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Climate change and forest management on federal lands in the Pacific Northwest, USA: Managing for dynamic landscapes☆

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ABSTRACT

The 1994 Northwest Forest Plan signified a watershed moment for natural resource management on federal lands in the Pacific Northwest. It established clear priorities for ecologically motivated management of terrestrial and aquatic ecosystems and biodiversity conservation on nearly 10 million hectares of public lands in Oregon, Washington, and northern California. Conservation reserves were the primary means of safeguarding remaining old forest and riparian habitats, and the populations of northern spotted owl, marbled murrelet, and Pacific salmon that depend on them. As envisioned, reserves would provide habitat for the protected species during a lengthy recovery period. However, reserve strategies were grounded on two tacit assumptions: the climate is stable, and there are limited disruptions by invasive species; neither of which has turned out to be true. Managing for northern spotted owls and other late-successional and old forest associated species within the context of static reserves has turned out to be incredibly challenging. As climatic and wildfire regimes continually shift and rapidly reshape landscapes and habitats, conservation efforts that rely solely on maintaining static conditions within reserves are likely to fail, especially in seasonally dry forests. Forest planners and managers are now occupied with efforts to amend or revise Forest Plans within the NWFP area. According to the 2012 Planning Rule, their charge is to focus management on restoring ecosystem integrity and resiliency and address impacts of climate change and invasive species. Here, we integrate information from ecological and climate sciences, species recovery planning, and forest plan monitoring to identify management adaptations that can help managers realize the original Plan goals as integrated with the goals of the 2012 Planning Rule. There are no guarantees associated with any future planning scenario; continual learning and adaptation are necessary. Our recommendations include managing for dynamic rather than static conditions in seasonally dry forests, managing dynamically shifting reserves in wetter forests, where dynamics occur more slowly, reducing stressors in aquatic and riparian habitats, and significantly increased use of adaptive management and collaborative planning.

1. Introduction

Regional climate influences the distribution of biome and lifeform patterns, species and community ranges, and spatial patterns of environments (Williams and Jackson 2007). Climate change is now redefining these relations and will do so at an accelerating pace, along with

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the terrestrial and aquatic ecosystem processes that are strongly tied to climatic drivers (Peterson et al. 2013, 2014). Rapid climate-driven changes to vegetation, fire and other disturbances are changing habitat and species distributions across the globe (Peterson et al. 2013, 2014).

In the first decade of the 21st-century, adaptation to a rapidly changing climate arose as a leading topic of scientific inquiry, policy and planning (Bengtsson et al. 2003, Moser et al. 2010). Drought, mega-fires, invasive species, rising sea levels, eroding shorelines, landscape fragmentation, wetland losses, and deteriorating water quality are swiftly creating a complex set of challenges for resource managers across the United States (US). These new problems will not settle out at some new normal level; system-level dynamics will continue to change. Addressing these problems requires working across disciplines of environmental science, technology, sociology, and national and local politics of place (Scarlett 2010, Falk 2016). This complexity combined with the speed and extent of climate change impacts creates potentially tremendous challenges for land managers. These challenges are accentuated by polarized political and social institutions, inflexible and out-dated planning processes, and a human tendency not to recognize the problems we will have in the future as a result of our actions today (Wiens and Bachelet 2009, Kemp et al. 2015). Innovative planning is needed at broad spatial and temporal scales as adaptive management strategies for dynamic landscapes.

The Northwest Forest Plan (hereafter, NWFP or the Plan), signed and implemented in 1994, refocused the intent of forest management on nearly 10 million ha of US federal lands in Washington, Oregon, and northern California (Fig. 1). It amended 19 National Forest (NF) Plans and 7 Bureau of Land Management (BLM) Land and Resource Management Plans within the range of the threatened northern spotted owl (NSO, *Strix occidentalis caurina*). The Plan followed decades of controversy over the primary intent of public land management in the Pacific Northwest (PNW). As crafted, it set a new goal for federal land management in the region—emphasizing a shift from a focus on timber harvest to recovering listed species and the ecosystems they depend upon under the 1973 federal Endangered Species Act. Within the limits of ecosystem management, the Plan was also designed to provide a sustainable supply of forest products (Thomas et al. 2006). After > 25 years, the Plan is overdue for revisions, which generally occur every 15–20 years. Forest managers are now considering what those revisions and amendments might be (e.g., see Triangle Associates 2015, USFS 2020). Addressing climate change will be critical among them.

In our review (Table 1), we summarize the relevant science concerning the intersection between forest management in Pacific Northwest Forests and the ongoing and anticipated impacts of climate change (Section 2). We also establish the management context by highlighting some of the original intent of the NWFP, but also key subsequent changes that have occurred in climate change policy, species recovery planning and monitoring results (Section 3). Finally, we draw upon nearly three decades of NWFP implementation to discuss key elements of the plan that could be adapted to address science, policy, and social issues that could be used to revise forest plans to create more resilient ecological and social systems (Section 4).

2. Pacific Northwest forests

Forests of the PNW encompass an exceptionally broad range of climatic, physiographic, floral, and faunal diversity. For example, Hargrove and Hoffman (2004) reported that well over half of all the environmental variation in the continental US could be found in Oregon and Washington alone. However, for consistency with the Plan, we bin that variability into two physiographic regions: a moist forest zone west of the crest of the Cascade Mountain range, and a dry forest zone located in a rain shadow east of the Cascade crest, and in southwestern Oregon/northern California (Fig. 2, Franklin and Johnson 2012).

The moist forest zone has a Mediterranean climate; winters are cool to cold and wet, and summers warm and dry, with most precipitation occurring as rainfall, except in middle and upper montane environments. The dry forest zone in eastern Oregon and Washington has a continental climate characterized by hot summers, low summer precipitation, and cold winters, with most precipitation falling as snow. The dry forest zone in southwestern Oregon and northern California is Mediterranean, and significantly hotter and drier in summer than the moist forest zone. Historical vegetation and fire regimes of these two zones also differed significantly, as do current distributions of forest structural conditions, summer wildfire risks, and forest management practices. Consequently, understanding the ecology and climate of these zones is fundamental to anticipating future responses to climate change and invasive species, and guiding adaptive management strategies (Wimberly and Liu 2014, Halofsky et al. 2018).

Forests of the moist zone are dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) in the Oregon and Washington Coast Ranges, the western Cascades, and in the western portions of the northern Cascades (Franklin and Dyrness 1973). Douglas-fir, Sitka spruce (*Picea sitchensis*), western hemlock, and western red cedar (*Thuja plicata*) are dominant along the Pacific coast. Big leaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*), and black cottonwood (*Populus trichocarpa*) are relatively abundant in early seral forests and openings. At higher elevations, mixed coniferous forests of Pacific silver fir (*Abies amabilis*), subalpine fir (*Abies lasiocarpa*), mountain hemlock (*Tsuga mertensiana*), Alaska yellow cedar (*Cupressus nootkatensis*), and noble fir (*Abies procera*) are common.

Historical fire regimes in the moist zone were dominated by infrequent, large, high-severity fires[1], with fire return intervals ranging from 200 to nearly 1200 yr (Agee 1996, Long and Whitlock 2002, Weisberg and Swanson 2003, Figs. 2 and 3). Large fire events comprised the majority of total area burned, but moderate and low-severity fires[2] were also common throughout moist zone forests (Figs. 2 and 3, Spies et al. 2018b, Tepley et al. 2013), and were relatively small ($<10^4$ ha) by today's standards. Today, most wildfires in moist zone forests are readily suppressed, and the modern disturbance regime is comprised of escaped wildfires, commercial thinning on public lands, clear-cut harvests on private lands, and large windthrow events. Other disturbances include root disease mortality and bark beetle outbreaks. As witnessed during the 2020 wildfire season, during some warm and dry summers, large wildfires can occur, and they have the potential to burn over large areas (e.g., the Yacolt, Tillamook, and 2020 Oregon fires). This was also true prior to the era of management (Spies et al. 2018b, Tepley et al. 2013), but today's fires can now affect a significant built environment.

At low- and mid-elevations, dry zone forests are mixed assemblages of fire-tolerant ponderosa pine (*Pinus ponderosa)*, Douglas-fir, and western larch (*Larix occidentalis*), and fire-intolerant and shade-tolerant grand fir (*Abies grandis*), interior lodgepole pine (*P. contorta)*, and intermixed aspen (*Populus tremuloides*) (Franklin and Dyrness 1973). In southern Oregon and northern California, dry forests transition to Sierran mixed-conifer forests containing sugar pine (*P. lambertiana*), white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), and Jeffrey pine (*P. jeffreyi*), and mixed evergreen forests of Douglas-fir, tanoak (*Notholithocarpus densiflorus*), madrone (*Arbutus menziesii*), and myrtlewood (*Umbellularia californica*). Historical fire regimes were generally characterized by low-severity fires[3] with return intervals of 5–25 years, and moderate-severity fire regimes with return intervals of 25–75 years (Merschel et al. 2014, 2018, Agee 1996, Heyerdahl et al. 2001, Hessburg et al. 2007, 2016; Perry et al. 2011, Stine et al. 2014).

[1] High-severity fires are those where >70% of the dominant basal area or tree cover is killed by fires (Agee 1996).

[2] Moderate-severity fires are those where 20–70% of the dominant basal area or tree cover are killed by first order fire effects (Agee 1996).

[3] Low-severity fires are those where <20% of the dominant basal area or tree cover is killed by fires (Agee 1996).

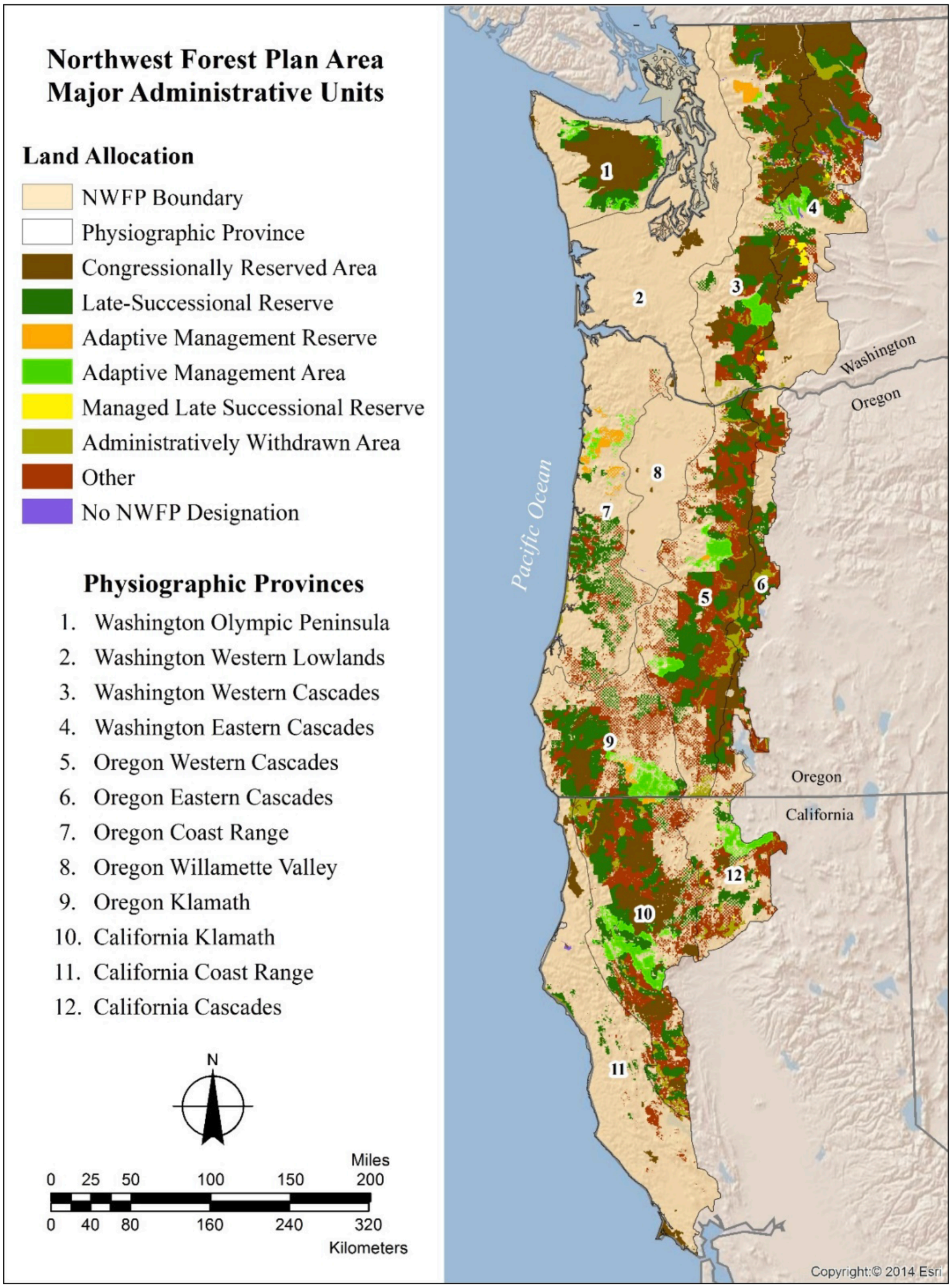

Fig. 1. The Northwest Forest Plan area showing the major administrative units.

Twentieth-century fire exclusion and selective harvest of large, old, fire-tolerant trees dramatically altered forest successional conditions and fire regimes in most dry zone forests (Merschel et al. 2014, 2018; Hessburg et al. 2000, 2005; Hessburg and Agee 2003, Wright and Agee 2004). These forest conditions in combination with ongoing and predicted effects of climate change (e.g., longer fire seasons, increased drought) present tremendous challenges for managers attempting to meet dual goals of biodiversity conservation and ecosystem resiliency (Stephens et al. 2010, 2020).

2.1. The PNW climate is rapidly warming

Climate change projections for the PNW are based on the Intergovernmental Panel on Climate Change (IPCC), fourth assessment report (May et al. 2018). In that report, the authors predicted that temperatures will rise an average of 0.54 °F *per decade* over the next century, a larger increase per decade than was experienced *over the last century*. Warming will occur in all seasons and include more extreme summer heat and drought events and higher summer moisture deficits, while extreme winter cold events will be less common (Snover et al. 2013, May et al. 2018).

Projected changes in PNW total annual precipitation vary according to different model predictions but generally tend to be small. However, large changes in snowpack and streamflow are projected due to warming temperatures, reduced snowfall and snowwater equivalent, and earlier snowmelt (Snover et al. 2013). Of interest to forest managers is

Table 1
The sections and topics covered in the Northwest Forest Plan climate change adaptation review.

Section	Topics
1. Introduction	
2. Pacific Northwest Forests	2.1 The PNW climate is rapidly warming 2.2 Wildland fire size and severity are increasing 2.3 Invasive species are prevalent 2.4 Larger insect outbreaks
3. Northwest Forest Plan	3.1 Northwest forest plan origins 3.2 Observations from NWFP monitoring 3.3 USFWS/NOAA recovery planning 3.3.1 Northern spotted owl 3.3.2 Marbled Murrelet 3.3.3 Listed salmonids and coldwater fish 3.4 The case for climate change adaptation
4. Climate adaptation and the NWFP	4.1 Landscape evaluations 4.2 Biogeographical context 4.2.1 Dry zone forests 4.2.2 Moist zone forests 4.3 Aquatic conservation and restoration 4.3.1 Roads and aquatic impacts 4.3.2 Grazing and aquatic impacts 4.3.3 Invasive fish 4.4 Survey and Manage 4.5 Post-fire harvest 4.6 Wildland fire use 4.7 Monitoring and adaptive management 4.8 Collaboration
5. Summary	

the projected increase in heavy rainfall events (+13% ±7%) by the 2050s (Snover et al. 2013), some of which will be winter rain-on-snow. Additionally, the PNW will experience decreasing winter snowpack, see a shifting balance between snow and rain in some watersheds, steadily increasing stream temperatures (Isaak et al. 2012), and changes in streamflow timing, peak flow events, and summer minimum flows (Snover et al. 2013). For example, the average spring snowpack in Washington will decline by 56 to 70% by the 2080s, relative to the 1916–2006 period (Elsner et al. 2009).

During this time of rapid climate change, PNW forests also face a number of additional stressors associated with 20th-century fire exclusion. In the absense of fire, patchworks of old, middle-age, and young forests, and open grasslands, shrublands, and sparse woodlands gradually infilled with more continuous tree cover (Hessburg et al. 2005). Forests also grew denser and more predisposed to high-severity fire, insects and disease and drought stress (Hessburg et al. 2019). Moreover, drought-induced mortality of old-growth forests is increasing (van Mantgem et al. 2009). Summer wildfire seasons are getting steadily longer, and large wind-driven fire events are becoming more common, with their associated large patches (>100 ha) of high-severity fire (Cansler and McKenzie 2014, Coop et al. 2020, Reilly et al. 2017).

Climate change is having a considerable impact on forests that comprise habitat for the NSO. Increases in the frequency and severity of large wildfires are the primary cause of declines in NSO nesting and roosting habitat (Davis et al. 2016, Spies et al. 2019, Stephens et al. 2019). The NSO is well adapted to a landscape patchwork of successional stages (e.g., Franklin et al. 2000), but its use of early-successional forest varies geographically. Recent high-severity fires have been linked to decreased survival rates and increased turnover in spotted owl popuations (Rockweit et al. 2017) and have decreased rather than created extensive areas of suitable nesting and roosting habitat (Lesmeister et al. 2018, 2019). In addition to indirect effects of climate change on forest habitats, there may be direct effects of climatic warming on NSO demography because variation in spotted owl life history traits is strongly linked to climate (Franklin et al., 2000). Most climate models predict warmer and wetter winters, and hotter, drier summers for the PNW (Elsner et al. 2009, Mote 2003, Mote et al. 2005). Results from Glenn et al. (2010) suggest that these conditions can adversely affect NSO annual survival, recruitment, and population growth.

Conservation of Pacific salmon and marbled murrelet (also protected in the NWFP) depends on many factors that are beyond the control of federal forest managers, including warming ocean and stream temperatures, and watershed and vegetation conditions on non-federal lands (Raphael et al. 2018; Reeves et al. 2018). Many salmonid spawning and rearing habitats in Pacific coastal areas fall within stream reaches that intersect non-federal lands. For these species, adaptations that address climate change are best coordinated across disciplines and ownerships (Raphael et al. 2018, Reeves et al. 2018).

2.2. Wildland fire size and severity are increasing

Since the mid-1980s, the size and intensity of wildfires in western US interior forests have both markedly increased (Westerling et al. 2006, Westerling 2016). Large fire frequency increased fourfold during the period 1987 to 2003 (in comparison to the period 1970 to 1986, Westerling et al. 2006), and it has continued to increase in recent decades (Westerling 2016). Comparing the 1973–1982 and 2003–2012 decades, Westerling (2016) found that the average fire season length had increased by 84 days. Westerling et al. (2006) attributed increased burned area to adequate fuel abundance and lower than normal fuel moistures – driven by higher spring and summer temperatures and reduced snowpack.

In the dry forest zone, studies using leading global circulation models (GCMs) and greenhouse gas (GHG) emissions scenarios project that wildfires will occur more frequently and burn larger areas under projected future climates (McKenzie et al. 2004, Littell et al. 2010, Rogers et al. 2011, Abatzoglou et al. 2017, McKenzie and Littell 2017). Even under relatively modest emissions scenarios, there will be a doubling in burned area in the western US (McKenzie et al. 2004); in the Interior Columbia Basin, burned area will likely triple by 2050 (Littell et al. 2010).

Increase in fire severity is partly driven by elevated surface and canopy fuels due to ongoing wildfire suppression and timber harvest (Agee and Skinner 2005, Hessburg et al. 1999c, 2000, 2005, Cansler and McKenzie 2014, McKenzie et al. 2004, Stephens et al. 2009a, 2009b) as well as historical fire exclusion (Agee 1998, Hessburg and Agee 2003, Mershel et al. 2014, Messier et al. 2012). Predicted increases in spring and summer temperatures, combined with earlier snow melt, will considerably increase fire frequency and intensity by decreasing fuel moisture, vapor pressure, and relative humidity (Littell et al. 2010, McKenzie et al. 2004, Westerling 2016, Wotton and Flannigan 1993). Because a greater fuel mass is available to burn when live and dead vegetation are dry, regional fire years will be characterized by synchronous large fire events that are strongly correlated with water deficits during hot, dry summers (Littell et al. 2010, McKenzie and Littell 2017).

2.3. Invasive species are prevalent

Invasive wildlife species such as the barred owl (BDO, *Strix varia*) and range expansions of some native species have significantly affected the native biota of the NWFP region (Marcot et al. 2018). Barred owl populations are widespread, affecting about 50-percent of the inventoried NWFP area (Gray 2008), where they have become a leading threat to NSO population viability. The impact of BDOs on NSO populations and the forest food web is profound, and it is unknown whether it can be reversed or stabilized (Holm et al. 2016, Lesmeister et al. 2018, Dunk et al. 2019). Likewise, native corvid populations (crows and ravens, linked to human settlement areas) are expanding. Corvids prey on marbled murrelet (*Brachyramphus marmoratus*) eggs and nestlings, and those of other native birds (Raphael et al. 2018).

Invasive species occur in aquatic and riparian ecosystems as well. Across the Plan area for example, 63 nonnative plant and animal species

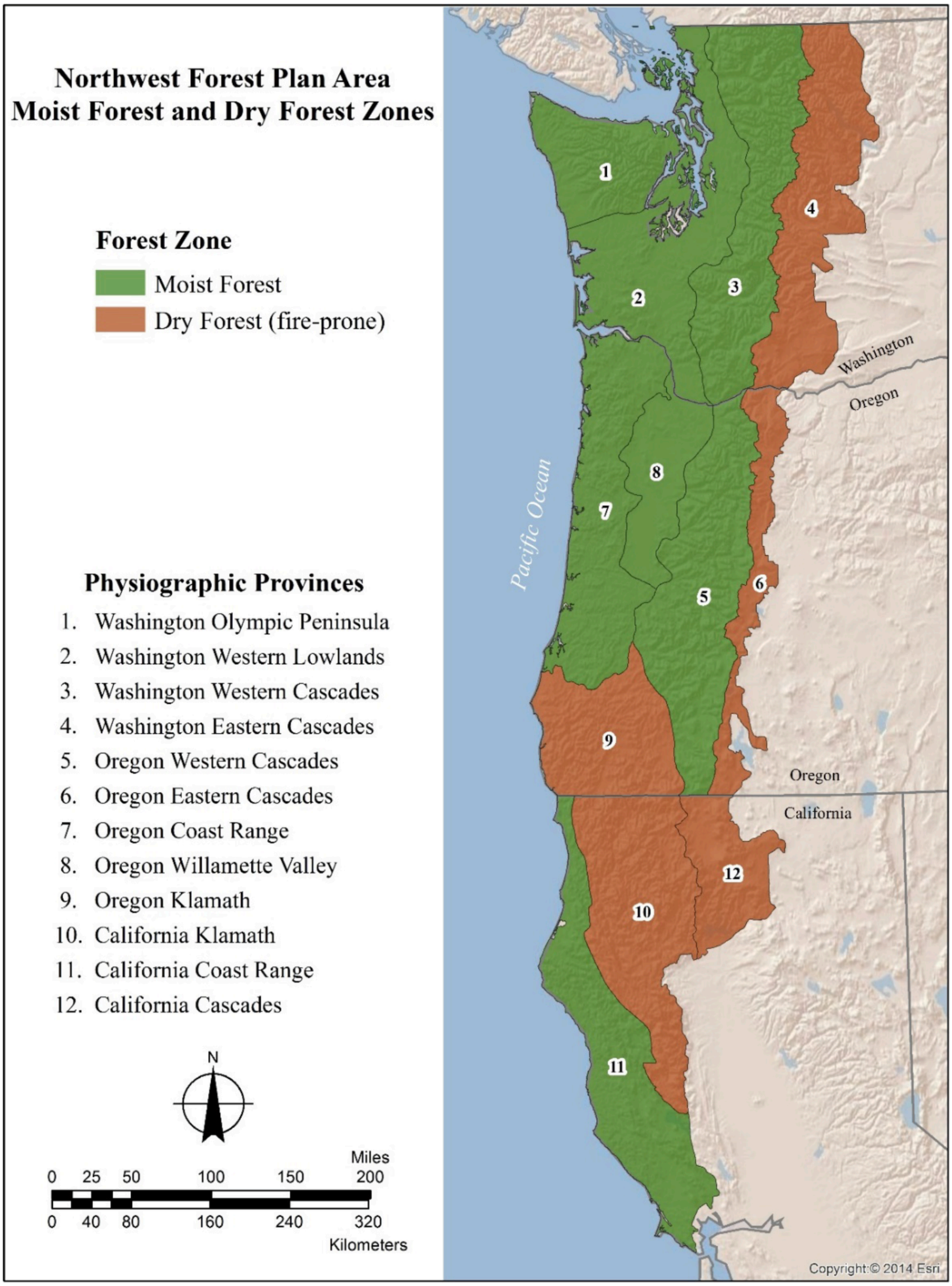

Fig. 2. The Moist Forest and Dry Forest Zones within the Northwest Forest Plan area.

and species groups are identified as regional aquatic-riparian invasive or nuisance species (Reeves et al. 2018). Of these, about half were designated as *high concern* and inventoried by the NWFP's Aquatic Riparian Effectiveness Monitoring Program (AREMP). Nonnative species are not always harmful to native fishes or their habitats, but they often: (1) compete with, prey upon, hybridize with, or infect native species with novel pathogens; (2) alter food webs; or (3) cause habitat changes that reduce the productivity of desirable aquatic organisms (Reeves et al. 2018 and references therein). Climate change will influence the expansion of nonnative plant and animal species in the NWFP area, by reducing or extirpating native species populations (Dale et al. 2001, Garcia et al. 2014).

2.4. *Larger insect outbreaks*

Many of the same factors that are leading to changing fire regimes are also leading to increases in the incidence and severity of forest insect outbreaks in western US and Canada (Bentz et al. 2010; Fettig et al. 2007, Hessburg et al. 1994, 1999a; Parker et al. 2006, Raffa et al. 2008, Kolb et al. 2016). In response to climatic changes underway, some forest insects have dramatically expanded their elevational and northward ranges, while others have switched from 2- to 1-year life cycles, showing increased overwintering survival, adaptation to smaller host sizes, and probability of large outbreaks (Kurz et al. 2008, Logan and Powell 2001, Logan et al. 2003). With continued warming, mountain pine beetle (*Dendroctonus ponderosae*) population viability will increase in high

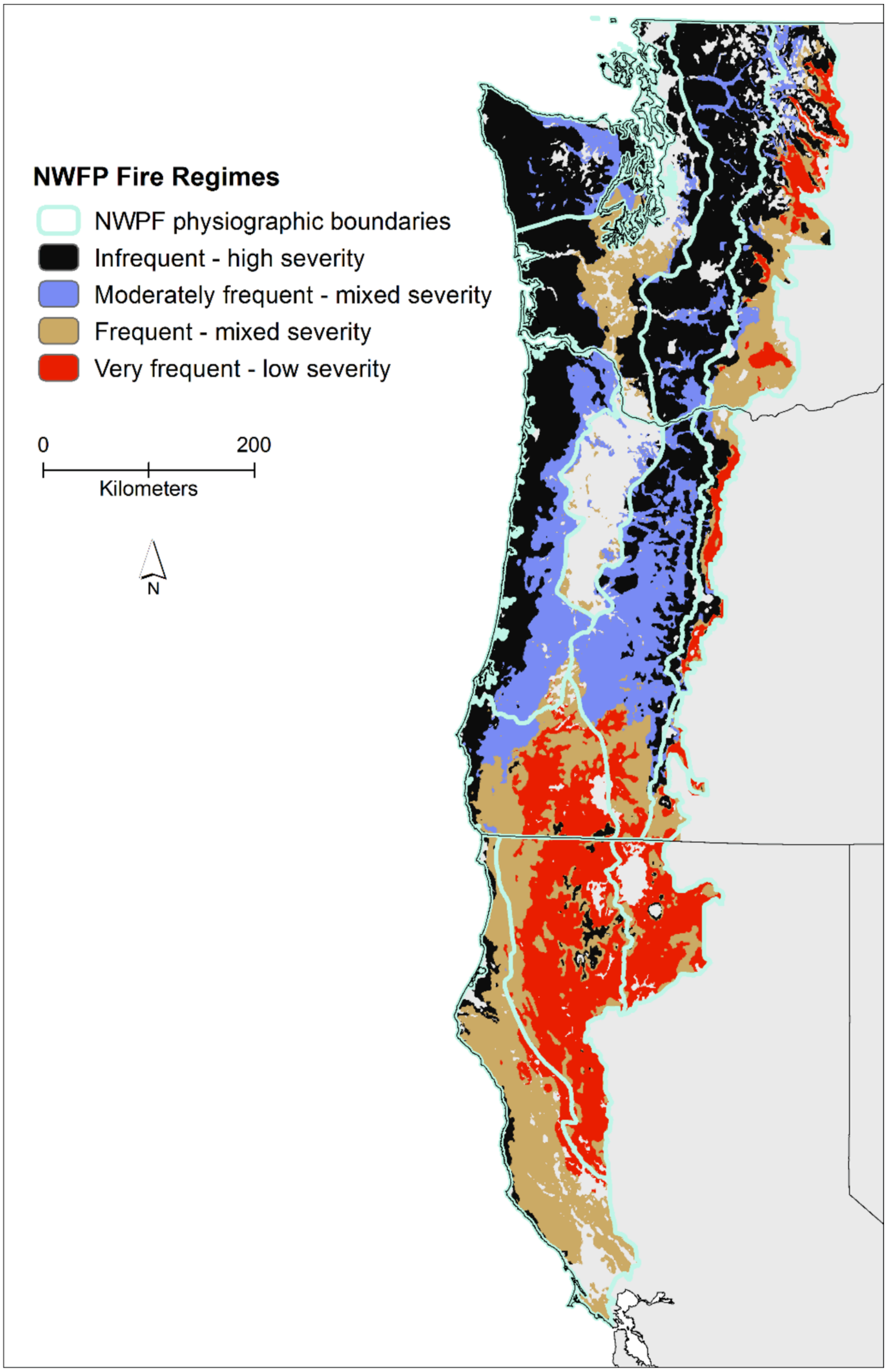

Fig. 3. Historical fire regimes of the Northwest Forest Plan area. Moist forests occur in historically infrequent and moderately frequent fire regimes, while dry forests occur in frequent and very frequent fire regimes. From Spies et al. (2018b).

elevation forests, leading to further outbreak incidence and severity increases (Bentz et al. 2010, Littell et al. 2010). Legacies of past forest management and fire exclusion have also led to increased forest cover and density, creating more contiguous areas of host trees for insect outbreaks, and greater susceptibility to drought stress and mass insect attack due to high stocking rates (Hessburg et al. 2019). Large fire and insect disturbances in dry zone forests will likely be the primary agents of sudden and large-scale change in forest structure and composition in the 21st century (Dale et al. 2001). Anticipating large future disturbances will be critical for successful climate change adaptation and habitat management.

3. Northwest Forest Plan

3.1. *Northwest Forest Plan origins*

Owing to historical fire regimes, old forests were historically a dominant component of moist zone forests (Spies et al. 2006). By the mid-1990s, more than a century of logging and land conversion had significantly reduced old forest area (Bolsinger and Waddell 1993, Wimberly et al. 2000), which threatened the viability of associated species (Spies et al. 2006). As a result, litigation, primarily to promote protection of the NSO, in addition to declining public trust and changing values about forest management (Charnley et al. 2006, 2018), shifted emphasis from timber production to conservation of native species and ecosystems. Three studies were triggered early in litigation, and they established the scientific basis for changes in forest management reflected in the NWFP[4]. Additionally, Nehlsen et al. (1991) provided an important contribution to the understanding of at-risk Pacific salmon stocks and the need for new policies to address them. Consequently, the Plan employed a recovery strategy based on two types of reserves: (1) a reserve network for late-successional and old forest associated species (Table 2), and (2) an Aquatic Conservation Strategy, including a system of Riparian Reserves and Key Watersheds (Table 2). Outside of the late successional reserves, in the "Matrix," where timber harvest was allowed, a Survey and Manage approach was employed for species that did not achieve a high likelihood of viability based on inclusion in either type of reserve[5].

Policies of the 1990s were designed to protect late-successional and old-growth forests (LSOF) and recover NSO and native salmonid populations (Thomas et al. 2006), but they did not explicitly address climate change (Spies et al. 2010a, 2018a). Spies et al. (2010a) highlighted that while Plan guidance provided a solid initial foundation for conservation, it was grounded in stable climate assumptions and management restrictions that inherently limited adaptation. They offered the following adaptive actions for all Plan forests: (1) increase landscape area devoted to critical NSO habitats and resilient ecosystem types; (2) maintain existing older forests; (3) use regional planning to coordinate changes across management units and jurisdictions; (4) revise land management goals and objectives to be consistent with dynamic processes and rapid warming under climate change; and, (5) incorporate uncertainty into planning and make adapting to climate change a long-term, iterative process.

Similarly, Carroll et al. (2010) evaluated the effectiveness of NWFP reserve networks under contemporary and predicted climate change. They recommended that planners consider potential range shifts when evaluating alternative network designs, and that a broader range of focal and local species and associated habitat conditions be used to design habitat networks. Despite calls for adapting the Plan to climate change and new critical habitat designations (USFWS 2012), there remains considerable reluctance to amend the Plan at a regional scale (e.g., compare DellaSala et al. 2015; Kemp et al. 2015). This is due, largely, to the considerable challenges conservationists faced in getting the protections for late-successional and old forests into the existing Plan and concerns that a revised plan may lessen protections.

3.2. Observations from NWFP monitoring

The NWFP included a comprehensive monitoring and adaptive management focus, and while the monitoring has largely been carried out, the ability to make significant plan adaptations has proven difficult (Stankey et al. 2003, Gregory et al. 2006). Plan implementation included a regional monitoring program to assess Plan effectiveness (Hemstrom et al. 1998, Hemstrom 2003, Ringold et al. 2003). The 20-yr monitoring report, released in 2015, compared LSOF mapped in 1993 with that mapped in 2012, showing increased occurrence of large wildfires, primarily in dry zone forests (Davis et al. 2011, 2015). Some loss of LSOF to

Table 2
The land allocations used in the Northwest Forest Plan.

Land Allocation	Description	Hectares	% of the NWFP Area
Congressionally Reserved Areas	These lands were reserved by Congress and include National Parks and Monuments, Wilderness Areas, Wild and Scenic rivers, National Wildlife Refuges, and other lands with congressional designations.	2,963,806	30%
Late Successional Reserves	These reserves will maintain a functional, interactive, late-successional and old growth forest ecosystem. They are designed to serve as habitat for late-successional and old growth related species including the northern spotted owl.	3,008,421	30%
Adaptive Management Areas	These areas are designed to develop and test new management approaches to integrate and achieve ecological, economic, and other social and community objectives. A portion of the timber harvest will come from this land allocation. There are 10 AMAs.	616,113	6%
Managed Late Successional Areas	These lands are either (1) mapped managed pair areas or (2) unmapped protection buffers. Managed pair areas are delineated for known northern spotted owl activity centers. Protection buffers are designed to protect certain rare and locally endemic species.	41,377	1%
Administratively Withdrawn Areas	These areas are identified in forest and district plans or draft plan preferred alternatives and include recreational and visual areas, back country, and other areas not scheduled for timber harvest.	598,016	6%
Riparian Reserves	Riparian Reserves are along streams, wetlands, ponds, lakes, and unstable or potentially unstable areas where the conservation of aquatic and riparian-dependent terrestrial resources receives primary emphasis. These reserves will help maintain and restore riparian structures and functions, benefit fish and riparian dependent non-fish species, enhance habitat conservation for organisms dependent on the transition zone between upslope and riparian areas, improve travel and dispersal corridors for terrestrial animals and plants, and provide for greater connectivity of late-successional forest habitat.	1,063,765	11%
Matrix	Matrix is the federal land outside of the six categories of designated areas set forth above. It is also the area in which most timber harvest and other silvicultural activities will be conducted.	1,609,433	16%

[4] (i) "*A conservation strategy for the northern spotted owl*" (Thomas et al. 1990); (ii) "*Alternatives for the management of late-successional forests of the Pacific Northwest*" (Johnson et al. 1991), and (iii) "*Viability assessments and management considerations for species associated with late-successional and old forests of the Pacific Northwest*" (Thomas et al. 1993).

[5] Survey and Manage was a late addition to the Plan and not included by the Forest Ecosystem Management Assessment Team (FEMAT, 1993), who designed the Plan. The Survey and Manage strategy required searching for identified species throughout their historical range and providing protection buffers around their sites prior to any timber harvest in Matrix.

large wildfires was anticipated in the original reserve network design, but findings by Westerling et al. (2006) and Miller et al. (2012a, 2012b) reveal that large wildfire frequency and annual burned area increased more than expected in the decades since Plan development (Davis et al. 2015), and several areas will be nonforests or slowly developing young forests for decades to centuries (Hemstrom et al. 1998, Davis et al. 2015).

Two decades into Plan implementation, the range-wide net amount of NSO nesting and roosting habitat within LSOF reserves after fires (accounting for losses and gains from in-growth) has declined by about 4-percent (Davis et al. 2016). Habitat losses from wildfire amounted to about a 6.1-percent reduction from what existed within the reserves at the time they were designated. Range-wide, the gross loss of nesting and roosting habitat from wildfire was slightly higher than the anticipated 5-percent over two decades (Davis et al. 2016). Losses were 2 to 3 times higher than what was anticipated in dry zone forests (Davis et al. 2016). Hence, the clear linkage between habitat losses from large and severe wildfires and a strong negative feedback to NSO turnover and survival identified by Rockweit et al. (2017) is unsurprising. Importantly, low- and moderate-severity fire does little to reduce habitat quality for NSO (Lesmeister et al., 2019), and may even increase habitat quality (e.g., see Kramer et al. 2021). Rather, it is the large patches of stand-replacing fire – a characteristic that has been increasing in forests of the Plan area – that removes limiting nesting habitat for NSO (Jones et al. 2020a).

Late successional reserves (LSRs) within dry zone forests were designed with wildfire in mind. Reserves were delineated to be large enough to withstand large wildfire events over 50 years, such that unburned portions could maintain a well-connected network of nesting, roosting and dispersal habitat. However, the projected amount of wildfire was based on the area burned in decades that preceded the plan; large wildfires since then have far exceeded the area burned in the decades leading up to the Plan (Davis et al. 2011, 2016). This increased area burned is overwhelming the Plan's accounting for habitat loss to fires, especially in those provinces with large amounts of dry zone forest.

3.3. USFWS/NOAA recovery planning

To identify potential climate change adaptations, we reviewed recovery plans, status and monitoring reports, and critical habitat rules for federally listed NSO, marbled murrelet, and Pacific salmon in the Plan area. Recovery plans and monitoring reports included discussions about climate impacts and adaptations, which we summarize below.

3.3.1. Northern spotted owl

The NSO was the focal species of the Plan (Thomas et al. 1990, 2006); reserve size and spacing were based on NSO nesting, roosting, and foraging habits, and dispersal ecology. Since implementation, considerable monitoring information has been produced concerning the effectiveness of the Plan habitat network, including wide-ranging efforts to monitor owl demography and habitat change (Lint et al. 1999, Lint 2005, Davis et al. 2011, 2016). After considering the new information, the USFWS completed a revised final recovery plan and critical habitat rule for the NSO (USFWS 2011, 2012), which included approaches to address NSO recovery while incorporating climate change adaptation strategies. A conclusion of the final recovery plan (USFWS 2011) was that climate change is exacerbating changes in forest ecosystem dynamics to a degree greater than was anticipated in the Plan. The USFWS, supported by other new research (USFWS 2011, 2012, Millar et al. 2007, Kennedy and Wimberly 2009, Spies et al. 2006, 2010a, 2010b, Franklin and Johnson 2012, Hessburg et al. 2015, 2016, Jones et al. 2016), recommended the use of active adaptive management to achieve improved results in dry zone forests.

Because both NSO population dynamics and forest conditions are influenced by changes in the regional climate, the USFWS attempted to account for these influences in the 2011 revised recovery plan (USFWS 2011), and in their designation of NSO critical habitat (USFWS 2012). They recognized that forest composition and structure may change beyond the range of historical variation, and that climate change will have unpredicted consequences for PNW forests and owls (USFWS 2012). The recovery plan and critical habitat rule recognized that management practices to improve forest health and landscape resilience under changing climatic conditions will be important for owl conservation (USFWS 2012):

> *In order to preserve the essential physical or biological features, these dynamic, disturbance-prone forests should be managed in a way that promotes northern spotted owl conservation, responds to climate change, and restores dry forest ecological structure, composition and processes, including wildfire and other disturbances (*USFWS 2011*, p. III–20)* (USFWS, p 132). *The following restoration principles apply to the management that may be required in this dry forest region (*USFWS 2011*, pp. III–34 to III–35):*

(1) *Conserve older stands that contain the conditions to support northern spotted owl occupancy or high-value northern spotted owl habitat as described in Recovery Actions 10 and 32 (*USFWS 2011*, pp. III–43, III–67). On Federal lands this recommendation applies to all land-use allocations (see also* Thomas et al. 2006, pp. 284–285*).*
(2) *Emphasize vegetation management treatments outside of northern spotted owl territories or highly suitable habitat;*
(3) *Design and implement restoration treatments at the landscape level;*
(4) *Retain and restore key structural components, including large and old trees, large snags, and downed logs;*
(5) *Retain and restore heterogeneity within stands;*
(6) *Retain and restore heterogeneity among stands;*
(7) *Manage roads to address fire risk; and*
(8) *Consider vegetation management objectives when managing wildfires, where appropriate. (USFWS, p 132).*

The NSO Critical Habitat Rule designated considerably more area and in a different spatial arrangement than that provided in the NWFP Plan reserve network, and it encouraged active management to restore characteristic dry forest zone successional patterns and wildfire regimes as a means of fostering climate change resiliency (USFWS 2012).

3.3.2. Marbled murrelet

The marbled murrelet is a seabird that spends most of its time living and foraging in coastal marine waters. Its distribution is almost entirely in the near coastal portion of the NWFP area. It was selected as a focal species for management and monitoring in the Plan area because its nesting habitat is strongly associated with coastal LSOFs (USFWS 1997, Madsen et al. 1999), which are key to murrelet conservation (Ralph et al. 1995, USFWS 1997, Raphael 2006, Piatt et al. 2007, USFWS 2009). The Plan identified several goals for murrelet nesting habitat, including providing more suitable habitat than existed at the start of the Plan, providing it in large contiguous blocks, and broadening the distribution of habitats (Madsen et al. 1999, Raphael et al. 2018).

Marbled murrelet monitoring under the Plan included both habitat and population components (Madsen et al. 1999, Raphael et al. 2018). Monitoring trends from 2000 to 2013 demonstrated clear declines in Washington, relatively stable populations in Oregon, and stable populations in California (Falxa and Raphael 2016, Falxa et al. 2016). From 1993 to 2012, the loss of high suitability habitat on reserved lands was ~2.5-percent, owing mostly to fires in Oregon (Raphael et al. 2016a). However, the loss of high suitability habitat was 10-fold greater (26.6%) on nonfederal lands, mostly to timber harvest (Raphael et al. 2016a). Raphael et al. (2016a) concluded (1) that recovery is impossible if losses at this rate continue, and (2) there are limits to which a public lands-only reserve network can protect remaining suitable habitat.

Raphael et al. (2016b) studied the factors that had the most influence on murrelet populations, considering both marine and terrestrial influences. Previous research had suggested that loss of nesting habitat and low food availability in the marine environment contributed to population decline in the 1990s and 2000s (Strong 2003, Peery et al. 2004, Becker et al. 2007, Norris et al. 2007, Miller et al. 2012a, 2012b, Raphael et al. 2015). Poor ocean conditions, related to climate warming, sea surface temperatures, and chlorophyll A concentrations during the 1990s may have influenced food availability (Peery et al. 2004, Becker et al. 2007, Norris et al. 2007, Raphael et al. 2016b), but Raphael et al. (2016b) showed that the amount and pattern of high suitability nesting habitat had the greatest influence.

Both murrelet nesting habitat and foraging success along the Pacific coast are sensitive to climatic variability (Becker et al. 2007), and climate may be contributing to the trends observed in murrelet abundance (Raphael et al. 2016b). On federal lands, climate change may be contributing to the loss of nesting habitat; more that 60% of the habitat loss from 1993 to 2012 was due to wildfires (Raphael et al. 2016a). Dry summers also reduce epiphyte (e.g., fern, arboreal lichen) growth on tree branches, which degrades the suitability of nesting platforms (Malt and Lank 2007). Climate change may already be decreasing the quality and quantity of murrelet nesting habitat, and projections for the acceleration of current climate trends raises the specter of even greater impacts in the future (Raphael et al. 2016b).

Raphael et al. (2016b, 2018) recommended that maintaining a system of LSOF reserves on federal forests may not be sufficient to recover the marbled murrelet in the short-term. The Plan reserve system on federal lands contributes critical conservation benefits, but fire and other natural disturbances are already influencing the availability of habitat on federal lands and may increase habitat losses in the future as a result of climate change. In the short-term, murrelet conservation might better focus on reducing losses to high suitability nesting habitat on all lands, including nonfederal lands, and recruiting replacement habitat, especially where federal lands are limited. Longer-term climate adaptations on federal lands could focus on reducing the likelihood of habitat loss from wildfires, restoration in plantations, and accounting for climate change in the design of future reserve networks (Raphael et al. 2018).

3.3.3. Listed salmonids and coldwater fish

Federally listed salmonids and coldwater fish are distributed throughout the Plan area. Their recovery was based on the Aquatic Conservation Strategy of the NWFP. Listed fish in the Plan include: steelhead (*Oncorhynchus mykiss*, Threatened), bull trout (*Salvelinus confluentus,* Threatened), spring chinook salmon (*Oncorhynchus tshawytscha,* Endangered), chum salmon (*Oncorhynchus keta,* Threatened), coho salmon (*Oncorhynchus kisutch,* Threatened), short-nose sucker (*Chasmistes brevirostris*, Endangered in OR) and lost river sucker (*Deltistes luxatus*, Endangered). Climate change will contribute ongoing cumulative impacts to foraging, migration, and overwintering habitats for listed salmon, steelhead, and bull trout through changes in water temperature and stream flow timing (Luce and Holden 2009, Mantua and Raymond 2014, Figure 4). In addition, climate changes alter flow and wildfire regimes that can greatly influence habitat conditions for listed fish (Mantua and Raymond 2014, Falke et al. 2015). Restoring and maintaining habitat connectivity and quality will be crucial for enhancing population resilience. Only in this context will fish be able to adjust their ranges to track suitable habitats and access cold waters during thermally stressful periods (Bisson et al. 2003, Rieman et al. 2000, 2007, 2010; Falke et al. 2015).

A central component of the Plan is the Aquatic and Riparian Ecosystem Monitoring Program (AREMP) (Reeves et al. 2004, Lanigan et al. 2012). This program is focused on determining whether the Aquatic Conservation Strategy is effective at improving in-channel conditions of streams, upslope and riparian conditions, and overall watershed conditions. Unfortunately, the aquatic monitoring program has been hindered by insufficient funding and changes to monitoring protocols. Even so, a 2012 assessment showed a small but consistent improvement in watershed condition scores owing to maturing vegetation and localized restoration actions (Lanigan et al. 2012). Road decommissioning, especially in landslide prone or riparian areas, has been the most effective action for improving watershed conditions (Lanigan et al. 2012). Nevertheless, concerns remain about the future of the reserve system. The AREMP concluded:

> …*the unpredictable nature and dynamic role of fire may have implications for the static reserve approach that lies behind the designated set of key watersheds.*

Potential climate change adaptations recommended for listed fish in recovery planning documents and monitoring reports included: minimizing stream water withdrawals and diversions, re-connecting floodplains, re-aggrading incised channels, restoring riparian shade, protecting or restoring beaver populations, reducing chronic sediment from roads, reducing non-native species invasions, restoring fire regimes to re-engage hillslope processes, and implementing a program of monitoring and adaptive management (Battin et al. 2007, Beechie et al. 2012, Bisson et al. 2003, Cristea and Burges 2009, Dunham et al. 2003, Falke et al. 2015, Furniss et al. 2010, Isaak et al. 2010, Justice et al. 2016, NMFS 2014, Perry et al. 2015, Rieman et al. 2015, USFWS 2015).

3.4. The case for climate change adaptation

Decades of NWFP implementation and monitoring, science development and significant policy changes (e.g., recovery plans, 2012 Planning Rule) have resulted in considerable body of evidence for climate change adaptations. For example, in dry zone forests, a growing body of evidence highlights the effectiveness of forest treatments to alter forest stand structure (Raymond and Peterson 2005, Wimberly et al. 2009, Prichard et al. 2010, 2020, Prichard and Kennedy 2012) and landscape-scale fire spread and severity (Collins et al. 2011, Finney et al. 2008,Wimberly et al. 2009, Ager et al. 2010, Safford 2012, Tubbesing et al. 2019, Hessburg et al. 2021). In addition, stand-level effects of restoration treatments have been monitored on a wide variety of ecosystem resources (Gaines et al. 2007, 2010a; Hurteau and North 2009, McIver et al. 2012 for a review, Moghaddas et al. 2010, Schwilk et al. 2009, Stephens et al. 2009a, 2009b, Stephens and Moghaddas 2005, Taylor et al. 2016). Based on study findings, there is evidence that properly designed treatments can reduce burned area and wildfire severity and improve forest resilience to climatic changes, but there are tradeoffs in terms of some kinds of wildlife (e.g., spotted owl nesting, roosting) habitats (Barros et al. 2018, Spies et al. 2017, Ager et al. 2020).

At present, there is uncertainty about the impacts of climate change on wildfire size and severity in moist zone forests, and appropriate management strategies that might be implemented in response (Wimberly and Liu 2014, Halofsky et al. 2018). Since fire events in moist zone forests are primarily climate and weather driven, it is unlikely that fuels management as practiced in dry zone forests is practicable given their high productivity and differing ecology (Franklin and Johnson 2012, Wimberly and Liu 2014). Fuels in moist zone forests are generally abundant owing to high site productivity and stocking, accumulated coarse downed wood, and organic soils. Historically, a significant area in the moist zone was frequented by moderate-severity fires (Fig. 3), and this area warrants special attention. There is good evidence (e.g., see Tepley et al. 2013, Weisberg 2004, Wimberly and Spies 2001) that moderate-severity fires at moderately frequent intervals historically increased the likelihood of future moderate-severity fires. This zone of the moderate-severity fire regime is where most early 21st-century fire regime change can be expected (Spies et al. 2018a), and this zone will continue to grow large as climate changes.

4. Climate adaptation and the NWFP

Climate change represents a dominant, broad-scale stressor that will exacerbate ongoing cumulative effects to aquatic and terrestrial ecosystems and species (Spies et al. 2010b, DellaSala et al. 2015, Reilly et al. 2018, Spies et al. 2018a). Because of this, forest managers in the NWFP area find themselves in a difficult bind. There has been considerable progress in our understanding of how climate change will interact with the natural resources they are responsible for managing, but policies and plans that govern daily actions (e.g. Forest Plans) are not flexible enough to adapt to these new challenges. Clearly, there is a need to amend or revise Forest Plans to give managers more flexibility to respond to climate change.

Incorporating climate change adaptation into Forest Plan amendments will be a formidable task due to the long history of controversy and mistrust that surrounds forest management in the Pacific West (e.g., see DellaSala et al. 2015; Spies et al. 2018a). Over the period 1989 to 2002, national forests in the PNW region experienced twice as many lawsuits as any other Region in the US (Keele et al. 2006). Moreover, funding for natural resource management was co-opted by "fire-borrowing" withdrawals for wildfire suppression until 2020, which severely limited agency efforts at proactive fire and fuels management or climate change adaptation (Gorte 2013). Effective management and policies regarding climate change adaptation on federal lands will require new efforts at engagement with stakeholders (Spies et al. 2010a, Gaines et al. 2012, Hessburg et al. 2015, Spies et al. 2018a, Wood and Jones 2019).

Several authors have offered suggestions on adaptations to the NWFP to create better alignment with our current understanding of climate change impacts (Carroll et al. 2010, Spies et al. 2010a, Frissell et al. 2014, DellaSala et al. 2015, Hessburg et al. 2016, Spies et al. 2018a, Hessburg et al. 2021). In addition, Forest Plans under the new 2012 Planning Rule could include plan components to maintain or restore ecological integrity so that ecosystems can resist some changes, adapt to changing climatic and wildfire conditions, and recover their ecological structure and organization after disturbances. Recommendations from recent climate change vulnerability and adaptation assessments are summarized in Table 3, then, we discuss in detail how specific components of the NWFP could be adapted to increase the likelihood of achieving the original conservation goals of the NWFP and the ecosystem integrity and resiliency goals of the 2012 Rule.

4.1. Landscape evaluations

By means of Forest Plan revision or amendment, carefully crafted plan guidance could include a well-defined, integrated terrestrial and aquatic landscape evaluation process to assess resiliency of each landscape, and to restore ecological integrity of those landscapes (Gaines et al. 2010a, 2012; Hessburg et al. 2013, 2015). According to the 2012 Rule, ecological integrity is:

> "*the quality or condition of an ecosystem when its dominant ecological characteristics (composition, structure, function, connectivity, and species composition and diversity) occur within the natural range of variation.*"

We know that the natural range of variation shifts with a changing climate. Thus, Forest Plans could provide Desired Conditions that are based on the full natural range of variability, including how climate change is altering this range (e.g., Gärtner et al. 2008, Donato et al. 2019). A process is needed to step down the broad-scale direction from the Forest (or Province, if a multi-Forest Plan) to the project level, by means of landscape evaluation (Cannon et al. 2018, Gaines et al. 2010a, Hessburg et al. 2013, 2015; Donato et al. 2019). At least two estimates of the range of variation are useful as guiding references for landscape evaluations: the 20th century range of variation, to understand where

Table 3
Recommendations from recently completed climate vulnerability and adaptation assessments grouped into three broad categories: (1) Partnerships, Collaboration, and Education; (2) Landscape and Watershed Restoration and Resiliency; and (3) Assessment, Planning, and Adaptive Management.

Climate Adaptation Category	Climate Adaptations	References
Partnerships, Collaboration, Education	Develop strong partnerships between managers, scientists, decision-makers, and stakeholders; use a variety of tools and strategies to facilitate trust-building, common language development, effective actions.	Blate et al. 2009, Charnley et al. 2018, Scarlett 2010, Gaines et al. 2012, Hudec et al. 2019, Halofsky et al. 2019
	Invest in collaborative planning and governance across jurisdictions.	Scarlett 2010, Halofsky et al. 2011, Peterson et al. 2011a, Gaines et al. 2012, Raymond et al. 2014, Hudec et al. 2019
	Through partnerships, collaboratively develop management strategies and targeted monitoring.	Scarlett 2010, Spies et al. 2010a, Halofsky et al. 2011, Gaines et al. 2012, Raymond et al. 2014, Hudec et al. 2019
	Active adaptive management is the key to forward-looking successes under climate change.	Pahl-Wostl 2007, Tompkins and Adger 2004, Walters 1986, Walters and Hilborn 1978
	Adequate resources are needed to underwrite monitoring, which provides the insights for adaptation.	Blate et al. 2009, Scarlett 2010, Peterson et al. 2011a, Gaines et al. 2012, Hudec et al. 2019, Halofsky et al. 2019
	Continually promote awareness about climate change to public, partners, and employees.	Blate et al. 2009, Scarlett 2010, Peterson et al. 2011a, Gaines et al. 2012, Hudec et al. 2019, Halofsky et al. 2019
	Monitoring of planned management actions is essential, must be adequately funded to be effective, and should be a collaborative venture. Partners viewing management prescription implementation and efficacy measurement contributes to group learning and trust building.	Charnley et al. 2018
Landscape and Watershed Restoration and Resiliency	Implement early detection and rapid response actions for invasive species and control the spread of existing populations.	Scarlett 2010, Peterson et al. 2011a, Gaines et al. 2012, Hudec et al. 2019, Halofsky et al. 2019
	Reduce the risks of large and frequent severe fires using strategies that restore more characteristic variability in wildfire regimes for each forest type, and the forest and non-forest successional variability that supports them.	Blate et al. 2009, Scarlett et al. 2010, Spies et al. 2010a, Peterson et al. 2011a, Gaines et al. 2012, Hessburg et al. 2015, 2016, 2019; Hudec et al. 2019, Halofsky et al. 2019
	Invest in broad-scale, landscape restoration projects to increase forest resiliency to climate change, wildfire and insects. In dry forest zones, short-term impacts and risks associated with managed wildfires and prescribed burning need to be balanced by longer-term risks	Hessburg et al. 2016

(*continued on next page*)

Table 3 (*continued*)

Climate Adaptation Category	Climate Adaptations	References
	associated with large disturbance events.	
	Use historical ecology to guide understanding of how ecological patterns drive succession and disturbance dynamics, mindful of how climate change may create novel patterns and dynamics different from the historical system.	Spies et al. 2010a, Gaines et al. 2012, Hudec et al. 2019, Bengtsson et al. 2003
	Restore freshwater ecosystems by restoring flow regimes, mainstem floodplain functioning, and network connectivity as central elements of climate change adaptation.	Scarlett 2010, Gaines et al. 2012, Raymond et al. 2014, Halofsky et al. 2011, 2019
	Match infrastructure and infrastructure engineering with expected changes in flow regimes.	Blate et al. 2009, Halofsky et al. 2011, Peterson et al. 2011a, Gaines et al. 2012, Raymond et al. 2014, Hudec et al. 2019, Halofsky et al. 2019
	Reduce effects of non-climate stressors, such as the impacts from roads and livestock grazing (among others), to maintain biological diversity and increase landscape area devoted to critical habitat and resilient ecosystems.	Spies et al. 2010a, Peterson et al. 2011a, Raymond et al. 2014, Hudec et al. 2019, Halofsky et al. 2019
	Adapt wildfire behavior and the forest successional patterns that support them to facilitate establishment of current and future climate-adapted species and communities.	Spies et al. 2010a, Hudec et al. 2019, Halofsky et al. 2019
	Use variable density and low thinning in uncharacteristically dense forest patches to safeguard residual trees of early seral species, promote forest resilience, and species and structural diversity.	Spies et al. 2010a, Peterson et al. 2011a
	Maintain existing old forests and work to restore more characteristic abundance	Camp et al. 1997, Spies et al. 2010a, Hessburg et al. 2015, Donato et al. 2019
	Manage terrestrial and aquatic ecosystems as a single interconnected system, where terrestrial disturbance regimes, their variability, and resulting vegetation patterns are critically important to the timing, intensity, and spatial extent of physical processes that are essential to the maintenance and derivation of aquatic habitats.	Bisson et al. 2003
	Native terrestrial species require a disturbance regime that exhibits characteristic variability in order to persist. Manage local and regional landscapes to restore more functional and characteristic disturbance regimes as a coarse-filter species conservation strategy.	Spies et al. 2010a, Gaines et al. 2012
Assessment, Planning, and Adaptive Management	Identify and protect to a practical extent potential climate change refugia in terrestrial and aquatic ecosystems at regional and landscape scales, where climate change effects may be buffered by local conditions or management of them	Spies et al. 2010a, Gaines et al. 2012
	Use regional and local planning to coordinate anticipated changes across management units and jurisdictions.	Carroll et al. 2010, Spies et al 2010a, Hudec et al. 2019, Halofsky et al. 2019
	Use downscaled climate predictions and modeling tools such as future actual evapotranspiration (AET) and climatic water deficit (Deficit) calculations to assess where moist forest assemblages will likely shift to dry forest assemblages, requiring a change in how they are managed. Adaptive management that guides realignment of landscape conditions (species composition, forest structure and fuels) to those that are more climate resilient will be necessary on drier sites within the moist forest zone.	Spies et al. 2018a, Kane et al. 2015, Lutz et al. 2010
	Use bioclimatic modeling to anticipate where forests will likely convert to nonforest assemblages in the dry forest zone. Recent research on "trailing edge" and "leading edge" forest zones provides an example of regional modeling to prioritize forests that are vulnerable to type changes after high-severity fire and guide post-fire management activities to avoid rapid transformation.	Parks et al. 2019, Coop et al. 2020
	Revise land management goals and objectives to be consistent with dynamic processes and uncertainty expected under climate change.	Bengtsson et al. 2003, Scarlett 2010, Spies et al. 2010a
	Revise land management plans around adaptive management principles in order to respond to changing climate and resource conditions in forward-looking ways where change in dynamics is the only constant.	Stankey et al. 2005, Gregory et al. 2006

ecosystems have come from, and the future range of variation, to gain insights into how climate change will likely alter conditions in the 21st-century (Gärtner et al. 2008; Keane et al. 2009, Hessburg et al. 2013, Moritz et al. 2013, Hessburg et al. 2015, Spies et al. 2018b). Landscape evaluations lead to landscape prescriptions that identify actions and their spatial arrangement to best move landscapes toward the Desired Conditions for landscape resiliency (Hessburg et al. 2013, 2015, Cannon et al. 2018).

4.2. Biogeographical context

There are profound differences in the landscape ecology, disturbance regimes, and management histories of dry and moist zone forests (Spies et al. 2006, Franklin and Johnson 2012, Wimberly and Liu 2014, Lehmkuhl et al. 2015, Spies et al. 2018b). In dry zone forests, rapid successional change driven by frequent disturbance is ordinary; spatial patterns of forest and non-forest successional conditions are in constant flux. In moist zone forests, these dynamics also occur, but their pace is slower—major disturbance events such as wildfire and insect outbreaks are spread out over a longer time frame than in dry zone forests, and changes (relative to the lifespan of observers) appear as episodic events, which at times may be quite large and severe. The discussion below uses dry vs. moist forest zones to remain consistent with what is used in the NWFP, but further subdivisions recommended by Spies et al. (2018a) could be applied in plan amendments or revisions.

4.2.1. Dry zone forests

Principal among climate adaptations is clear direction that recognizes the unique challenges of managing dry zone forests (Franklin and Johnson 2012, Hessburg et al. 2015). Dry zone forests represent 43-percent of the NWFP area, where wildfire regimes are highly altered. Closed-canopy, multilayered forest habitats in dry zone forests exist in unprecedented abundance due to fire exclusion, and many of these now have some structural characteristics of spotted owl habitat (Gaines et al. 2010a, 2015; Stephens et al. 2019). These dense and layered forests are not only prone to large stand replacing wildfires, but are also vulnerable to projected increases in drought stress and resulting insect outbreaks (Kolb et al. 2016, Littell et al. 2010, Stephens et al. 2019).

In many dry zone forests, broad-scale re-alignment is required (Kates et al. 2012, Stine et al. 2014, Hessburg et al. 2016). The cumulative interactions of increasing moisture deficits, insect vulnerability, and occurrence of uncharacteristically large and severe fires within the fire-prone provinces rises to this level of concern (Jones et al. 2016). Recent large-scale mortality events from drought, insects, and wildfire in the central and southern Sierra Nevada (Stephenson et al. 2018, Stephens et al. 2018) foreshadow the trajectory of many dry zone forests in the PNW. Regional analyses of where forested area is likely to constrict and expand under climate change and disturbances (e.g., Parks et al. 2019) are needed to both guide prioritization of restoration projects to increase forest resilience to drought, insect outbreaks and wildfires, and to guide post-disturbance management of areas that are slow to recover or convert to non-forest vegetation after high-severity wildfires and other stand-replacing disturbances.

The existing stationary Reserve and Matrix system has little capacity to respond to large LSOF habitat losses, changes in owl distribution, or to meet fundamental expectations of the Plan in the dry zone. In dry zone forests, the current Plan strategy includes intermixed Matrix lands, which occur outside of wilderness and roadless areas, in spaces between the Reserves). In Matrix lands, timber harvest is allowed and considered alongside other values. However, in eastern Washington State, about 40-percent of the historical nesting owl pairs resided in Matrix rather than Reserve lands (Gaines et al. 2010a). In addition, many Matrix lands are within NSO Critical Habitat (USFWS 2012). A proactive strategy based on whole ecosystem restoration could reasonably replace the static Matrix and Reserve lands, where NSO and LSOF habitats are managed dynamically across landscapes (Spies et al. 2006, Hessburg et al. 2015, 2016). The focus of a revised strategy would then be to restore more characteristic fuel and vegetation conditions within seasonally dry mixed-conifer forests, where the historical wildfire regime would have characteristically been frequent fire, and where climate change will likely expedite forest transitions. As such, it could anticipate impacts of climate change and wildfire, mitigate those impacts to owl habitat by reducing loss to stand-replacing fire, protect the best Critical Habitats regardless of their position in Matrix or Reserved lands, and restore a more characteristic fire regime in the surrounding area.

A key issue often overlooked in debates over appropriate management actions in dry zone forests is the historical abundance, diversity, and spatial arrangement of LSOF habitats (Spies et al. 2006, Gaines et al. 2010a, Franklin and Johnson 2012, Hagmann et al. 2017, Spies et al. 2018b). Historically, a considerable portion of the landscape was dominated by forests with open canopies of medium and large-sized, fire-tolerant, early-seral trees (Hessburg et al. 1999a; Spies et al. 2006; Hagmann et al. 2013, 2014, 2017). Open canopy patches rarely possessed the structural characteristics associated with NSO habitat (see Gaines et al. 2015 for a review, Spies et al. 2018a, 2018b). Most of these forests were selectively harvested in the 20th century, removing the largest and most fire-resistant pine, Douglas-fir, and western larch, and they now display a dense ingrowth of younger trees as a result of natural regeneration and release of shade-tolerant trees and continuing fire exclusion (Collins et al. 2017, Everett et al. 1997, 2003, Franklin et al. 2008, Hessburg et al. 2000, 2005, Hessburg and Agee 2003). Much of these forests are now in NSO reserves and/or Critical Habitat but they are highly susceptible to insect and fire disturbances. Historically, these forests provided important open canopy old forest habitat for species such as white-headed woodpecker (Mellen-Mclean et al. 2013, Gaines et al. 2017), a USFS (hereafter FS) Sensitive Species.

Thoughtfully applied active management has been used to restore dry zone forests and their native fire regime (Churchill et al. 2013, Harrod et al. 1999; Larson and Churchill 2012, Gaines et al. 2007, 2010b, Bailey et al. 2015), but such treatments are cited by forest management critics as having negative impacts to NSOs (e.g., contrast Odion et al. 2014, and Peery et al. 2019). Beyond a single-species focus on NSOs, a broader view of forest biodiversity and ecosystem ecology highlights the importance of forest restoration to rebuild the integrity of dry forest patterns and processes, and key pattern and process linkages between inter-digitated dry, moist and cold forests, for the species that depend on them (Fontaine and Kennedy 2012, Henson et al. 2018). Maintaining the current levels of closed canopy forests in the dry forest zone is not sustainable given the ongoing and anticipated effects of climate change and wildfires. Adaptations to the NWFP in dry forest zone provinces could encourage the use of landscape-scale active management to target amounts and patterns of LSOF that are more characteristic of the native fire regime (Franklin et al. 2008, Franklin and Johnson 2012, Lehmkuhl et al. 2015), and that can be maintained in topo-edaphic settings where they are at lowest risk to losses from wildfires (Camp et al. 1997). As climate continues to warm, many fire-refugia locations will become less viable for supporting LSOF because of their highly flammable context.

Landscape evaluations are an important reference for habitat management that can be used to compare the composition, structural classes and spatial arrangement of contemporary forests to historical and future climate change reference conditions (Cannon et al. 2018, Gaines et al. 2010a, Keane et al. 2009, Moritz et al. 2013, Wiens et al. 2012, Hessburg et al. 1999b, 1999c, 2013). At broad spatial scales, the historical evidence and projections under future climate suggest that dry zone forests historically supported more open, heterogeneous successional conditions. These conditions offered greater resilience to climate change and extreme forest disturbances by interrupting the flow of disturbances and the likelihood of extensive severe events (Hessburg et al. 1999a, Hagmann et al. 2017). Frequent, low and moderate-severity fires supported the maintenance of heterogeneous successional patchworks and the maintenance of medium and large-sized old trees and open forest structures (Hessburg et al. 2016, 2019). Plan guidance could provide protections for large trees and snags and restoration of within-patch spatial heterogeneity (Larson and Churchill 2012, Churchill et al. 2013, Spies et al. 2018a, 2018b), both within and outside of LSOF within these fire regime areas (Hessburg et al. 2015). Management direction for large and old trees could replace the “80-year-old standard” that does not match the landscape or fire ecology of dry zone forests. Many 80-year-old trees are not very large and most today are shade-tolerant and a product of fire exclusion. Fire-maintained dry zone forests that are dominated by large-diameter (>60 cm dbh) and old (>150 yrs) ponderosa pine, western larch and Douglas-fir offer greater resilience to disturbances and climate change than the dense, often multi-layered forests that dominate the fire-excluded dry zone landscapes of today (Hessburg et al. 2019, Prichard et al. 2020).

4.2.2. Moist zone forests

In moist zone forests, management concerns stem from cumulative impacts of past old forest harvests, ongoing fire exclusion (loss of the heterogeneous successional patchwork), continued harvest on non-federal lands, and anticipated impacts of climate change of forested environments and their fire regimes (Thomas et al. 2006, Spies et al. 2010a, Spies et al. 2018a, 2018b). These cumulative impacts place a greater emphasis on the LSOF that remains, whether inside a NWFP reserve or not (Thomas et al. 2006, Spies et al. 2010a, DellaSala et al. 2015, Raphael et al. 2016a, 2016b). Thus, adaptations to the NWFP in the moist zone forests could emphasize protection of all existing LSOF in Critical Habitat, especially that found in larger patches, regardless of whether it occurs in NWFP Matrix or Reserve lands (USFWS 2012). As specified in the existing NWFP (Franklin and Johnson 2012), emphasis could also be placed on forest treatments inside previously harvested units composed of young forests to accelerate the development of old forest characteristics. Treatments could emulate disturbance influences associated with the variability of the dominant historical fire regime (Cissel et al. 1999, Tepley et al. 2013, Spies et al. 2018a, Weisberg and Swanson 2003).

Moist zone forests in the area that historically supported moderate frequency mixed-severity fire regimes (Spies et al. 2018a, 2019, 2018b: Figure-3) could be readily adapted from second-growth plantations that currently dominate landscape conditions to clumped and gapped forest conditions as described and illustrated by Tepley et al. (2013: Figure-4). Restoration of more resilient forest and landscape structure, including patchy harvest and burning sequences in second-growth and in the smaller tree sizes and crown classes of old forests in the heart of the moderate frequency mixed-severity regime zone (*sensu* Spies et al. 2018b), would reduce the likelihood of running crown fires during particularly hot and dry years and enhance the likelihood of moderate-severity effects (Spies et al. 2018a, 2018b, 2019). Elsewhere, the long-term retention of LSOF could be achieved in a system of “dynamic reserves” (*sensu* Bengtsson et al. 2003), with the amount and spatial arrangement informed by the natural range of variability (e.g., Donato et al. 2019), protected from commercial logging through the life of the plan and reevaluated after large disturbances (Spies et al 2018a). The controversy of moving from fixed to dynamic reserves is likely to be intense and may only be overcome by considerable efforts to collaborate on adaptive management and monitoring to assure agreed to outcomes (Culhane 2013, Walpole et al. 2017).

4.3. Aquatic conservation and restoration

There are several adaptations to the NWFP Aquatic Conservation Strategy (ACS) in Forest Plan revisions that could reduce non-climatic stressors and help riparian and nearby aquatic ecosystems become more resilient to climate change. Current non-climatic stressors include poorly placed timber harvests, damaging timing, location, and levels of domestic livestock grazing, damaging roads, and invasive species. Roads that constrain floodplain functioning or have direct hydrologic connectivity with streams are the most detrimental to fish-bearing reaches (Furniss et al. 1991, Dunham and Rieman 1999, Jones et al. 2000, Luce and Black 1999, Meredith et al. 2014, Trombulak and Frissell 2000). In this context, efforts to move roads out of the floodplain and to restore channel-floodplain-hillslope linkages would become high priority.

Floodplains and their associated hyporheic zones are unique because the primary disturbance regime is hydrologic and typically driven by ice at spring break up and peak flow events (Beechie et al. 2006, Latterell et al. 2007). Floodplains are where rivers and streams dump their bed load of soil, rocks, boulders, and trees during peak flow events (Beechie et al. 2006, Latterell et al. 2007). The NWFP ACS allowed for timber harvest within floodplain Riparian Reserves for the primary objective of restoring aspen or cottonwood forests where conifers have encroached, often in relationship to channel incision and floodplain dewatering. However, timber harvest in floodplain Riparian Reserves can impact a variety of stream and riparian functions (Olson et al. 2007, Frissell et al. 2014) and may increase stream temperatures in the short term by temporarily decreasing vegetative shade (Johnson 2004, Cristea and Burges 2009). Managed wildfire use or prescribed burning can also be useful to converting conifer-encroached floodplain riparian areas back to former hardwood conditions once floodplains are restored, and it provides the added advantage of providing proximal future inputs of dead trees with root wads.

Key management objectives in restoring floodplains are to 1) restore their full wetted width by eliminating channel incision and 2) restore pulsed sediment delivery processes associated with more characteristic wildfire regimes and ensuing hillslope erosion processes. Climate change adaptations to the Plan could explicitly limit other types of timber harvest activities and associated road building within floodplain Riparian Reserves and retain the existing Riparian Reserve widths (Olson et al. 2007). Because management actions influence aquatic and riparian habitats and their associated species, management within floodplain Riparian Reserves could be conducted on an experimental basis, with scientists and managers collaborating on design, implementation, and monitoring (Reeves et al. 2016).

Within Riparian Reserves, areas next to streams that have slope gradients steeper than 5 or 6% typically share the same fire history as their adjacent upland forests and are more influenced by wildfire than flood disturbances (Beechie et al. 2006, Everett et al. 2003). On these slopes adjacent to streams, Riparian Reserves could benefit from treatments that restore the characteristic wildfire regime. Historical wildfires of characteristic frequency, severity, and spatial extent influenced riparian areas and included occasional landslides, debris flows, and mass failures on the landscape, some of which found their way to streams (Beechie et al. 2006, Waples et al. 2009). In this light, the wildfire regime provided the pulsed events that initiated erosion and depositional events that contributed to spawning gravels, deep cold plunge pools, riffles and glides, and their ongoing revitalization of streams. Restoring the wildfire regime in upslope Riparian Reserves is one key to aquatic habitat restoration; however, site conditions and context are important considerations.

Another component of the NWFP ACS is the designation of Key Watersheds with their associated Standards and Guidelines. Key Watersheds are given priority for scarce stream restoration dollars (USFS 2018). Forest Plan revisions and amendments could address ongoing changes to stream flow regimes and stream temperatures in Key and other watersheds. It will be essential to consider how warming trends affect the long-term distribution of habitats capable of serving as climate refugia for cold-water species (Isaak et al. 2015). Warming trends and changing stream temperature patterns may require a new distribution of Key Watersheds and vastly improved linkages for fish movement. This will focus new attention on restoring the floodplains of lower mainstem rivers, where temperatures will be warmest and intermittently spaced cold deep pools will be doubly important.

4.3.1. Roads and aquatic impacts

Roads and road networks have considerable impacts to aquatic and terrestrial resources (Jones et al. 2000, Gaines et al. 2003, Reeves et al. 2016). The magnitude of road impacts on watersheds and streams in the NWFP area may in some places exceed the sum of effects of all other activities combined (Kaufmann and Hughes 2006, Frissell et al. 2014). The impacts of roads are often cited as a non-climate stressor that contributes long-term cumulative effects. Where these impacts are reduced, greater ecosystem resilience will be fostered in aquatic ecosystems (Mantua and Raymond 2014). Changes to hydrologic regimes because of climatic warming are resulting in higher peak flow events, which are causing damage to valley bottom and floodplain roads and related culvert and bridging infrastructure. The NWFP provided limited guidance to reduce the negative impacts of roads. Clearly, where improving floodplain functionality and hillslope stability are the management goals, additional guidance could be considered in adaptations to the

NWFP. Because road crossings at stream channels can inhibit fish movement and fragment populations, up-sizing or removing culverts and pulling back bridges and bridge fill to accommodate higher peak runoff will improve connectivity and the ability of aquatic organisms to track shifting habitats.

4.3.2. Grazing and aquatic impacts

Grazing on national forest lands has long been controversial. Domestic livestock grazing can have considerable impacts to many stream and riparian habitats if not well managed (Al-Chokhachy et al. 2010, Beschta et al. 2013, Frissell et al. 2014). Some have called for a complete grazing moratorium on public lands due to impacts to aquatic environments (DellaSala et al. 2015) and efforts to restore native large carnivores (Beschta et al. 2013). Where elimination of grazing is not possible, strengthening protections for floodplains and Riparian Reserves is essential. For example, preventing grazing in Riparian Reserves with current or potential habitat for listed fish by means of offsite watering, fencing, and modifications to grazing timing or duration would all be beneficial practices (Al-Chokhachy et al., 2010; Beschta et al., 2013; Frissell et al. 2014; Nussle et al., 2015). As part of forest planning, these measures can be targeted where they would have the highest likelihood of mitigating climate change impacts adjacent to cold-water reaches.

4.3.3. Invasive fish

Invasive fish species can pose a major threat to native fishes, yet there is limited direction in the NWFP to address them. For example, in some locations, brook trout (*Salvelinus fontinalis*) invasions have been so successful that native species such as cutthroat trout (*Oncorhynchus clarkia*) persist only above artificial barriers maintained to exclude invasive species (Fausch et al. 2009). When considering climate change adaptations to address invasive aquatic species, it is important to consider species interactions alongside temperature and passage in understanding climate effects on fish and their ability to adjust their distribution to changing habitat conditions (Wenger et al. 2011).

4.4. Survey and Manage

The Survey and Manage program was established under the NWFP as a means of collecting information on and providing conservation direction for rare and poorly known LSOF associates (Marcot et al. 2018). The program was controversial because the costs of the surveys were funded by projects and projects were often delayed due to survey requirements. As a result, the Survey and Manage approach was litigated numerous times by both conservation organizations and the timber industry. At one point, both the FS and BLM attempted to abolish the program, but after litigation, the program was reinstated by a court ruling. The FS and BLM jointly instituted a program known as the Interagency Special Status and Sensitive Species Program (ISSSSP) to address species for which there are viability concerns. The Program maintains species lists, conducts periodic status reviews, provides funding for monitoring and research, and provides survey protocols and management recommendations.

One of the challenges of the Survey and Manage approach was the difficulty of developing adequate protocols for species that were little known and difficult to identify and survey in the field. This became a serious financial issue as many surveys were pre-project surveys; i.e., any fuel treatment or vegetation management project bore the brunt of the survey expense. If the FS transitions to an emphasis on large-scale ecosystem restoration projects that focus on ecosystem resiliency as per the intent of the 2012 Rule, some of the challenges associated with an emphasis on individual species may lessen (Spies et al. 2018a). However, it is important to have a funding mechanism for collecting information and adapting management for Sensitive species as this program is transitioned to the Species of Conservation Concern approach described in the 2012 planning rule (Hayward et al. 2016).

4.5. Post-fire harvest

Several recent reviews of the ecological effects of post-fire timber harvest ("timber salvage", Peterson et al. 2009, Leverkus et al. 2021) suggest that there is little ecological justification for post-fire timber harvest of large to very large trees (>63.5 cm DBH). These large and old trees have been the focus of timber harvest for many decades, and their occurrence has been markedly reduced from historical levels in dry and moist zone forests (Hessburg et al. 1999a). Adaptations to the NWFP could discourage post-fire timber harvest of dead or dying large early seral trees but encourage removal of small to medium-sized shade-tolerant and fire-intolerant trees where there is good evidence of highly increased density over the period of fire exclusion and where the effects of timber harvest can be appreciably mitigated (Leverkus et al. 2021). In areas of high post-fire snag densities, dead wood accumulations constitute an appreciable future fuel source for an uncharacteristically hot reburn (Prichard et al. 2017). In these instances, post-fire timber harvest could be used to reduce small to medium tree fuels (Fraver et al. 2011, Peterson et al. 2015), as long as Plan guidance protects large to very large live and dead trees and snags (Hessburg et al. 2015, 2016; Spies et al. 2018a), and requires adequate maintenance fuel treatments as intentional follow-up to post-fire timber harvest (Donato et al. 2006).

4.6. Managed wildfire

Adaptations to the NWFP could consider increasing opportunities to use managed wildfire to restore landscape resiliency and achieve restoration objectives, especially in the backcountry, as often as fuel and fire weather conditions allow (Barros et al. 2018). Managed wildfire has been shown to reduce fuels, increase landscape resilience to future fires, and reduce firefighting costs while restoring more characteristic landscape heterogeneity than presently occurs (Barros et al. 2018, Miller and Aplet 2016). Managed wildfire that results in predominately low- to moderate-severity effects also produces co-benefits for spotted owls through the maintenance and development of owl habitat (Jones et al. 2020b, Kramer et al. 2021). Fire managers can evaluate, at each instance of wildfire, opportunities to use fire for resource benefit where people and structures can be protected and where wildfire behavior can be managed at severities and in patch sizes that are characteristic for the forest type. Forest Plan amendments and revisions could consider including plan components that guide the use of managed wildland fires to achieve Desired Conditions wherever possible, directing that wildland fire be used to restore landscape pattern, structure, and composition in dry forests (Hessburg et al. 2015, 2016) and to create complex early-seral and heterogeneous forest and landscape structure in moist forests (Franklin and Johnson 2012, Hessburg et al. 2016, Spies et al. 2018a).

4.7. Monitoring and adaptive management

Adaptive management is both a conceptual framework and a collection of management practices designed to accomplish at least four goals: (1) clearly identify desired outcomes for the area of interest, (2) match the management actions to the desired outcomes using the best available science, (3) monitor to determine if management actions were implemented as designed, and are leading to the desired outcomes, and (4) where outcomes are not achieved, modify future actions based on lessons learned to ensure that outcomes can be met in future actions. Adaptive management is a key component of the *Forest Service Strategic Framework for Adapting to Climate Change* (USDA FS 2008) and is essential to have any chance of achieving goals of biodiversity conservation and restoring ecosystem integrity and resiliency. Past efforts of adaptive management often lacked adequate funding and any significant success (Stankey et al. 2003). The NWFP attempted to institutionalize monitoring and adaptive management. It even identified land allocations (Adaptive Management Areas) where management experiments could be carried out. Unfortunately, social license and funding to implement adaptive management never materialized, and adaptive management fell short of expectations (Stankey et al. 2003, Bormann et al. 2007, Spies et al. 2018a). Nonetheless, some NWFP monitoring has resulted from strong independent collaborations between individual scientists and managers, and it provides information upon which to build adaptive management into Forest Plan amendments.

Adaptations to the NWFP could emphasize the importance of monitoring, and the monitoring framework described in the 2012 Rule could be directly incorporated. To assure that climate-sensitive variables are included, monitoring can be adjusted each time plans are revisited to address anticipated climate change impacts. For example, climate warming is altering peak flows, low flows, timing of spring runoff, and total flows in NWFP rivers and streams (Mote et al. 2005, 2008; Mote and Salathe 2010) that are home to listed Pacific salmon and cold water fish. Moreover, stream water temperatures are rising, and some river reaches will become inhospitable as breeding or rearing locations for native fish. Adaptive management strategies will be needed to provide deep, cold water pools as reliable refuges for native fish as they migrate. This will focus new attention on lower mainstem channels. Warming temperatures and wildfires will shift dominant lifeform areas on the landscape, eliminating some habitats in current areas for decades to centuries. Alternative habitat arrangements will be needed to provide continued connectivity across shifting disturbance, lifeform, and forest type landscapes.

Climate change in shifting areas of moist mixed-conifer forest to dry mixed-conifer forests, and areas of sparse woodland and shrub steppe or chaparral are likewise expanding within former areas of dry pine and dry mixed-conifer forest (Littell et al. 2010, Halofsky et al. 2020). Accompanying these shifts will be transitions in fire frequency and severity. As a consequence, LSOF networks will be in flux throughout the 21st-century. These changes will require highly adaptive and innovative thinking to maintain high-functioning and connected habitat networks for a variety of species, including, but not limited to, the NSO and other LSOF associates. Adaptive management solutions could be integrated into Forest Plans, so that changes can be made to address unanticipated climate impacts rapidly.

4.8. Collaboration

Collaboration will be important during all phases of forest planning and implementation because developing and obtaining social license is a key to success (Culhane 2013, Walpole et al. 2017). In the pre-planning phase, collaborators would be involved in the development and implementation of ecological and social assessments. In the NWFP area, the climate vulnerability assessments that have been completed using the Peterson et al. (2011b) approach included a broad network of collaborators (managers, scientists, agency staff, etc.), and they provide an opportunity for organizations to identify and advocate for climate adaptations.

The 2012 Planning Rule requires collaboration throughout the planning process. Multi-partner collaboration on restoration projects from conception through design, implementation, and monitoring can expand options for management and invest stakeholder groups in outcomes (Culhane 2013). To be ecologically effective, it is essential that landscape restoration be planned, implemented, and monitored at relatively broad scales, and a host of terrestrial and aquatic ecosystem dimensions must be co-considered in application. Departed wildfire regimes, fragmented terrestrial and aquatic habitat networks, range expansion of invasive species, and broad landscape vulnerability to climatic warming are wicked problems (*sensu* Rittel and Webber 1973) with no one-size-fits-all solution, and no grand "fix everything" alternative is available. Positive solutions concerning one landscape dimension may produce negative cascades to another. In this light, decision support methods will be extremely useful for evaluating these trade-offs, and for tuning landscape prescriptions across multiple dimensions (Gregory et al. 2012, Reynolds et al. 2014).

Broad- to meso-scale planning and implementation will require a high level of cross-boundary and cross-disciplinary collaboration and problem solving (Tabor et al. 2014, Urgenson et al. 2016, Wondolleck and Yaffee 2000). Adapting NWFP landscapes to rapid climatic warming and the associated and often sudden spatial rearrangements of cold water networks, seasonal flow regimes, and forest habitats will require new behaviors from all stakeholders, and an unprecedented collaborative and adaptive spirit among disciplines within agencies. Focusing on restoring ecosystem processes and the variation in conditions that supports them likely represents the highest ground managers can attain in the context of forecasted climatic changes (Henson et al. 2018).

5. Summary

The decision to implement the NWFP in 1994 signified a watershed event for natural resource management on public lands, establishing a clear priority for ecologically motivated management of terrestrial and aquatic ecosystems and native biodiversity conservation (Spies et al. 2019). This shift was momentous, especially considering the politics surrounding the prior emphasis on timber harvest and commodity uses in earlier forest plans. It is understandable that conservationists may be reluctant to risk gains (e.g., old growth protections) made during the heated debates leading to the NWFP. However, a considerable body of science and implementation experience warrants that serious consideration be given to proactive and broad-scale climate change adaptation, and the grave risks of inaction. The necessity of these adaptations is supported by two significant science and policy decisions, the 2011 Recovery Plan for the Northern Spotted Owl and the 2012 Planning Rule, which were summarized by the USFWS Oregon State Supervisor Paul Henson (Henson et al. 2013):

> *We agree that caution is always warranted when one takes any habitat-altering action. But what of the potential for novel conditions to be created or perpetuated as a consequence of management inaction? Many scientists are concerned about climate-driven disturbances speeding up ecological conversions among forest types and recommend research and intervention (*e.g., Collins et al. 2011, Perry et al. 2011, Davis et al. 2011*). Given the tremendous landscape scale of climate-driven changes, we suggest that this is a much more serious conservation challenge for northwest forests (*Millar et al. 2007*). We* [USFWS 2011, 2012] *have structured NSO recovery to fit within science-based landscape strategies that address this challenge and to work closely with our land management partners such as the USDA Forest Service and other landowners.*

The 2012 Planning Rule emphasizes ecosystem integrity and resiliency and inseparably linked terrestrial and aquatic ecosystem functioning. Coarse filter management strategies that sustain landscapes and plant and animal communities are the backbone of the approach, while fine filter strategies for listed or sensitive species are woven into this larger fabric. The 2012 Rule also emphasizes restoring natural patterns, landscapes regulated by biotic and abiotic processes that function more like they once did historically, and habitats for various native species that are an emergent property of these dynamics. Perhaps the greatest breakthrough of the 2012 Rule is that it explicitly links ecological, economic, and social outcomes of land stewardship. In this context, Plan implementation leads to advancement of economic, ecological, and social objectives together, without trading one off against another. It requires forest plans to function within the capacities of ecological systems, and it represents an ideological shift in management for public lands.

These two policies (the 2011 Recovery Plan and the 2012 Planning Rule) set the stage for what Thomas et al. (2006) described as putting "*a substantial portion of our science and policy towards considering and preparing for futures we cannot predict but might help create.*" Revisions to the NWFP could emphasize landscape-scale ecosystem restoration and resiliency in a rapidly changing climate in order to have any chance of preparing our forests and communities for the ongoing and rapidly changing conditions we are experiencing. To implement these changes will require that revised forest plans make climate change adaptation and resiliency a key issue and that plan components be devised to allow managers and collaborators to respond rapidly to changing conditions. To implement these needed adaptations will likely require large-scale investments and substantial structural and organizational changes to our existing institutions to address existing barriers to implementation (Scarlett 2010; Jantarasami et al. 2010). Time is of the essence.

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.

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