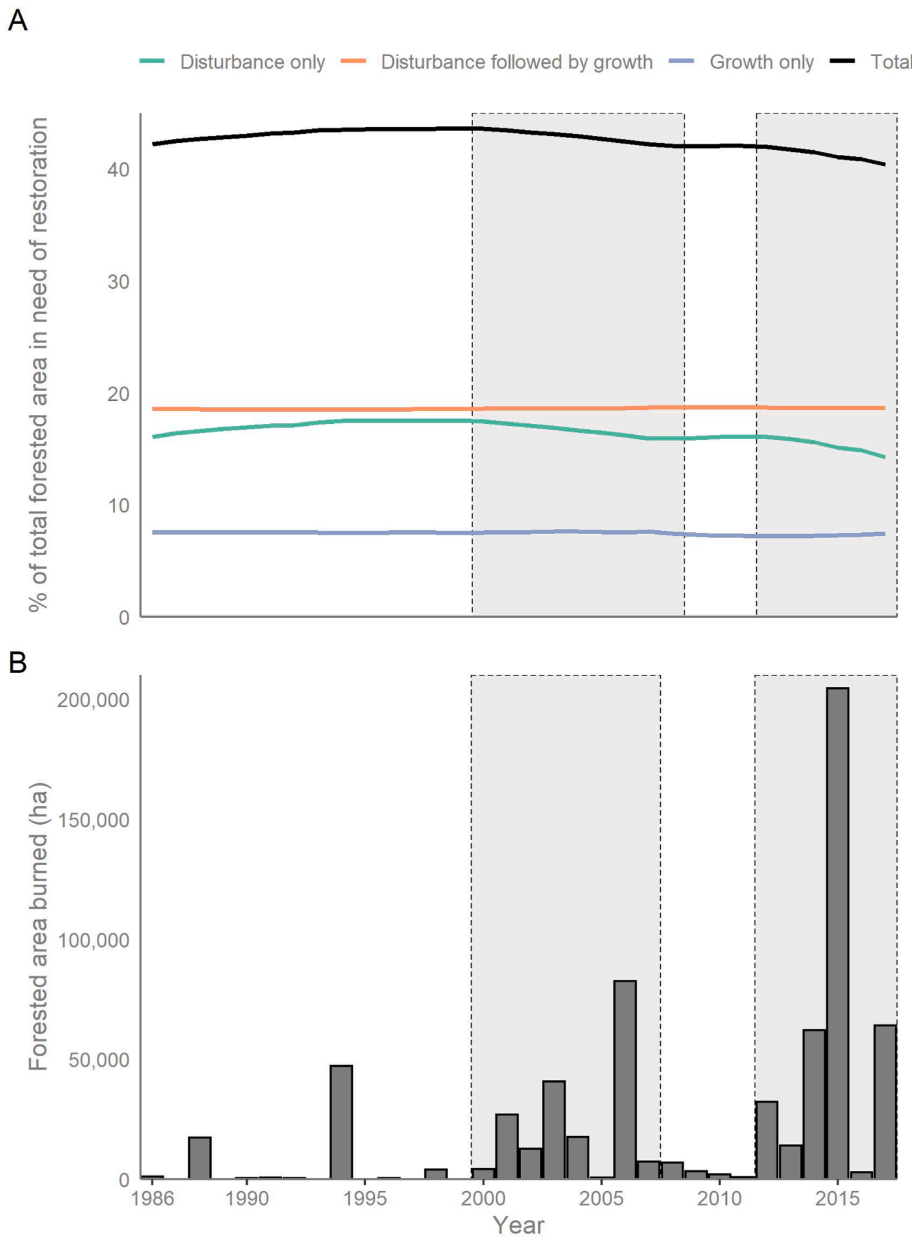

Fig. 2. Ecoregion trends in restoration need and wildfire- A Long-term trend in disturbance only, disturbance followed by growth, growth only, and total restoration need and **B** annual forested area burned in eastern Washington from 1986 to 2017. Dashed boxes indicate periods of declining overall need. Annual forested area burned for 2017 is displayed in this figure, though changes to forest structure and corresponding restoration need from 2017 wildfire are not included in subsequent analyses.

year time intervals and decreased consistently with greater forested area burned (Fig. 4a). The greatest increases in total disturbance need occurred within time periods of trace wildfire activity (e.g., 1986 to 1992; Fig. 4a), while the greatest decreases in disturbance need occurred in time periods of relatively high wildfire activity (e.g., 2012 to 2017; Fig. 4a). For each 5-year time interval, the observed area of overlap between wildfire and decreasing disturbance need within FRG I forests was greater than expected (e.g., by chance or random overlap), providing strong evidence that wildfire is contributing to the decrease in disturbance need (Fig. 4b). While the relationship between decreasing disturbance need and forested area burned is not 1:1, fire produced a net decrease in disturbance needs.

Restoration needs within FRG III forests changed minimally from 1986 to 2017. The dominant restoration need type within FRG III forests was growth only (16.4 %) followed by disturbance only (10.6 %) and disturbance followed by growth (3.7 %). From 1986 to 2016, 9.3 % (98,100 ha) of FRG III forest experienced wildfire (43.8 % high severity, 43.9 % moderate severity, 12.1 % low severity; Table 4).

FRG IV forests primarily required disturbance only and growth only, averaging at 18.5 % and 7.9 %, respectively. Disturbance followed by growth was not needed within FRG IV forests (average need of < 1 %) and did not change over the 32-year period. Disturbance only restoration peaked in 1994 at 19.4 % and declined minimally to 17.2 % in 2017. Growth only, however, experienced a steady rate of decline from 9.8 % in 1998 to 4 % in 2017 (Fig. 3a). From 1986 to 2016, 31.7 % (115,300 ha) of FRG IV forest experienced wildfire (61.6 % high severity, 30.7 % moderate severity, and 7.7 % low severity; Table 4).

FRG V forests required primarily disturbance only, which averaged at 12.3 % over the 32-year period and did not change substantially. Twenty percent (62,500 ha) of FRG V forests experienced wildfire from 1986 to 2016 (53.0 % high severity, 36.7 % moderate severity, and 10.2 % low severity; Table 4).

3.3. *Case study: FRG I subregions with and without wildfire*

Large wildfires in 2006, 2014, and 2015 burned 9.0 % (12,800 ha), 23.7 % (33,700 ha), and 9.5 % (13,600 ha) of FRG I forests within the subregion with wildfire (Fig. 5a; Fig. 5b). From 1986 to 2017,

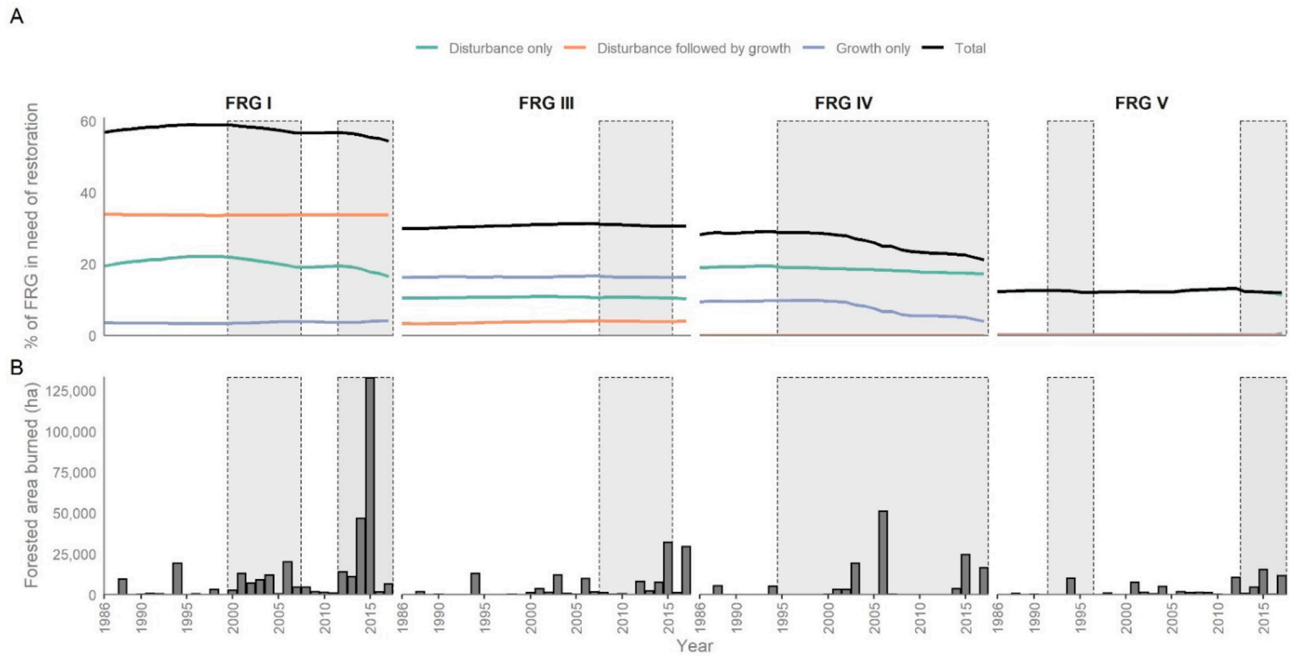

Fig. 3. Fire regime group trends in restoration need and wildfire- A Long-term trend in disturbance only, disturbance followed by growth, growth only, and total restoration need and **B** annual forested area burned in eastern Washington from 1986 to 2017, separated by fire regime group (FRG). Dashed boxes indicate periods of declining overall need within each FRG. Patterns for all forested lands are shown in Fig. 2. Note that FRG V experienced trace disturbance followed by growth and growth only restoration need (<1%) over the 32-year period, so the total restoration need line mostly overlaps with the disturbance only line in this figure. Annual forested area burned for 2017 is displayed in this figure, though changes to forest structure and corresponding restoration need from 2017 wildfire are not included in subsequent analyses.

Table 3
Long-term average need for each type of restoration treatment in each fire regime group (FRG). The minimum and maximum of restoration need from 1986 to 2017 are in parenthesis following the long-term average need. Restoration need values from 1986 and 2017 are also presented for each restoration need type and FRG.

Fire Regime Group	Disturbance Only Need (%)		Disturbance followed by Growth Need (%)		Growth Only Need (%)	
	Average (min – max)	1986–2017	Average (min – max)	1986–2017	Average (min – max)	1986–2017
I	20.2 (16.5–22.1)	19.4–16.5	33.7 (33.6–33.9)	33.9 – 33.7	3.6 (3.3–4.2)	3.6–4.2
III	10.6 (10.2–10.8)	10.5–10.2	3.7 (3.2–4.0)	3.3 – 4.0	16.4 (16.2–16.7)	16.2–16.4
IV	18.5 (17.2–19.4)	18.9–17.2	< 1.0 (0–0.02)	0.02 – 0.01	7.9 (3.9–9.8)	9.3–3.9
V	12.3 (11.2–13.1)	12.2–11.2	< 1.0 (0–0)	0–0	< 1.0 (0.06–0.6)	0.06–0.6

Table 4
Cumulative forested area burned from 1986 to 2016 (ha and percentage of total area within each fire regime group). The percentage of cumulative forested area burned that burned in each burn severity class (low, moderate, and high) is also presented for each FRG.

Fire Regime Group	Total cumulative forested area burned 1986–2017	% low severity	% moderate severity	% high severity
I	317,082 ha (17.0)	15.8	50.5	33.7
III	98,135 ha (9.3)	12.1	43.9	43.8
IV	115,315 ha (31.7)	7.7	30.7	61.6
V	62,461 ha (20.4)	10.2	36.7	53.0

collectively 47.2 % (67,410 ha) experienced wildfire (48.9 % high severity, 41.8 % moderate severity, and 9.3 % low severity). Total disturbance need increased gradually from 1986 to 1999, peaking at 53.1 %, then declined modestly to 51.2 % in 2005, followed by steeper declines between 2006 and 2008 (from 53.1 to 46.8 %) and again between 2013 and 2017 (from 46.6 to 38.6 %) when wildfire activity was greater (Fig. 5b). During these periods of declining disturbance need, the proportion of early development and mid-development open canopy forest increased while mid-development closed canopy forest decreased (Fig. 5c). Specific structural/successional class transitions from 2011 to 2017 show that 67.2 % of area in the wildfire subregion remained in the same class (Fig. 6a; Table A.4), followed by 12.6 % of area transitioning from mid-development closed canopy to mid-development open canopy and 4.0 % mid-development open canopy to early development (Fig. 6a; Table A.4). The subregion also experienced 3.7 % of area that transitioned from mid-development open canopy to mid-development closed canopy forest from 2011 to 2017 (Fig. 6a; Table A.4).

The contrasting subregion experienced minimal wildfire (1.6 % of FRG I forests burned cumulatively since 1986; 800 ha; Fig. 5b). Disturbance only, disturbance followed by growth, and growth only restoration need averaged at 25.2, 38.9, and 7.3 % (Fig. 5b). Long term trends in restoration need remained relatively steady, with slight increases in total disturbance need from 60.6 % in 1986 to 64.9 % in 1999. During this period, the proportion of early development and mid-development open canopy forest decreased, and mid-development closed canopy forest increased (Fig. 5c). From 1999 to 2017, restoration need changed minimally (Fig. 5b). Eighty-three percent of structural/successional classes did not change between 2011 and 2017 (Fig. 6b; Table A.4). However, 5.7 % of area transitioned from mid-development closed canopy to mid-development open canopy forest and 5.5 % transitioned in the opposite direction from mid-development open-canopy to mid-development closed canopy (Fig. 6b; Table A.4).

Both subregions were dominated by mid-development closed canopy

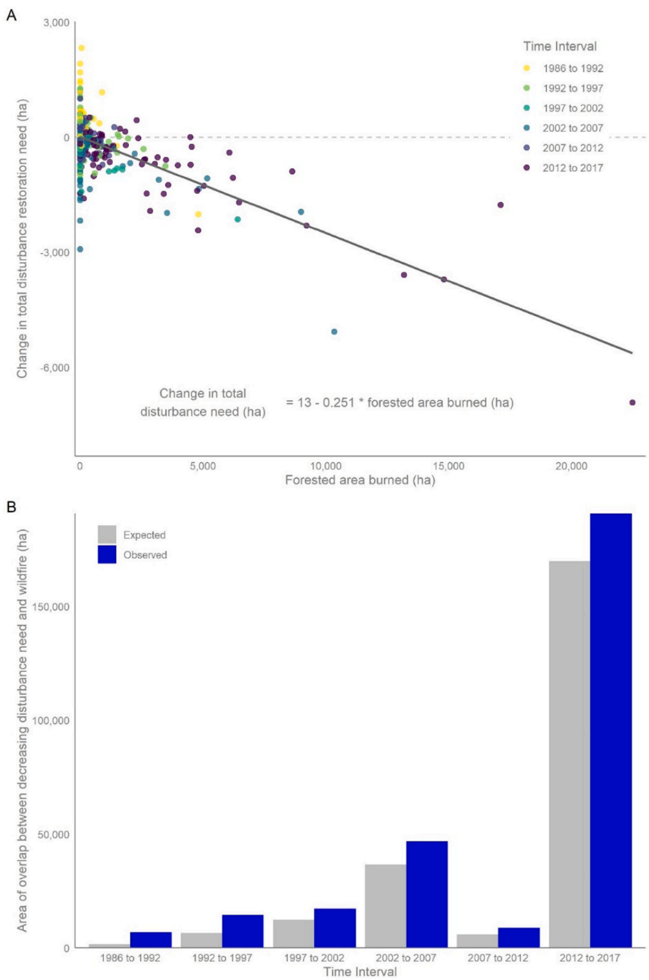

Fig. 4. Wildfire and decreasing disturbance need within fire regime group I- A Change in total disturbance restoration need (i.e., disturbance only + disturbance followed by growth; ha) and forested area burned (ha) within fire regime group (FRG) I forests in the study area. Each point represents a stratum within a time interval (231 stratum, 6 time intervals). A linear regression trendline is plotted over the scatterplot. For analogous figures for other FRGs, see Fig. A.4. **B** Observed versus expected area of overlap between decreasing disturbance need and forested area burned of FRG I forests within time intervals. Observed and expected values were calculated for each FRG I strata, then summed within time intervals.

forest (59.5 % and 75.7 %, with and without wildfire, respectively), followed by mid-development open canopy (23.5 % and 17.0 %), early-development (9.0 % and 2.2 %), late-development closed canopy (6.8 % and 4.7 %), and late-development open canopy (1.3 % and 0.3 %) (Fig. 5c).

4. Discussion

Our findings highlight key insights into the role of contemporary fire activity in achieving forest management needs. First, despite the occurrence of large, record-breaking fire years in recent history at the ecoregional level, broad-scale temporal trends in restoration need were remarkably steady—highlighting the magnitude of the challenges facing management of fire-prone forests. Second, at finer spatial scales, our findings present strong evidence that wildfires can shift landscapes toward their HRV, especially in FRG I (frequent-fire) forests that have experienced > 100 years of fire exclusion followed by large areas burned in recent decades. Third, our findings and approach have broad relevance and implications for guiding management activities, as well as future research applications that could incorporate additional disturbances and their effects on restoration needs/trends in relation to HRV.

4.1. Broad-scale restoration need trends remained steady over time despite increased wildfire activity

At the ecoregion scale (eastern Washington), trends in restoration needs over the last 3 decades did not change substantially despite increasing wildfire activity. Subtle declines in disturbance-only restoration need occurred during periods of increased wildfire activity (2000–2007; 2012–2017), likely driven by declines within FRG I forests (Fig. 3) which account for 52 % of forests within the study area (Table 1) and 53.5 % of cumulative forested area burned from 1986 to 2016 (Table 4). However, fires in forests that did not require disturbance (e.g., in less fire-prone FRGs or within FRG in areas not in need of fire) could offset net decreases in disturbance need at the aggregate scale of the ecoregion and contribute to further departure from reference conditions within strata by facilitating structural/successional class transitions away from the HRV. Loss of scarce forest structural classes to high severity fire (e.g., late-development forests or open-canopy conditions; Haugo et al., 2015; Reilly et al., 2018) could further offset net decreases in disturbance need. In essence, it is likely that the magnitude of disturbance needed across the ecoregion greatly exceeds the amount of area burned in strata that needed that disturbance and where wildfire facilitated structural/successional class transitions towards the HRV. In addition, total aggregate growth and succession in unburned areas may increase disturbance need at the scale of the study area, offsetting the effects of fire decreasing disturbance need elsewhere (Reilly et al., 2018).

The relative stability of landscape restoration need at the aggregate scale has important implications for understanding recent large fire years in the context of broader landscape dynamics. First, these findings suggest a high amount of landscape inertia from over a century of altered fire regimes. For example, fires in 2012–2016 burned > 315,000 ha (8.8 %) of forest in eastern WA, yet only reduced region-wide disturbance-related restoration need by 1.8 %. Such differences between area burned and effects on disturbance need provide important context for tempering expectations by the general public about the extent to which wildfire can actually change landscapes at broad ecoregional scales – even in relatively large fire years. Second, these findings highlight that even though these recent large fire years were remarkable in many ecological and societal dimensions, they are likely only approaching the amount of area burned in many 'normal' years throughout the longer evolutionary and cultural history of dry, historically fire-frequent landscapes. For example, despite recent increases in fire, the fire deficit is still high (Haugo et al. 2019), and so are the corresponding restoration needs. Third, whether or not fires were burning at levels that are uncharacteristically severe for the fire regime where they occurred will affect the direction and speed at which landscape structure is moving closer to, or away from the HRV (WA DNR, 2022, Churchill et al., 2022). Contemporary wildfire in dry, historically fire-frequent forests has been characterized by increasing trends of large and high-severity fire (Haugo et al., 2019). While the ecoregion remains in a high fire deficit in terms of total area burned (Haugo et al., 2019), the characteristics of many contemporary wildfire events (i.e., size and severity) often deviate from historical conditions which has consequences for structural/successional class transitions and corresponding restoration needs. Finally, the cumulative pace and scale of growth and succession occurring outside of burned forests at finer scales likely offsets net decreases in disturbance need at broad, aggregate scales (Reilly et al., 2018).

4.2. Wildfire activity modestly addresses disturbance restoration need within dry, historically fire-frequent forests at intermediate and local scales

In contrast to the aggregate stability in broader landscape trends, our

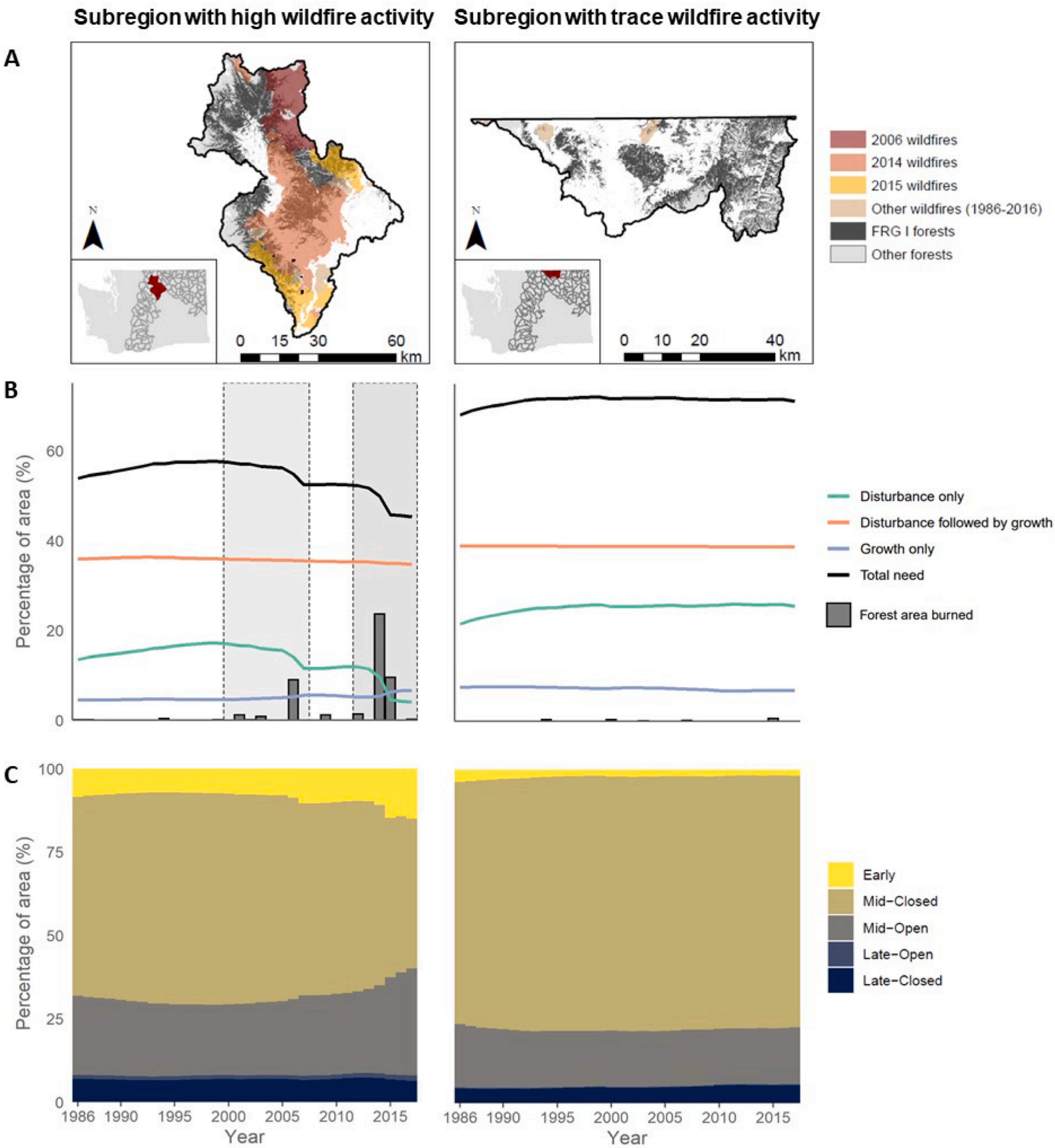

Fig. 5. Fire regime group I subregion case study areas with high and trace wildfire activity- A Maps of the case study subregions (left: subregion with high wildfire activity; right: subregion with trace wildfire activity). **B** Disturbance only, disturbance followed by growth, growth only, and total restoration need from 1986 to 2017 expressed as a percentage of fire regime group (FRG) I forests within each subregion. Grey bars indicate the percentage of FRG I forests that burned annually (1986 – 2016). Dashed boxes indicate periods of declining total restoration need. **C** Annual trends in the relative abundance of each structural/successional class within FRG I forests of each subregion (1986 – 2017).

findings at finer spatial scales suggest that some wildfires are doing a meaningful, though modest amount of ecological restoration 'work' in shifting landscapes back toward the HRV of landscape conditions (North et al., 2021; WA DNR, 2022). Differences in landscape trends among FRGs and between subregions that did and did not experience fire suggest that effects of wildfire with relation to the HRV and restoration needs are a matter of where, when, and what severity fire occurs, and that spatial scale is critical.

Among fire regimes, the greatest reductions in restoration need occurred when fire intersected with locations characterized by historically frequent fire (FRG I). FRG I forests were most departed from reference conditions and were in the greatest need of total disturbance restoration (disturbance only + disturbance followed by growth) need throughout the time period examined, consistent with previous findings (Haugo et al., 2015; DeMeo et al., 2018) and suggesting strong evidence for a fire deficit within historically fire-prone forests (Haugo et al. ,2019). These forests were the only FRG where the observed area of overlap between decreasing disturbance need and wildfire area burned was consistently greater than expected (i.e., evidence for an effect) for every time interval (Fig. 4b; Fig. A.3), suggesting wildfire within these forests is contributing to a reduction in disturbance need and shifting forest structure conditions towards the HRV. Depending on severity, wildfire can reduce disturbance-related need by converting dense, mid-development closed canopy forest either to early development forest (if

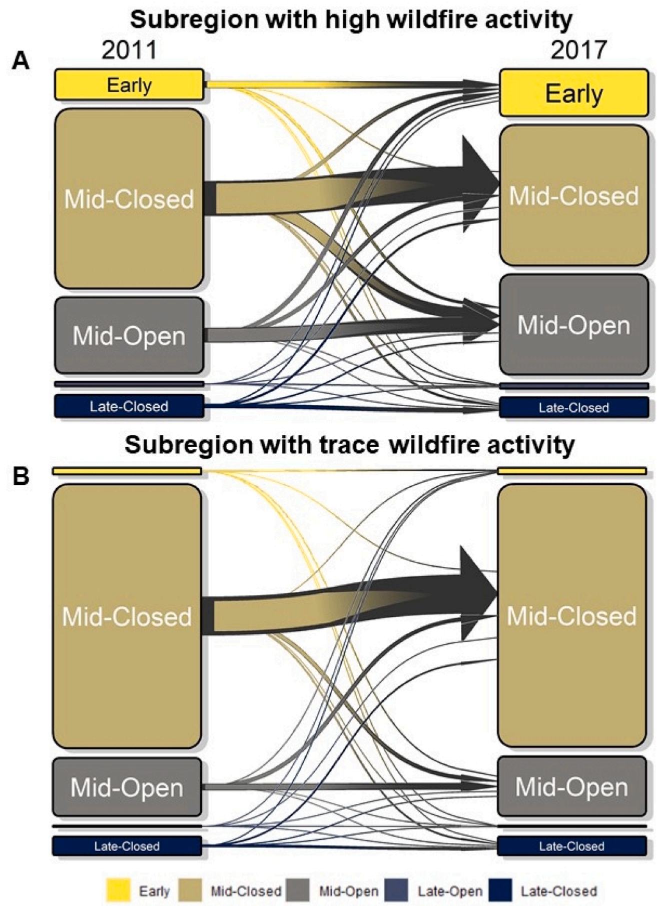

Fig. 6. Structural/successional class transition matrices in subregions with high and trace wildfire activity - Transition matrices showing how structural/successional classes changed from 2011 to 2017 within the case study subregions with high (**A**) and trace (**B**) wildfire activity. The thickness of the arrows is proportional to the amount of area that underwent a specific structural/successional class transition. Structural/successional classes are abbreviated as follows: early development = early; mid-development closed canopy = mid-closed; mid-development open canopy = mid-open; late-development open canopy = late-open; and late-development closed canopy = late-closed.

severe) or to mid-development open canopy forest (if low to mixed severity) (e.g., Kane et al., 2013; Reilly et al., 2018; Fig. 6a). However, even with FRG I showing this trend most consistently and strongest among regimes, declines are modest at the scale of the entire FRG and a substantial amount of disturbance restoration need remains in dry, historically frequent-fire forests. At least some of this divergence from a 1:1 relationship between area burned and decreasing restoration needs is likely due to the greater proportion of high-severity fire (34 %) occurring in FRG I over our study period, relative to the expected levels of 6–9 % high-severity fire under the HRV (Haugo et al., 2019).

At localized scales within the case-study subregion that experienced wildfire, area burned was associated with an overall 27 % (53.1 to 38.6 %) reduction in disturbance restoration need for FRG I forests (Fig. 5b). In contrast, the subregion that experienced trace wildfire did not change substantially throughout the 32-year period (Fig. 5b). Mid-development closed canopy forest was the dominant forest structural/successional class in both subregions (Fig. 5c), reflecting more than a century of fire suppression and exclusion. Within the subregion that experienced wildfire, wildfire facilitated net losses in the overabundant mid-development closed canopy forest and net gains in early development and mid-development open canopy-forest (Fig. 5c; Fig. 6a) which are generally in a deficit within FRG I forests (Haugo et al., 2015; DeMeo et al., 2018)—moving conditions towards the HRV. Late-development forests are also currently scarce and in high deficit within FRG I forests (Haugo et al., 2015; DeMeo et al., 2018), though the relative abundance of late-development forests was not substantially affected by wildfire within the subregion (Fig. 5c). Small amounts of late-development forests were converted to early development (<1 % of the total subregion area; Fig. 6a), reflecting areas that burned at high severity. However, overall, the minimal change in late-development forest suggests they did not burn or burned at low enough severity that changes were undetected by GNN-derived forest structure datasets. From 1986 to 2017, 67,400 ha of forested area burned and total disturbance restoration needs declined by 27.3 %, highlighting that at localized scales, wildfire can restore forest structural conditions primarily through changes in early and mid-development structural classes. This has important implications for land managers, who may consider prioritizing restoration treatments in areas that have recently burned under low and moderate severity to have the greatest impact on restoring localized landscapes to their HRV (Churchill et al., 2022; Larson et al., 2022). Restoration treatments and management could also focus on protecting existing late-development stands or applying treatments that facilitate a trajectory towards open-canopy late development (i.e., gap creation to release growth) to complement structural transitions facilitated by wildfire.

One important dimension of fire and the effect it has on landscape structure that is outside the scope of this study is how burn severity is spatially configured within burned landscapes. Relatively modest contributions of wildfire to declining disturbance restoration need within FRG I forests could be attributed to higher proportions of severe (e.g., >75 % canopy tree mortality caused by fire) fire in contemporary wildfires relative to historical fires (Haugo et al., 2019; Churchill et al., 2022). Large patches of high-severity wildfire produce open early-development conditions and are unlikely to promote late-development open-canopy conditions (Kane et al. 2013)—those that are currently in the greatest deficit within dry forest regions of western North America (Hagmann et al. 2021). High severity wildfire can also convert forest to non-forested shrubland or grassland in areas where climatic conditions are no longer suitable for seedling establishment and survival (Donato et al. 2016; Davis et al. 2019; Coop et al. 2020), which could move conditions further away from the HRV. However, patches of converted forest to non-forest may also break up contiguous patches of closed-canopy forest that can promote heterogeneous conditions in subsequent fires (Churchill et al. 2022; Cansler et al. 2022). Future work that relates the spatial configuration of burn severity (e.g., Cansler and McKenzie 2014; Harvey et al. 2016b; Reilly et al. 2017) to changes in forest structure trajectories and restoration need can contribute valuable dimensions to understanding how stand structures within fires relate to the patch mosaics within the HRV.

Our findings of fire-associated changes in forest structural condition are likely most representative of changes that are occurring at a spatial resolution (i.e., grain) of several hundred square meters to several hectares, and may be a conservative estimate of the effects of wildfire on structural change that incorporates finer grain information. The GNN procedure we used derives forest structure information using a combination of satellite imagery and imputation from forest inventory and analysis (FIA) plots. Data at such resolution (e.g., 0.81 ha for FIA plots or 0.09 ha for Landsat satellite pixels) are more likely to detect coarse-scale changes to forest structure, such as changes caused by severe wildfire (i.e., transitions from forested to open/early-development). Therefore, our approach does not likely register subtle changes to forest structure that occur under the canopy of the tallest tree strata or at a scale finer than the size of FIA plots or Landsat pixels. The discrete, but important work that low and moderate severity wildfire is doing to remove understory biomass and create canopy gaps (e.g., Barros et al. 2018; Cannon et al. 2022) is difficult to detect using GNN inputs and therefore underrepresented in our results. Future work using complementary approaches with photogrammetry or LIDAR to characterize structural changes at a finer scale can improve these challenges (Kane et al. 2019), though such data are limited in their temporal and spatial coverage compared to existing data using moderate resolution satellite data and FIA plots. Finally, GNN-derived structural data are modeled, as opposed to measured, and with any broad-scale regional dataset are likely to contain some background noise in trends associated with inherent uncertainty. As such, we attributed changes of small magnitude (<1%) to background variability as opposed to indicators of meaningful change.

In contrast to FRG I, wildfire did not relate to shifting disturbance needs in other FRGs. FRG III, IV, and V required less overall disturbance restoration relative to FRG I (Fig. 3), reflecting differences in how fire suppression and exclusion has affected forest structure in forests characterized by longer fire return intervals (Table 1). For example, forests within the Northern Rocky Mountain mixed conifer biophysical setting (within FRG III; Table 2) had an excess of both mid-development open and closed canopy forest and large deficits in early development and open and closed-canopy late-development. In this particular biophysical setting, growth only or disturbance followed by growth were needed to facilitate transitions from mid-development to late-development, which is not achieved immediately following fire. High severity fire could have created early development forest, potentially addressing some disturbance need. However, over the study period, it appears that fire mainly reduced mid-development closed canopy and created mid-development open canopy, both of which were in excess. In FRG IV, where the HRV is characterized by infrequent and generally more severe fire, wildfire also had less of an effect on disturbance restoration. FRG IV experienced a steady decline in growth-only restoration need throughout the 2000 s, which overlapped with a large fire year in 2006 and a period of increased insect outbreak (Meigs et al. 2015). Overall loss in mid-development closed canopy forest and an increase in mid-development open canopy forest facilitated the decrease in growth-only restoration, as this type of forest structure transition is associated with growth-only restoration within spruce and fir forests of FRG IV within the Haugo et al. (2015) framework. Differences in the structural/successional transitions needed to move conditions towards the HRV between FRG I and other FRGs reflect differing restoration need contexts and may explain why fire had less effect on shifting disturbance restoration needs within FRG III, IV, and V.

4.3. Management implications and future additions to this approach

Although our findings illustrate that wildfires are accomplishing restoration work associated with managing fire and forest conditions in dry fire-prone forests back toward the HRV, they also demonstrate how far departed from HRV conditions forests remain even after large fire years. A potential reason for this persistent gap between current conditions and the HRV may be the magnitude of growth and succession occurring outside of burned areas within a given year (e.g., Reilly et al. 2018). Wildfires can address disturbance need at fine scales, but the amount of forest across the ecoregion that does not experience fire within a given year greatly exceeds those that do experience wildfire. The magnitude of disturbance related need region-wide highlights the potential benefit of opportunistically managing low-risk wildfire as a restoration tool. For example, in Washington State the amount of low to moderate severity wildfire area burned in 2021 (~93,000 ha) affected as much area as mechanical fuel reduction treatments over the preceding four years from 2017 to 2020 (~85,000 ha; WA DNR, 2022). In a comparable 4-year window, approximately 147,800 ha of total forested area burned from 2017 to 2020 (WA DNR, 2022). Prioritizing fuel reduction treatments in areas where fire has reduced disturbance restoration need and moved forest structure towards the HRV may help efficiently achieve management goals at restoring landscapes to conditions resilient to future fire. In addition, the<1:1 correspondence between wildfire area burned and effects on disturbance restoration needs provides insight into what areas benefit from fire and under what conditions. Our results suggest that wildfire is most effective within FRG I forests where early and mid-development open canopy conditions can be created and mid-development closed canopy can be reduced. Wildfire burning through scarce structural/successional conditions such as late-development forest at moderate to high severity can impede benefits of wildfire to restoring HRV forest structure conditions.

Another potential reason for the persistent gap between current conditions and HRV is that a 'treatment' by a single fire is only a first necessary step in restoring forest conditions to those created by a regime of repeated and frequent fires. The large majority of the burned area in our study burned once, though multiple short-interval reburns have additive, and sometimes compound effects on fuels and forest structure in dry (Larson et al. 2013; Stevens-Rumann and Morgan 2016) and cold (Turner et al. 2019) forests of the U.S. In addition, repeated mechanical or prescribed fire treatments are often needed to sustain the effects of a single treatment (e.g., Kalies and Yocom Kent 2016), as vegetation grows back and fuels continue to accumulate. Different outcomes for whether areas that reburn in a short interval or where fires intersect treatments (or vice versa) produce different outcomes for restoration needs than first-entry fires (i.e., areas that are burning once after nearly a century of fire exclusion) is an important question that has key management implications. Future work could look specifically at taking our approach and examining locations with combinations of recent wildfire, past wildfire, and restoration treatments to see if trends in restoration needs differ.

Future work could test the sensitivity of our approach to examining the effects of other natural disturbances or management actions on landscape structure and restoration needs with regard to HRV. For example, the efficacy of our approach could be tested on ground-truthed fuel reduction treatments across a range of treatment type (e.g., mechanical thinning or prescribed fire), size, intensity, and frequency (i.e., number of repeated treatments). Since the establishment of the Forest Health Strategic Plan in 2017 (i.e., 2017–2021; WA DNR, 2017), the Washington Department of Natural Resources has treated approximately 99,500 footprint ha in eastern Washington across all land ownerships (note: this number is a conservative estimate as not all timber harvest areas have yet been reported; WA DNR, 2021). In this analysis, we did not assess the efficacy of fuel reduction treatments as we did not have reliable data describing the amount or spatial configuration of mechanical treatments at an annual scale prior to 2017. However, we recognize that fuel reduction treatments are an important component to assessing aggregate and long-term restoration needs within our study area, and that some of the structural/successional class transitions and trends in corresponding restoration needs were likely influenced by fuel reduction management efforts during the time period examined. As it is unknown how well our approach can detect more subtle structural changes, future work could address this area of uncertainty. Future research could also examine how well our approach can detect other natural disturbances (e.g., insect outbreaks or pathogens) in addressing restoration need over time. Many native forest insects selectively target certain host species or diameter classes (e.g., bark beetles; Buonanduci et al. 2020; Harvey et al. 2021) which can alter forest composition, structure, and successional dynamics in ways that differ from wildfire disturbance. For example, insect outbreaks often remove the largest diameter individuals or trees with less vigor, creating canopy gaps that may be more likely to produce open-canopy conditions than stand-replacing early development conditions. Alternatively, some pathogens are generalists and can affect multiple species through contagious spread (Worrall et al. 2004; Harvey et al. 2021), resulting in larger swaths of mortality across tree sizes. Differences between the effects of fire and other disturbances on landscape structural conditions as well as the efficacy of this approach to detect a range of gradients in forest disturbance remains an area of important exploration in future study.

Future work can also complement our approach by considering how contemporary forest structure compares to the future range of variability (FRV) in comparison to the HRV. In ecosystems where forest conditions are highly departed from those that conferred resilience to past frequent and low severity fire, restoration toward the HRV via reducing fuels and lowering tree density will likely continue to foster resilience to fire and drought-associated mortality in the future (Prichard and Kennedy 2014; Young et al. 2020). However, future projections of climate and fire activity may not align with historical forest composition (Davis et al. 2019). In such contexts, restoration toward the HRV is likely not as useful as fostering adaptation toward the FRV and embracing uncertainty in future conditions (Schuurman et al. 2022). Further research can build on our approach by integrating a blended approach within landscapes that integrates restoration toward HRV and adaptation toward FRV as locally appropriate across a region. For example, simulation modeling could be used as a tool to test how different composition and stand structure may confer resilience to projected future climate and disturbance activity (Halofsky et al. 2017). Finally, we note a need for other research that integrates structural and compositional changes within forests, and that incorporates transitions among forested and non-forested ecosystems.

5. Conclusion

Our findings show that restoration need has been remarkably steady over three decades across an interior fire-prone dry-forest region. A substantial proportion of forested landscapes region-wide remain in need of disturbance restoration despite increased wildfire activity and fuel reduction treatments. Wildfire modestly addresses disturbance-related restoration need at intermediate and local scales within historically fire-frequent forests, though our results suggest an increased scale and pace of restoration is required to address the magnitude of broad-scale restoration needed. Our study also offers an approach to examining the role of natural disturbances and/or management actions in guiding conditions toward the HRV and addressing restoration need that could be applied in a wide range of applications.

CRediT authorship contribution statement

Madison M. Laughlin: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jonathan D. Bakker:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Derek J. Churchill:** Conceptualization, Funding acquisition, Writing – review & editing. **Matthew J. Gregory:** Data curation, Software, Writing – review & editing. **Tom DeMeo:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Writing – review & editing. **Ernesto C. Alvarado:** Funding acquisition, Writing – review & editing. **Brian J. Harvey:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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