Classification and Assessment of Riparian Ecosystems in Northwest Oregon for Restoration Planning

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Abstract

Riparian ecosystems are a critical ecological component in the Pacific Northwest. Many have been altered by human activities and need restoration. Establishing restoration objectives is daunting because of inherent spatial and temporal variation of geomorphology, disturbance regimes, and vegetation. We developed an analytical framework using geology and climate as the template for natural disturbance processes influencing riparian vegetation in northwest Oregon. We identified three ecoregions with contrasting geology and climate: Coast Range, with dissected topography and rain-dominated hydrology; West Cascades, with dissected topography and rain- and snow-dominated hydrology; and High Cascades, with undulating topography and snow-dominated hydrology. For all three, the most abundant stream reach type was small (< 15 m channel width) with wildfire the predominant natural disturbance. However, reaches affected by geomorphic disturbance were common for the Coast Range and West Cascades. Riparian vegetation dominated by large trees (≥ 51 cm diameter) was underrepresented compared to reference conditions for the Coast Range and West Cascades. Variation between subbasins in departure of current conditions from reference conditions was greatest in the West Cascades and negligible in the High Cascades. Vegetation in the Coast Range has moved in recent decades towards reference conditions. Wildfires since the latest remote-sensing-derived data (2017) may have altered riparian vegetation, affecting departure of current from reference conditions. Since the remote sensing of vegetation continues, it should be possible to assess these effects. Our results support restoration of riparian forests dominated by large trees in the Coast Range and West Cascades. Areas dominated by smaller trees may represent restoration opportunities.

Keywords: natural disturbance, northwest Oregon, restoration, riparian vegetation

Introduction

Riparian forests throughout much of the world have been changed by land use and other human activities (Nilsson and Berggren 2000, Zedler and Kercher 2005). This is particularly true in the Pacific Northwest of the United States, where present-day riparian forests frequently differ in structure and composition from pre-settlement forests (Naiman et al. 2000, Swanson et al. 2011, McIntyre et al. 2015). Up until policy changes beginning in the 1970s, timber harvest in the region was extensive and often extended to the edges of streams (Everest and Reeves 2007, Spies et al. 2018). Following harvest, the riparian zones in many areas were planted with the most commercially valuable conifers, primarily Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), resulting in the development of dense, relatively uniform conifer stands and a decrease in hardwoods (Reeves et al. 2018). In other cases, conifers were not successfully reestablished in areas now dominated by shrubs and hardwoods (Hibbs and Giordano

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1996, Villarin et al. 2009, Wondzell et al. 2012). Additionally, fire suppression has likely altered the structure and composition of riparian vegetation by increasing the density of shade-tolerant conifers and reducing hardwoods and early seral conditions (Spies et al. 2018). Though the consequences of timber harvest in the 20th century on structure and composition of riparian forests in the Pacific Northwest are varied, the current distribution of vegetation conditions is markedly different than conditions that would result from the natural disturbance regimes (Reeves et al. 2018). Because of their ecological importance, riparian areas are a major focus of restoration efforts on public and private lands throughout the region (USDA Forest Service and USDI Bureau of Land Management 1994, Oregon Department of Fish and Wildlife 2016).

Ecological restoration requires a target condition or conditions in order to effectively plan and communicate project goals (Gann et al. 2019). One way to select a target for restoration is to identify a minimally disturbed condition and use it as a reference to which the current condition can be compared. Although intellectually appealing, the selection of reference conditions are fraught with potential biases (Reeves et al. 2018); minimally disturbed areas are often rare and may not represent the historical range of conditions that existed before extensive anthropogenic modification of upland and riparian vegetation. Ideally, reference conditions would be identified in areas with similar potential vegetation and in relatively close proximity, or at least within the same ecoregion, so that the reference provides an appropriate comparison (National Research Council 2000). Because pristine areas may no longer exist in many, if not most ecosystems, the reference-condition approach sometimes has been modified to use "least-disturbed conditions" as a reference (referring to "human disturbance or alteration," Stoddard et al. 2006). But depending on how this approach is applied, it may not include the full range of potential ecosystem conditions, especially in naturally dynamic landscapes where natural disturbance processes have been excluded.

An alternative to reference conditions is to consider the historical variability of ecosystems in the absence of overt human management (Landres et al. 1999, Pollock et al. 2012). One means to address such questions is to apply scientific understanding of species' biology and landscape dynamics in the context of detailed geographic information to describe the inherent potential of different segments of a landscape to produce ecological attributes (e.g., Benda et al. 2007, Burnett et al. 2007). As a consequence of a variety of fluvial and non-fluvial disturbances, as well as geologic and climatic constraints, unmanaged riparian and aquatic ecosystems in the Pacific Northwest are characterized by a high degree of spatial and temporal variability in attributes such as abundance of sediment and large wood, and vegetation structure and composition (Naiman et al. 1992, Reeves et al. 1995). Thus, to appropriately construct reference conditions and interpret results, it is important to understand the climatic, geologic, and biotic factors underlying variability in riparian systems, as well as the ecological functions of different system states.

Vegetation states all along the continuum, from recently disturbed to old-growth forest, promote productivity of aquatic habitats in different ways. Areas with little vegetation permit high levels of solar radiation to reach streams, stimulating primary production and providing nutrient-rich inputs to aquatic food webs (Warren et al. 2016). Areas with riparian vegetation dominated by deciduous tree species contribute nutrient-rich leaf litter and terrestrial invertebrates to streams (Richardson et al. 2005, Leroy and Marks 2006, Wipfli and Baxter 2010, Hart et al. 2013), enhancing aquatic productivity. Large conifers are important sources of durable wood (Harmon et al. 1986) for streams and provide a suite of ecological functions, including influencing channel morphology, flow hydraulics (Wilcox and Wohl 2006, Wilcox et al. 2011), sediment storage (Piégay and Gurnell 1997, Everest and Reeves 2007, Beckman and Wohl 2014, Roni et al. 2015) and transport (Ryan et al. 2014, Wohl and Scott 2017), and habitat diversity (Wondzell and Bisson 2003, Chen et al. 2008). At any one time, different key attributes of riparian ecosystems are present to varying degrees in different locations, largely due to time since disturbance (Reeves et al. 1995). Since coniferous species dominate forests in the Pacific Northwest in the absence of disturbance (Waring and Franklin 1979), the temporal pattern of destruction and renewal of habitat patches by natural disturbance processes (e.g., floods, fire, mass erosion, wind storms) is essential for sustaining the long-term diversity and productivity of riparian and aquatic ecosystems (Reeves et al. 1995, Everest and Reeves 2007, Naiman et al. 2010).

Large-scale patterns of bedrock geology and climate set the template for geomorphic disturbance processes affecting aquatic and riparian habitats (Beechie et al. 2006, Everest and Reeves 2007, Jefferson et al. 2010). Geomorphic processes, in turn, are among the most important drivers of heterogeneity within riparian and aquatic habitats (Montgomery 1999, Beechie et al. 2006). Channel migration is responsible for destruction and creation of floodplain surfaces, and in the Pacific Northwest, is strongly linked to vegetation age and life-form composition (Beechie et al. 2006). Different types of channel patterns (e.g., straight, meandering, braided) differ in their propensity to erode and deposit floodplain surfaces. Debris flows originating in the upslope fringes of channel networks are another important geomorphic process in some landscapes, inasmuch as they can be major sources of large wood and sediment for streams (Montgomery 1999, Everest and Reeves 2007).

In order to provide a consistent approach for developing restoration targets for riparian ecosystems, we have developed an analytical framework for evaluating reference and current conditions of riparian vegetation on forest lands and applied it to northwest Oregon. The scope of our work is the predominantly forested ecoregions of the area (i.e., excluding the Willamette Valley; Omernik and Griffith 2014). Our approach explicitly takes into account the natural disturbance processes that generate variability in space and time. The goal is to provide a transparent, logical pathway for identifying restoration needs and opportunities to inform planning for management of riparian vegetation. In essence, our approach is to apply the concept of historical range and variability (Landres et al. 1999) to riparian vegetation. We use understanding of the spatial distribution of climate, geology, disturbance regimes, and landforms to divide riparian networks into segments with similar potential disturbance and vegetation development characteristics. The classified riparian network forms an appropriate template for evaluating variability of ecosystems in the absence of overt human management, which in turn permits comparison of current conditions to reference conditions and identification of restoration needs.

In this paper we address three questions for forested areas of northwest Oregon across all land ownerships:

1. How do current conditions of riparian vegetation compare to reference conditions?
2. How have the current conditions of riparian vegetation changed over recent time (i.e., the period with remote sensing data from 1986 to 2017)?
3. How does the relationship between current and reference conditions vary spatially (i.e., by the watershed delination subbasin, or 8-digit Hydrologic Unit [US Geological Survey n.d., Seaber et al. 1987])?

Methods

Study Area

We identified differences in geology and climate between and within Level III ecoregions (i.e., areas of broad similarity in biotic and abiotic characteristics relevant to ecosystem management, at the sub-regional scale; Omernik and Griffith 2014) in northwest Oregon, with clear implications for patterns of hydrology, geomorphology, disturbance, and vegetation development (Figure 1; the latter two factors are addressed under Stream Delineation and Classification, below). The geology of the Coast Range, a Level III ecoregion, is dominated by sedimentary rocks, with some areas of volcanic rocks (McCain 2004, Burnett et al. 2007, Omernik and Griffith 2014). The terrain is generally highly dissected (Burnett et al. 2007). Precipitation is mostly in the form of rain; peak stream flows occur in winter due to run-off from storms

(Burnett et al. 2007, Omernik and Griffith 2014). The Level III Cascades ecoregion consists of two parts with distinct differences in geology, climate, and hydrology. The West Cascades are composed of highly weathered tuffs, flows, and other volcanic rocks dating from the Eocene and Miocene (Tague and Grant 2004, Jefferson et al. 2010). The terrain is generally highly dissected (Tague and Grant 2004, Omernik and Griffith 2014). Precipitation is a mix of both rain and snow; peak stream flows occur in the winter due to run-off from storms, including rain events that follow snow accumulation and cause extensive snow melt (Tague and Grant 2004, Cashman et al. 2009, Jefferson et al. 2010). The High Cascades are composed of relatively unweathered flows, cones, and other volcanic rocks dating from the Pleistocene and Holocene (Tague and Grant 2004, Jefferson et al. 2010). Though generally higher in elevation than the West Cascades, the terrain has generally muted relief and very high permeability (Tague and Grant 2004, Omernik and Griffith 2014). Drainage density is notably lower than in the West Cascades, and large springs are common (Tague and Grant 2004). Precipitation is dominated by snow; annual variability in stream flow is muted compared to the West Cascades, with lower winter peaks and higher summer base flows (Tague and Grant 2004, Jefferson et al. 2010, Omernik and Griffith 2014).

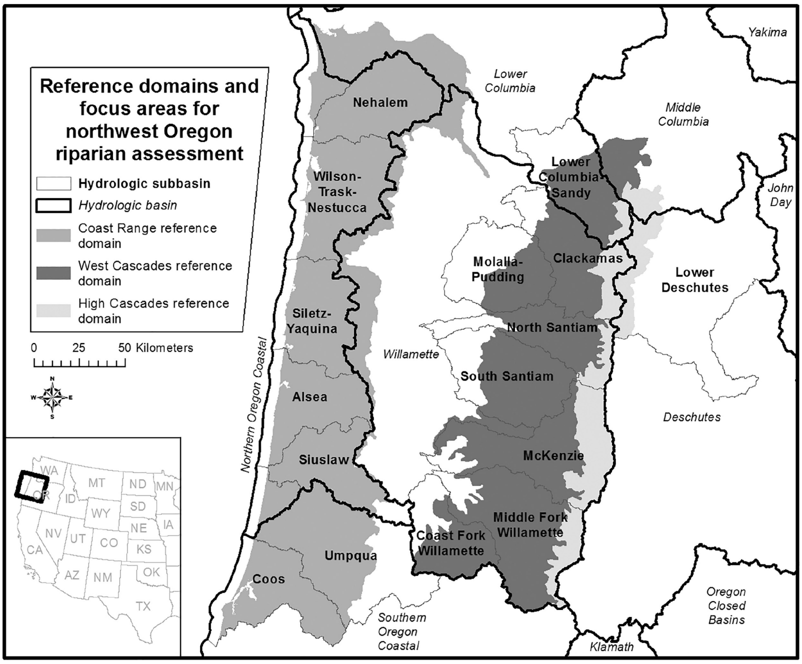

Figure 1. Portions of ecoregions within northwest Oregon (reference domains) used for evaluating reference and current conditions of riparian vegetation and the subbasins (focus areas, labels in bold) comprising the majority of each of the reference domains.

We refer to these three areas as reference domains, to signify that they represent areas within which it is reasonable to seek data to characterize reference conditions, though it is unlikely that the entirety of such an area could be exploited for the purpose, given the ubiquity of human alteration in recent decades.

Within the reference domains, we identified the subbasins comprising the majority of the area (Figure 1; Tables 1, 2, 3). There are 16 subbasins that overlap with the Coast Range reference domain (Table 1). Eight lie completely within the reference domain, and three subbasins have less than a quarter of their area in the reference domain. Individual subbasins account for up to 14% of the area of the reference domain. The seven subbasins that comprise the greatest area (Umpqua, Wilson-Trask-Nestucca, Nehalem, Siletz-Yaquina, Coos, Siuslaw, Alsea) together account for more than three-quarters of the reference domain.

There are 11 subbasins that overlap with the West Cascades reference domain (Table 2). Although none lie completely within the reference domain, seven of the subbasins have at least half of their area in the reference domain. Three subbasins have less than a quarter of their area in the reference domain. Individual subbasins

TABLE 1. Representation of subbasins in the Coast Range reference domain.

Subbasin	8-digit Hydrologic Unit Code[1]	Percentage of subbasin in reference domain	Percentage of reference domain in subbasin
Alsea	17100205	100.0	9.4
Coos	17100304	100.0	9.9
Lower Columbia	17080006	100.0	4.5
Lower Columbia-Clatskanie	17080003	87.7	4.2
Lower Willamette	17090012	29.9	1.7
Middle Willamette	17090007	3.6	0.3
Necanicum	17100201	100.0	1.9
Nehalem	17100202	100.0	11.7
Siletz-Yaquina	17100204	100.0	10.4
Siltcoos	17100207	100.0	1.8
Siuslaw	17100206	88.8	9.4
Tualatin	17090010	18.2	1.8
Umpqua	17100303	65.5	13.6
Upper Willamette	17090003	13.0	3.4
Wilson-Trask-Nestucca	17100203	100.0	13.0
Yamhill	17090008	29.4	3.1

[1] US Geological Survey n.d., Seaber et al. 1987.

TABLE 2. Representation of subbasins in the West Cascades reference domain.

Subbasin	8-digit Hydrologic Unit Code[1]	Percentage of subbasin in reference domain	Percentage of reference domain in subbasin
Clackamas	17090011	63.2	11.1
Coast Fork Willamette	17090002	67.6	8.4
Lower Columbia-Sandy	17080001	53.9	8.8
McKenzie	17090004	59.7	14.9
Middle Columbia-Hood	17070105	10.7	4.3
Middle Fork Willamette	17090001	77.5	19.7
Middle Willamette	17090007	0.6	0.1
Molalla-Pudding	17090009	44.9	7.3
North Santiam	17090005	67.7	9.6
South Santiam	17090006	72.8	14.1
Upper Willamette	17090003	5.6	1.9

[1] US Geological Survey n.d., Seaber et al. 1987.

account for up to 20% of the area of the reference domain. The eight subbasins that comprise the greatest area (Middle Fork Willamette, McKenzie, South Santiam, Clackamas, North Santiam, Lower Columbia-Sandy, Coast Fork Willamette, Molalla-Pudding) together account for more than 90% of the reference domain.

There are seven subbasins that overlap with the High Cascades reference domain (Table 3). The portions of the subbasins within the reference domain are relatively small, ranging from less than one tenth to almost one third of their respective areas. Individual subbasins account for up to 30% of the area of the reference domain. The four subbasins that comprise the greatest area (McKenzie, Lower Deschutes, Middle Fork Willamette, Clackamas) together account for more than 75% of the reference domain.

Stream Delineation and Classification

We took advantage of the compilation of watershed data and analytical tools known as NetMap (Benda et al. 2007) to delineate and describe stream networks by stream reach. NetMap consists of synthetic stream networks generated from and integrated with topographic data using explicitly stated algorithms, subject to some modification by end-users, coupled with an extensive set of analytical tools for computing a host of properties relevant to management, regulatory, and restoration questions (Benda et al. 2007, 2015). As stream networks are calculated in NetMap, attributes are generated for each stream reach to allow application of the analytical tools. In recognition of the need to ground the simulated stream networks from NetMap in field-based information (Benda et al. 2015), we conferred with land-management agency personnel with extensive experience (i.e., hydrologists and fish biologists from the US Forest Service) to assess whether or not the synthetic stream network generated by NetMap appropriately represented the density and location of streams. The consensus was that there were areas where the synthetic network was too dense and others where it was too sparse, but overall it was sufficiently accurate for this analysis, with some modifications necessary for the High Cascades due to the highly permeable geologic surface there.

TABLE 3. Representation of subbasins in the High Cascades reference domain.

Subbasin	8-digit Hydrologic Unit Code[1]	Percentage of subbasin in reference domain	Percentage of reference domain in subbasin
Clackamas	17090011	21.3	13.9
Lower Columbia-Sandy	17080001	8.1	4.9
Lower Deschutes	17070306	12.3	19.7
McKenzie	17090004	32.5	30.3
Middle Columbia-Hood	17070105	5.4	8.1
Middle Fork Willamette	17090001	14.9	14.1
North Santiam	17090005	17.0	9.0

[1] US Geological Survey n.d., Seaber et al. 1987.

We intended our results to pertain to management of forests as opposed to other types of vegetation. To thus constrain and simplify the analysis, we sought to exclude areas without the potential to support forest. For this purpose, we made use of a raster layer of non-forest ecosystem types leveraged in previous work to exclude non-forest ecosystems (Ohmann and Gregory 2002, Davis et al. 2015). In particular, we excluded areas that were identified in this layer as open water, sand dunes, volcanic rock, alpine and subalpine rock, alpine and subalpine dwarf-shrubland, meadow, or dry grassland, and perennial ice or snow.

We used two empirical studies of relationships between stream channels and adjacent landforms in the Pacific Northwest as the starting point for describing the portion of the stream network likely to be subject to fluvial disturbances (Montgomery and Buffington 1997, Beechie et al. 2006). Several authors have described general trends in channel types from headwaters to large rivers, corresponding to decreasing connection to hillslope processes, decreasing stream gradient and bed load, and increasing probability of channel migration and destruction and creation of floodplain surfaces (Montgomery and Buffington 1997, Montgomery 1999, Beechie et al. 2006). To take such patterns into account, we first addressed the distinction between small and large channels, using a channel width of 15 m to define stream reaches with large channels (Beechie et al. 2006). For reaches with large channels, the key characteristic for identifying those subject to fluvial disturbance was the degree of valley constraint (floodplain width divided by channel width); following Beechie et al. (2006), we set a lower limit of four for this ratio to identify unconstrained reaches. For smaller channels, Montgomery and Buffington (1997) defined a range of channel types, distinguishable by gradient, that vary with respect to sediment transport and tendency to affect adjacent landforms. Those most likely to affect streamside landforms (e.g., pool-riffle and dune-ripple types) can be distinguished by a gradient less than 1.5% (Montgomery and Buffington 1997). We used this value to identify reaches with small channels where fluvial disturbance predominates. Due to the generally low temporal variability in streamflow in the High Cascades, and consequent rarity of fluvial disturbance (Tague and Grant 2004, Jefferson et al. 2010), we limited assignment of the fluvial disturbance type for both large and small channels in the High Cascades to two generalized landform types (USDA Forest Service 2013). Based on consultation with local experts (see above), we delineated glacial valley and glacial valley bottom landform associations as areas with the potential for fluvial disturbance in the High Cascades.

In addition to fluvial processes, mass wasting may significantly affect aquatic and riparian habitats in mountainous areas (Nakamura et al. 2000).

Debris flows initiate as shallow landslides on hillslopes and primarily affect small, steep channels at the distal ends of stream networks (Benda 1990, Montgomery 1999, Skaugset et al. 2002, Hassan et al. 2005). Thus, we evaluated small channels with a gradient of at least 1.5% to determine whether or not lithology and local topography indicated debris flows as the predominant disturbance process (Nakamura et al. 2000, May and Gresswell 2004, Jefferson et al. 2010). In the Oregon Coast Range, debris flows are much more common in areas of sedimentary bedrock than igneous bedrock (Massong and Montgomery 2000, Skaugset et al. 2002); channels with a gradient of 20% or higher are the most likely to be scoured to bedrock by debris flows (May and Gresswell 2004). Consequently, for the Coast Range we assigned debris flow as the predominant disturbance process for small channels located in areas of sedimentary bedrock with gradients of at least 20%. In the West Cascades, the bedrock geology favoring debris flows consists of relatively weak and weathered rocks of volcaniclastic origin, especially tuffs and breccias, between 18 and 25 million years old (Swanson and Swanston 1977, Nakamura et al. 2000). Catchments with steep slopes of 58% or more are the most likely to produce landslides leading to debris flows (Snyder 2000). We evaluated bedrock geology (Oregon Department of Geology and Mineral Industries 2015) and catchment steepness on a 1-km fishnet grid across the West Cascades reference domain; small reaches with a gradient $\geq 1.5\%$ (i.e., not subject to fluvial disturbance), and not occurring wholly on earthflows (see below), but with 1-km cells in which at least half the area was characterized by weak geology and steep slopes, were assigned debris flows as the predominant disturbance process.

Earthflows are large, slow-moving mass-wasting events that are common in the West Cascades and impart unique hydrologic characteristics (Swanson and Swanston 1977, Nakamura et al. 2000). Thus, for the West Cascades we recognized as a separate category those small stream reaches which were judged not to be subject to fluvial or debris-flow disturbance but occurred entirely within the confines of an earthflow (as determined from the landslide deposits layer in Oregon Department of Geology and Mineral Industries 2014). Earthflows can also serve to constrain large stream reaches and subsequently deliver large amounts of material (Nakamura et al. 2000). For large, unconstrained reaches (i.e., subject to fluvial disturbance) in the West Cascades, we distinguished reaches downstream of constraining earthflows from reaches downstream of bedrock constraint, given the probability of greater entrainment of sediment and wood in the former (Swanson and Swanston 1977, Grant et al. 1990, Grant and Swanson 1995).

Since fire is a ubiquitous natural disturbance of forests in upland portions of the study area (Agee 1993), we investigated spatial variability of fire regimes for forested portions of northwest Oregon. We exploited the set of results derived from LANDFIRE disturbance and succession models for Oregon and Washington, produced as part of a regional assessment of forest restoration needs (Haugo et al. 2015). We linked these models to the map of potential vegetation from the Integrated Landscape Assessment Project (Oregon Explorer Natural Resource Digital Library 2014, Institute for Natural Resources 2017), and evaluated the presence of various wildfire regimes within the various reference domains. To avoid undue complexity in the analysis, we collapsed the LANDFIRE disturbance and succession models into two generalized fire regimes: stand replacing and mixed severity. Stand-replacing wildfire characterized most of the Coast Range (72%), while the majority of the other two reference domains were characterized by mixed-severity fire (82% for the West Cascades and 66% for the High Cascades). All stream reaches that were not assigned fluvial or geomorphic processes as the predominant disturbance type in the steps described above were assigned one of the two wildfire disturbance types, depending on their location.

Due to profound differences in the ecological significance between coniferous and broad-leaved deciduous tree species (e.g., size and durability of wood for stream channels, abundance and nutrient content of leaf litter), we sought to distinguish areas with and without the potential for deciduous broad-leaved tree species to occur over the course of vegetation development following disturbance. By this we are adding to previous concepts of reach classification (e.g., Grant and Swanson 1995) which focused on abiotic controls such as geology, landforms, stream discharge, and stream gradient. We employed information from various publications (DeBell 1990, Harrington 1990, Minore and Zasada 1990, Diaz and Mellen 1996, McCain 2004) and data from a systematic grid of forest inventory plots (Forest Inventory and Analysis Database 2015) to determine whether or not the distribution of three key deciduous trees species (*Acer macrophyllum* Pursh, *Alnus rubra* Bong., and *Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw) was associated with elevation. Two of the three species were common below 305 m and rare or absent above 1,067 m, so we selected the latter elevation as the upper limit for potential importance of deciduous, broad-leaved tree species. It should be noted that the assessment of the elevation range within which deciduous, broad-leaved tree species are likely to be an important component of riparian vegetation did not affect detection of vegetation patches with such species (see "Characterizing Riparian Vegetation" below). Thus, our approach does not preclude detection of riparian vegetation at higher elevations with deciduous, broad-leaved tree species, such as *Alnus incana* (L.) Moench ssp. *tenuifolia* (Nutt.) Breitung (Diaz and Mellen 1996).

Combining the categories of channel size (large, small), predominant disturbance (fluvial, debris flow, earthflow, mixed-severity fire, stand-replacing fire), and hardwood potential (yes, no), resulted in 8 reach types for the Coast Range, 17 types for the West Cascades, and 12 types for the High Cascades. The relative paucity of reach types for the Coast Range is mostly due to the limited area above 1,067 m elevation.

Riparian Delineation

We sought to define the area within which to evaluate riparian vegetation on the basis of ecosystem processes such as sediment scouring and deposition, and wood delivery to channels. We used the riparian zone delineation tool from NetMap, taking advantage of the floodplain delineation and wood recruitment zone functions. Parameters were 2.0 multiples of bankfull depth (i.e., area inundated at this stream stage), no limit to floodplain extent for the floodplain function, and one site potential tree height using values from Forest Ecosystem Management Assessment Team (1993) for the wood recruitment function (76 m for Coast Range; 52 m for West Cascades and High Cascades). The riparian zone delineation tool evaluates the width returned from both functions for each side of each reach and returns the larger of the two values.

Identification of Reference Reaches

We used geographic information delineating wilderness and roadless areas as the first step in identifying stream reaches with minimal management influences for calculation of reference conditions. Land in these designations is common in the High Cascades but not in the other two reference domains. For the other two domains, we also included Areas of Critical Environmental Concern, Research Natural Areas, and other natural areas on federally managed land. We included state parks and municipal watersheds for those cases in which management plans indicated minimal manipulation in recent decades. Similarly, we included Forest Park in the City of Portland (within the Coast Range reference domain). Finally, we added the Franklin and Harvey Creek areas in the Smith River drainage to the set of unmanaged areas for the Coast Range reference domain (see Reeves et al. 1995). The proportion of unmanaged area ranged from 3% for the Coast Range, to 19% for the West Cascades, and 49% for the High Cascades.

Characterizing Riparian Vegetation

Due to the extensive area over which current vegetation conditions are assessed, and the need for as large a sample size as possible to capture variability in reference conditions, we required a detailed, digital vegetation dataset covering the entire study area. These requirements were best met by a combination of remote imagery and existing plot data. The gradient nearest neighbor imputation method (GNN) is one approach which combines both, as well as environmental data

(Ohmann and Gregory 2002). GNN has been used to characterize current land cover in riparian areas in northwest Oregon (Burnett et al. 2007). As with any depiction of vegetation based on remote sensing, interpretation is most appropriate at spatial scales much larger than individual pixels (e.g., 30 × 30 m for GNN; Ohmann et al. 2014). Recently, GNN has been extended to the interval of collection of Landsat remote sensing data (Bell et al. 2021), allowing us to examine annual data from 1986 to 2017.

We took advantage of the VEGCLASS field from GNN, which describes vegetation states using a combination of canopy cover of live trees, the proportion of tree basal area consisting of hardwood species, and the quadratic mean diameter of dominant and codominant trees (Ohmann et al. 2014). To simplify the analysis while still maintaining functionally important distinctions between vegetation states, we collapsed the original 11 values for VEGCLASS into six: 1) sparse (canopy cover < 10%); 2) open (canopy cover ≥ 10% and < 40 %); 3) broad-leaf (canopy cover ≥ 40%, proportion of basal area in hardwoods ≥ 0.65); 4) sapling/pole (canopy cover ≥ 40%, proportion of basal area in hardwoods < 0.65, quadratic mean diameter of dominant and codominant trees < 25 cm); 5) small/medium (canopy cover ≥ 40%, proportion of basal area in hardwoods < 0.65, quadratic mean diameter of dominant and codominant trees ≥ 25 cm and < 51 cm); and 6) large/giant (canopy cover ≥ 40%, proportion of basal area in hardwoods < 0.65, quadratic mean diameter of dominant and codominant trees ≥ 51 cm).

To estimate reference conditions within a reference domain, we computed the percentage representation of each of the collapsed VEGCLASS states within each of the delineated riparian zones within unmanaged areas, using the entire time series of annual data from 1986 to 2017. For the central tendencies, we computed the average percent of each vegetation state within each reach type. To estimate variability around the central tendencies, we bootstrapped the vegetation state data by reach type, calculated mean values using 1,000 iterations of random sampling with replacement (first by reach, then by year within reach) (Crawley 2007), and examined the distributions of the bootstrapped means (box-and-whisker diagrams). For current conditions, we computed the percentage representation of each vegetation state within entire reference domains or subbasins by reach type, allowing comparison with reference results from unmanaged areas.

In comparing current conditions to reference conditions by reference domain, we focused on underrepresentation of vegetation states, inasmuch as we consider that the full range of variation in vegetation conditions contributes to productivity and diversity of aquatic and riparian systems. Thus, it seems likely that a paucity of a particular vegetation state relative to reference conditions is more likely to contribute to loss of ecosystem function than an excess of a vegetation state. That said, combinations of reference domain and reach type that are markedly in excess of reference conditions were also of interest, as they may represent appropriate situations to apply restoration treatments.

In assessing variation between subbasins in the relationship of current conditions to reference conditions, we similarly focused on underrepresentation of vegetation states for particular combinations of subbasin and reach type. In recognition of the presumed inherent variability of these systems, we used the lower quartile of the reference conditions as the threshold for identifying departure of current conditions from reference conditions. We weighted departures for each combination of reach type and vegetation category within a subbasin by the prevalence of the reach type within the subbasin. We then summed these individual components of departure for each subbasin, referring to the sum as the index of departure. The index can vary from zero (no departure from reference conditions) to slightly less than 100 (i.e., all vegetation currently in least-common category for reference conditions). We limited the analysis to the subbasins that accounted for the greatest area within each reference domain, as described above.

We used R for data analysis and graphics (R Core Team 2020).

TABLE 4. Most abundant reach types across the three reference domains. Included are all reach types that were among the three most abundant in any one of the reference domains. All reach types presented here are characterized as small channel size.

Natural disturbance regime	Hardwood potential	Percent of reaches		
		Coast Range	West Cascades	High Cascades
Debris flow	Yes	19.2	4.2	n/a
Earthflow	Yes	n/a	13.5	n/a
Mixed-severity fire	Yes	15.0	45.0	18.7
Mixed-severity fire	No	0.0	9.2	44.7
Stand-replacing fire	Yes	52.2	18.1	1.3
Stand-replacing fire	No	n/a	1.6	28.4

Results

Predominant Reach Types by Reference Domain

All of the reach types that were among the three most abundant for any reference domain represented small channels (Table 4). For all three reference domains, the most abundant reach type had wildfire as the predominant natural disturbance process (stand-replacing fire for the Coast Range; mixed-severity fire for the other two reference domains). However, reaches predominantly affected by geomorphic disturbance were among the three most abundant for both the Coast Range (debris flow) and the West Cascades (earthflow).

Comparison of Current Conditions to Reference Conditions by Reference Domain

Riparian vegetation dominated by the largest trees was mostly underrepresented across the study area (Figures 2, 3, 4). This was the case in all of the common reach types in the Coast Range and West Cascades reference domains, and one of the three common reach types in the High Cascades (Figures 4A, 4B) reference domain. Riparian vegetation with a significant component of broad-leaved, deciduous trees was underrepresented in 3 of the 11 common reach types across the study area, two of them in the Coast Range reference domain (Figures 2B, 2C, 4B). However, only for small channels with mixed-severity fire regime and hardwood potential in the Coast Range reference domain was the difference more than 10% (Figure 2C). Riparian vegetation dominated by small and medium-sized trees was underrepresented in two of the three reach types in the High Cascades reference domain, but nowhere else. Sparse vegetation was underrepresented on one reach type (Figure 2D) in the Coast Range reference domain.

Riparian vegetation dominated by saplings and pole-sized trees was overrepresented in all the common reach types across the study area (Figures 2, 3, 4). Both riparian vegetation dominated by small and medium-sized trees and sparsely-covered areas were overrepresented in 9 of the 11 common reach types. Open conditions were overrepresented in 6 of the reach types, while riparian vegetation dominated by the largest trees was overrepresented on 2 reach types in the High Cascades, and nowhere else.

Changes over Time (1986 to 2017) of Riparian Vegetation Conditions by Reference Domain

For riparian vegetation in both the Coast Range and West Cascades reference domains, there was a nearly consistent decline in the area dominated by saplings and pole-sized trees between 1986 and 2017, along with other similarities and differences between the two areas (Figures 5, 6). Change was more muted and less consistent in the High Cascades reference domain (Figure 7).

The strongest pattern of change in the Coast Range reference domain was the decline in area dominated by saplings and pole-sized trees by roughly 50% on all four common reach types (Figure 5). There were smaller, though consistent, increases in area dominated by both small and medium-sized trees and by the largest trees. The broad-leaf category increased on three of four reach

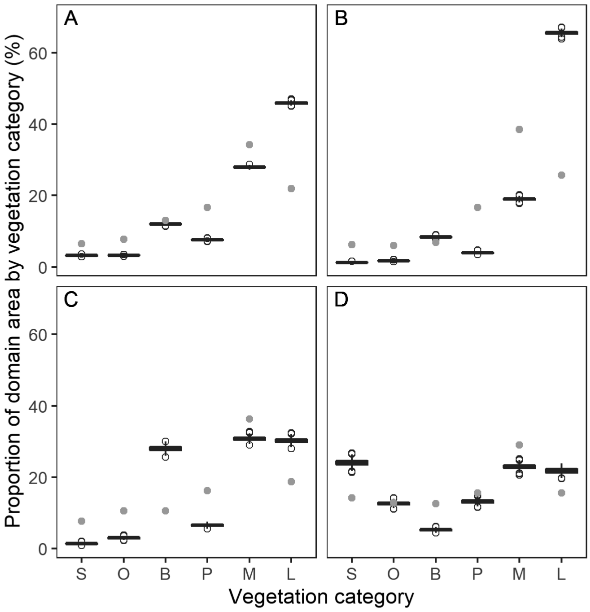

Figure 2. Comparison of current conditions of riparian vegetation (gray circles) to range of reference conditions for the Coast Range reference domain (box-and-whisker diagrams), for the four most common reach types: A) small channels with stand-replacing fire regime and hardwood potential (52% of reaches in the reference domain); B) small channels with debris flow disturbance and hardwood potential (19% of reaches in the reference domain); C) small channels with mixed-severity fire regime and hardwood potential (15% of reaches in the reference domain); and D) small channels with fluvial disturbance and hardwood potential (9% of reaches in the reference domain). The thinner vertical lines (whiskers) represent the most extreme data points which are no more than 1.5 times the interquartile range. Individual values beyond the whiskers are represented by open circles. Note that the horizontal facets of the boxes, representing the 25th percentile, median, and 75th percentile, are so close in value that they appear as a single horizontal line in most cases. Vegetation categories are: S—Sparse (canopy cover < 10%); O—Open (canopy cover ≥ 10% and < 40%); B—Broad-leaf (canopy cover ≥ 40%, proportion of basal area in hardwoods ≥ 0.65); P—Sapling/pole (canopy cover ≥ 40%, proportion of basal area in hardwoods < 0.65, quadratic mean diameter of dominant and codominant trees < 25 cm); M—Small/medium (canopy cover ≥ 40%, proportion of basal area in hardwoods < 0.65, quadratic mean diameter of dominant and codominant trees ≥ 25 cm and < 51 cm); L—Large/giant (canopy cover ≥ 40%, proportion of basal area in hardwoods < 0.65, quadratic mean diameter of dominant and codominant trees ≥ 51 cm).

types, while the open category decreased on three of four reach types.

The area dominated by saplings and pole-sized trees also decreased on the three most common reach types in the West Cascades reference domain, though the decline was smaller than in the Coast Range (Figure 6). Also, a similar trend was the consistent increase in the area dominated by small and medium-sized trees and the consistent decrease in the area occupied by open conditions in the West Cascades and Coast Range. Unlike the Coast Range, change in the area occupied by the largest trees was minimal and variable in the West Cascades (Figure 6).

For the three common reach types in the High Cascades reference domain, most vegetation categories changed little between 1986 and 2017; the changes that did occur were not consistent across reach types (Figure 7). Area occupied by the sparse category increased for small channels within the stand-replacing fire regime lacking hardwood potential (Figure 7B), and decreased for small channels within the mixed-severity fire regime with hardwood potential (Figure 7C). Changes in area dominated by small and medium-sized trees were reversed, decreasing for small channels within the stand-replacing fire regime lacking hardwood potential (Figure 7B), and increasing for small channels within the mixed-severity fire regime with hardwood potential (Figure 7C).

Comparison of Current Conditions to Reference Conditions by Subbasin

Coast Range Reference Domain—The seven subbasins that comprise the majority of the Coast Range reference domain varied with respect to how closely current conditions of riparian vegetation in 2017 approximated reference conditions (Figure 8). The Alsea subbasin most closely approached reference conditions, while the Siletz-Yaquina, Coos, and Umpqua subbasins represented the largest departures from reference conditions in the reference domain.

Most of the large departures for combinations of subbasin, reach type, and vegetation category for the largest subbasins represented a lack of vegetation dominated by the largest trees (20 of 37 cases; data not shown). For all seven subbasins, the largest individual component represented a lack of vegetation dominated by the largest trees. There were also many cases representing a lack of the broad-leaf category (12 of 37 cases). There was at least one instance of a lack of the broad-leaf category for each of the seven largest subbasins.

The only other vegetation category included in these larger individual components was the sparse category. All of the notable departures for the sparse category were for channels with fluvial disturbance (small channels for four subbasins, large channels for one subbasin).

West Cascades Reference Domain—There was marked variation among the eight subbasins that comprised the majority of the West Cascades reference domain. The Lower Columbia-Sandy subbasin most closely approached reference conditions, while the Coast Fork Willamette, Molalla-Pudding, and South Santiam subbasins represented the largest departures from reference conditions in the reference domain (Figure 8).

All of the large departures for combinations of subbasin, reach type, and vegetation category for the largest subbasins represented a lack of vegetation dominated by the largest trees (data not shown). For all eight subbasins, there was a large deficit of vegetation dominated by the largest trees for both small channels within the mixed-severity fire regime with hardwood potential and small channels within the stand-replacing fire regime with hardwood potential. For seven of the subbasins, there was also a large deficit for small channels on earthflows with hardwood potential. For all eight subbasins, the deficit for small channels within the mixed-severity fire regime with hardwood potential made the largest contribution to the overall departure.

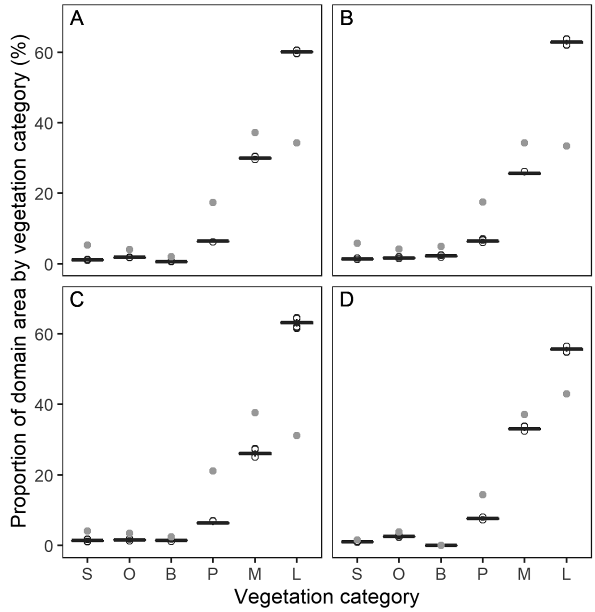

Figure 3. Comparison of current conditions of riparian vegetation (gray circles) to range of reference conditions for the West Cascades reference domain (box-and-whisker diagrams), for the four most common reach types: A) small channels within the mixed-severity fire regime with hardwood potential (45% of reaches in the reference domain); B) small channels within the stand-replacing fire regime with hardwood potential (18% of reaches in the reference domain); C) small channels on earthflows with hardwood potential (14% of reaches in the reference domain); and D) small channels within the mixed-severity fire regime lacking hardwood potential (9% of reaches in the reference domain). The thinner vertical lines (whiskers) represent the most extreme data points which are no more than 1.5 times the interquartile range. Individual values beyond the whiskers are represented by open circles. Note that the horizontal facets of the boxes, representing the 25th percentile, median, and 75th percentile, are so close in value that they appear as a single horizontal line in most cases. Vegetation categories identified as S–sparse, O–open, B–broad-leaf, P–sapling/pole, M–small/medium, L–large; see Figure 2 caption for detailed definitions of vegetation categories.

High Cascades Reference Domain—There was minimal variation in departure from reference conditions among the four subbasins that comprised the majority of the High Cascades reference domain (Figure 8). All four subbasins had relatively low values of the index compared to the other reference domains, with the lowest values in the McKenzie and Middle Fork Willamette subbasins.

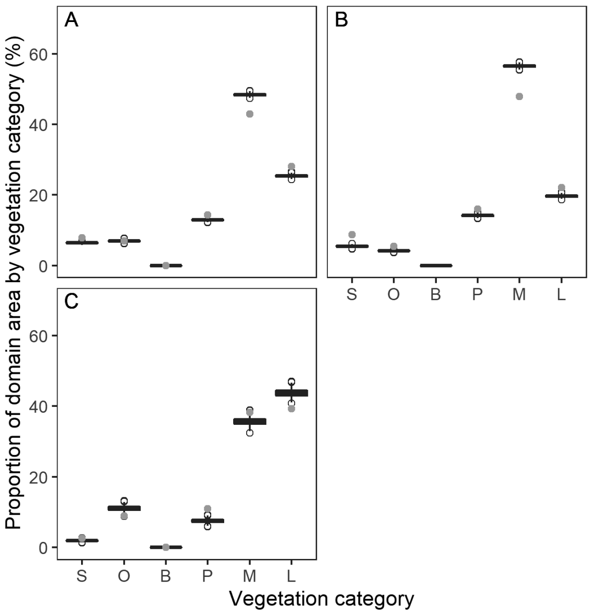

Figure 4. Comparison of current conditions of riparian vegetation (gray circles) to range of reference conditions for the High Cascades reference domain (box-and-whisker diagrams), for the three most common reach types: A) small channels within the mixed-severity fire regime lacking hardwood potential (45% of reaches in the reference domain); B) small channels within the stand-replacing fire regime lacking hardwood potential (28% of reaches in the reference domain); C) small channels within the mixed-severity fire regime with hardwood potential (19% of reaches in the reference domain). The thinner vertical lines (whiskers) represent the most extreme data points which are no more than 1.5 times the interquartile range. Individual values beyond the whiskers are represented by open circles. Note that the horizontal facets of the boxes, representing the 25th percentile, median, and 75th percentile, are so close in value that they appear as a single horizontal line in most cases. Vegetation categories identified as S–sparse, O–open, B–broad-leaf, P–sapling/pole, M–small/medium, L–large; see Figure 2 caption for detailed definitions of vegetation categories.

For the four subbasins that comprised the majority of the reference domain, over half of the large departures for combinations of subbasin, reach type, and vegetation category represented a lack of area dominated by small and medium-sized trees (data not shown). There were three cases of large deficits of the open category and two cases of large deficits of vegetation dominated by the largest trees. Large deficits of area dominated by small and medium-sized trees occurred in all four subbasins.

Discussion

Assessment of Restoration Needs

The results from this new analytical approach suggest that the clearest need for restoration of riparian vegetation across northwest Oregon is to increase the area occupied by forests dominated by the largest trees. This was especially true for the Coast Range and West Cascades reference domains and was evident for all the largest subbasins in both reference domains. There was a consistent and considerable increase in the area occupied by forests dominated by the largest trees in the Coast Range reference domain between 1986 and 2017; increases in the West Cascades reference domain were smaller and less consistent. Presumably, this is due in part to the greater productivity of the Coast Range (Van Tuyl et al. 2005). Differences in disturbance (both historical and recent) due to wildfire and timber harvest are also likely to have played a role. For example, Davis et al. (2015) note that the prevalence of older forests in the Oregon Coast Range has been increasing in areas not subject to timber harvest in recent decades, due to growth following extensive wildfires between the mid-1800s and the early 1900s. By contrast, older forest area declined on federal land in the Oregon West Cascades, coinciding with recent, large wildfires (Davis et al. 2015). Davis et al. (2015) also note that the decline in older forest in recent decades has been greater on non-federal lands (where most loss is attributed to timber harvest) as opposed to federal lands. However, analysis of the relationships between land ownership and status of riparian vegetation in northwest Oregon is beyond the scope of this study. Given that riparian forests across much of the region appear to be depauperate in large-diameter trees, our results imply that management aimed at retaining large-diameter trees and making those trees more resilient to

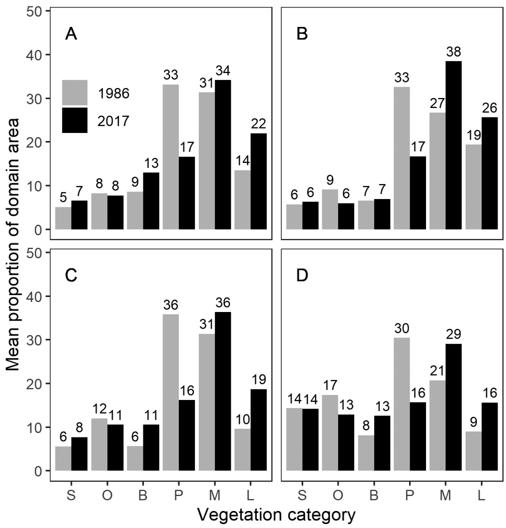

Figure 5. Comparison of conditions of riparian vegetation in 1986 (gray bars) to conditions in 2017 (black bars) for the Coast Range reference domain, for the four most common reach types: A) small channels with stand-replacing fire regime and hardwood potential; B) small channels with debris flow disturbance and hardwood potential; C) small channels with mixed-severity fire regime and hardwood potential; and D) small channels with fluvial disturbance and hardwood potential. Numbers above each bar are the mean values for the indicated combination of reach type, year, and vegetation category, rounded to integers. Vegetation categories identified as S–sparse, O–open, B–broad-leaf, P–sapling/pole, M–small/medium, L–large; see Figure 2 caption for detailed definitions of vegetation categories.

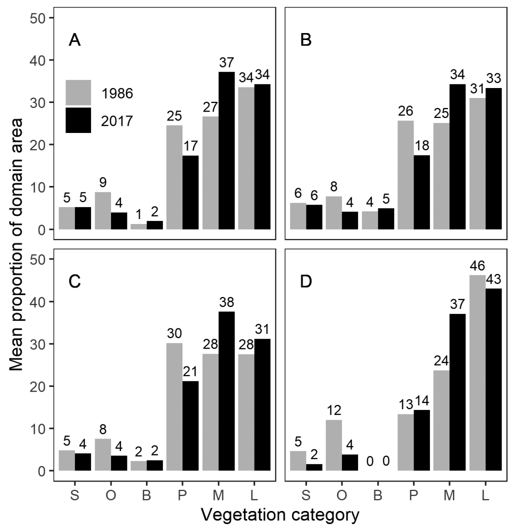

Figure 6. Comparison of conditions of riparian vegetation in 1986 (gray bars) to conditions in 2017 (black bars) for the West Cascades reference domain for the four most common reach types: A) small channels within the mixed-severity fire regime with hardwood potential; B) small channels within the stand-replacing fire regime with hardwood potential; C) small channels on earthflows with hardwood potential; and D) small channels within the mixed-severity fire regime lacking hardwood potential. Numbers above each bar are the mean values for the indicated combination of reach type, year, and vegetation category, rounded to integers. Vegetation categories identified as S–sparse, O–open, B–broad-leaf, P–sapling/pole, M–small/medium, L–large; see Figure 2 caption for detailed definitions of vegetation categories.

stresses such as drought and pathogens may be a component of an effective restoration strategy.

There were also two common reach types in the Coast Range reference domain, and one in the High Cascades reference domain, in which there was currently a dearth of riparian vegetation with a significant component of broad-leaved, deciduous trees compared to reference conditions. There was a large deficit of riparian vegetation with broad-leaved, deciduous trees for all the largest subbasins in the Coast Range. The deficit in the High Cascades reference domain is less noteworthy, given that the representation of riparian vegetation with broad-leaved, deciduous trees is quite minimal under reference conditions. Riparian vegetation with broad-leaved, deciduous trees increased between 1986 and 2017 on three of four reach types in the Coast Range reference domain. These results suggest that restoration activities aimed at increasing broad-leaved tree components in riparian forest could continue to move vegetation towards reference conditions in the Coast Range.

Three categories of vegetation were currently overrepresented compared to reference conditions on all or most of the common reach types in the three reference domains: vegetation dominated by trees of sapling and pole size; vegetation dominated by trees of small and medium size; and sparsely vegetated areas. The former two presumably are a consequence of timber harvest and re-planting; sparsely vegetated areas presumably result from

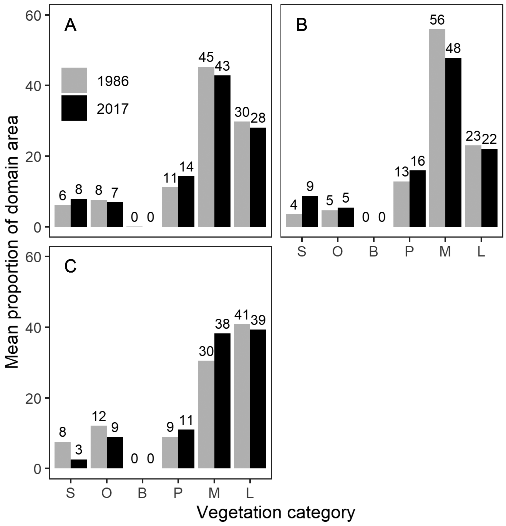

Figure 7. Comparison of conditions of riparian vegetation in 1986 (gray bars) to conditions in 2017 (black bars) for the High Cascades reference domain for the three most common reach types: A) small channels within the mixed-severity fire regime lacking hardwood potential; B) small channels within the stand-replacing fire regime lacking hardwood potential; C) small channels within the mixed-severity fire regime with hardwood potential. Numbers above each bar are the mean values for the indicated combination of reach type, year, and vegetation category, rounded to integers. Vegetation categories identified as S–sparse, O–open, B–broad-leaf, P–sapling/pole, M–small/medium, L–large; see Figure 2 caption for detailed definitions of vegetation categories.

current and/or chronic disturbance. These areas may represent opportunities to apply vegetation treatments such as variable-density thinning (Anderson and Ronnenberg 2013) to promote development of stands dominated by larger trees, as well as more complex stands with vigorous understory trees (Gould and Harrington 2013).

Our results show that differences between the three reference domains with respect to climate and geology are reflected in different arrays of reach types and differences in relative abundance of the types that are common to all three. In addition, there are similarities (especially between the Coast Range and the West Cascades) and differences between the reference domains with respect to which aspects of current riparian vegetation are most dissimilar to reference conditions inferred from unmanaged areas. Examination of departures from reference conditions by subbasin illustrates both spatial variability of the degree of departure and consistency in the types of departure for both the Coast Range and the West Cascades reference domains. This step also revealed that departure from reference conditions in the High Cascades reference domain is much less pronounced and consistent than in the other two areas.

Alternative Sources of Reference Information

Our estimation of reference conditions for riparian vegetation in northwest Oregon relied on a space-for-time substitution, one of several methods put forward for this essential task by Keane et al. (2009). Simulation models incorporating processes of disturbance and succession are one potential alternative (Keane et al. 2009). Comparison to results from models that address broad landscape patterns (e.g., Wimberley 2002) could suggest whether or not the distribution of vegetation states under reference conditions is reasonable, especially for reach types with wildfire as the predominant disturbance. It may also be possible to develop more fine-scaled, state-and-transition models to explicitly include fluvial and other geomorphic disturbance processes (e.g., Wondzell et al. 2012).

Another potential source of reference information is imagery representing earlier time periods. The most robust such datasets would span long time intervals but are rarely available (Keane et al. 2009). However, interpretation of the earliest aerial imagery, with appropriate caveats for human interventions that may have occurred prior to the date of the imagery, has proved useful (e.g., Kennedy and Spies 2004, Hessburg et al. 2007).

It is also worth noting that the study of disturbance regimes continues to be an active area of research (e.g., Spies et al. 2018, Wohl 2020). Incorporating the most current information on geographic distribution of disturbance regimes will be important for any future applications of our approach. However, we suspect that applying the map of wildfire regimes developed by Spies et al. (2018) would not be likely to substantially alter our results, since we evaluated processes related to fluvial and geomorphic processes first.

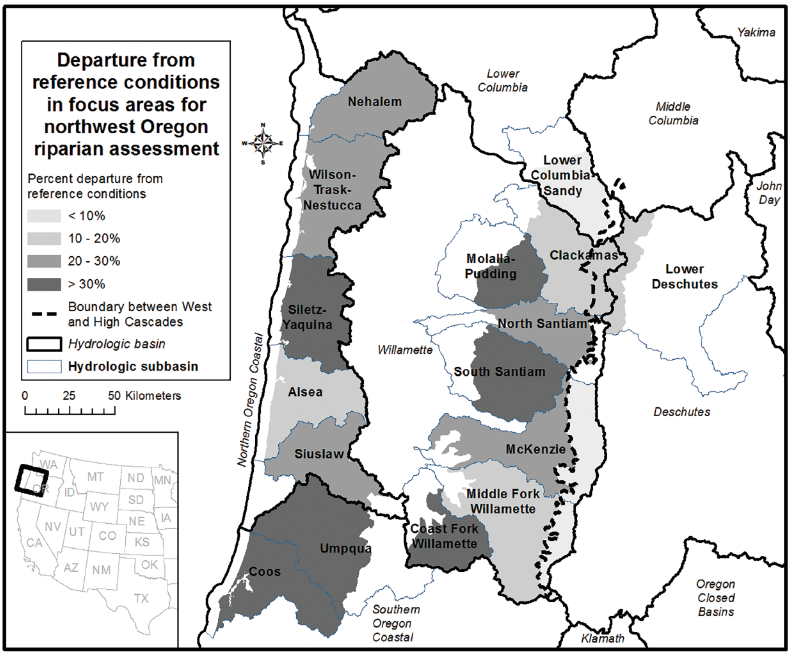

Figure 8. Departure of current conditions (2017) from reference conditions of riparian vegetation for the subbasins comprising the majority of each of the reference domains.

Caveats in Application of Historical Range and Variability

In interpreting these results, or any application of the historical range and variability concept, it is necessary to maintain a critical perspective towards the information exploited to characterize reference conditions (Keane et al. 2009). Understanding the natural range of variability for an ecosystem is often difficult, owing to the extent and magnitude of anthropogenic effects (National Research Council 2000, Stoddard et al. 2006, Steel et al. 2016). Although anthropogenic effects such as alteration of disturbance regimes may be most apparent in drier forests where frequent disturbance formerly prevailed, the Pacific Northwest moist coniferous forest region has been profoundly transformed by timber harvest, fire suppression, and other management activities (Spies et al. 2018).

Regional fire regimes have varied markedly from century to century in the last millennium, due to both climate and societal factors (Weisberg and Swanson 2003). The decades leading up to the early 20th century were characterized by extensive burning in the Pacific Northwest, associated with Euro-American settlement of the region (Weisberg and Swanson 2003). For most of the 20th century, fire suppression appears to have decreased wildfire occurrence in this area, with the likely effect of reducing heterogeneity of vegetation conditions (Reilly et al. 2018, Spies et al. 2018). The increased incidence of wildfire in recent decades is also likely to have left some mark on the areas we used for reference conditions, especially in the High Cascades (Reilly et al. 2017, 2018). In addition, some areas included in the set of unmanaged areas may have a history of timber harvest prior to being placed in protected status. There is clearly a variety of legacies of temporal variability in disturbance patterns that affect areas we considered as unmanaged. These legacies cannot be removed, but are mitigated to some extent due to the large areas used to search for reference conditions. The alternative sources of reference information described above would provide valuable, complementary perspectives.

A key consideration in development of reference distributions is including the entire natural range of conditions that an ecosystem can experience (National Research Council 2000, Stoddard et al. 2006, Lisle et al. 2007). It is noteworthy that our results include rather narrow ranges of variability in the abundance of particular vegetation states under reference conditions for the various combinations of reference domain and reach type. Evidently, this is a consequence of our decision to estimate variability of mean values in the boot-strapping process, though it may also reflect the relatively limited occurrence of wildfire during the period of availability of remote-sensing data (1986 to 2017). Such a paucity of wildfire over several decades is not surprising, given that wildfire regimes in the study area most commonly feature return intervals of one to several centuries (Spies et al. 2018). An alternative would be to estimate means of measures of variability (e.g., interquartile ranges) through boot strapping. Such an approach might provide a more useful depiction of variation in reference conditions and correspond more closely to the degree of variability from simulation studies (e.g., Wimberley 2002).

It is also worth considering how current conditions may have changed since 2017, the latest date for the GNN vegetation data. In particular, very large wildfires occurred in Oregon in 2020, eventually affecting over 400,000 ha (Oregon Office of Emergency Management 2021). Fire perimeters encompassed large areas in both the West Cascades and High Cascades reference domains. Given that GNN vegetation data are based on remote-sensing data that continue to be collected, it should be possible to build on our work to assess how riparian vegetation has changed due to these events.

Conclusions

Our results support restoration of forests dominated by large trees for riparian areas in the Coast Range and West Cascades of northwest Oregon. Large live trees, and the standing dead and downed wood they become, are critical for ecological functions of riparian areas and associated streams by providing habitat for myriad aquatic and terrestrial species, moderating stream flow and sedimentation, and providing shade to moderate stream temperatures (Everest and Reeves 2007, Pollock et al. 2012). The need for restoration of forests dominated by large trees is present throughout both the Coast Range and the West Cascades, though the extent of departure from reference conditions varies spatially, especially in the West Cascades. Vegetation conditions in the Coast Range have moved in recent decades in the direction of reference conditions, possibly due to changes in management on federal land initiated in the mid-1990s under the Northwest Forest Plan (Reeves et al. 2018), as well as forest development following extensive wildfires in past centuries (Davis et al. 2015). Areas dominated by smaller trees may represent opportunities for applying restoration treatments. Departure from reference conditions is much less apparent for the High Cascades, suggesting less need for restoration of riparian vegetation.

Due to the use of well-documented, comprehensive data sets and analytical tools, it will be possible to apply our method to assessments and planning at a variety of scales, from individual project areas (as long as they are large enough for appropriate interpretation of vegetation data; Ohmann et al. 2014) to entire ecoregions. That different processes and geologic constraints have emerged as relevant in the different reference domains validates the approach of stratifying northwest Oregon by ecoregion. While we have used current information from unmanaged areas to characterize reference conditions, alternative approaches, such as simulation modeling or historical imagery, could be used within the same framework. The method should be adaptable to other areas where management of riparian forests is of interest, provided there is a sufficient understanding of fluvial and other natural disturbance processes that give rise to spatial and temporal variability in riparian vegetation structure and ecosystem function.

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