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Review

Building on Two Decades of Ecosystem Management and Biodiversity Conservation under the Northwest Forest Plan, USA

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Abstract: The 1994 Northwest Forest Plan (NWFP) shifted federal lands management from a focus on timber production to ecosystem management and biodiversity conservation. The plan established a network of conservation reserves and an ecosystem management strategy on ~10 million hectares from northern California to Washington State, USA, within the range of the federally threatened northern spotted owl (*Strix occidentalis caurina*). Several subsequent assessments—and 20 years of data from monitoring programs established under the plan—have demonstrated the effectiveness of this reserve network and ecosystem management approach in making progress toward attaining many of the plan's conservation and ecosystem management goals. This paper (1) showcases the fundamental conservation biology and ecosystem management principles underpinning the NWFP as a case study for managers interested in large-landscape conservation; and (2) recommends improvements to the plan's strategy in response to unprecedented climate change and land-use threats. Twenty years into plan implementation, however, the U.S. Forest Service and Bureau of Land Management, under pressure for increased timber harvest, are retreating from conservation measures. We believe that federal agencies should instead build on the NWFP to ensure continuing success in the Pacific Northwest. We urge federal land managers to (1) protect all remaining late-successional/old-growth forests; (2) identify climate refugia for at-risk species; (3) maintain or increase stream buffers and landscape connectivity; (4) decommission and repair failing roads to improve water quality; (5) reduce fire risk in fire-prone tree plantations; and (6) prevent logging after fires in areas of high conservation value. In many respects, the NWFP is instructive for managers considering similar large-scale conservation efforts.

Keywords: biodiversity; climate change; ecological integrity; ecosystem management; global forest model; Northwest Forest Plan; northern spotted owl

1. Introduction

The 1994 Northwest Forest Plan (NWFP) ushered in ecosystem management and biodiversity conservation on nearly 10 million ha of federal lands within the range of the federally threatened northern spotted owl (*Strix occidentalis caurina*) from northern California to Washington State, mostly along the western slopes of the Cascade Mountains, USA (Figure 1). The plan was prepared in response to a region wide legal injunction on logging of spotted owl habitat (older forests) issued in 1991 by U.S. District Court Judge William Dwyer. After reviewing the NWFP, Judge Dwyer ruled that the plan was the "*bare minimum*" (emphasis added) necessary for the Bureau of Land Management (BLM) and the U.S. Forest Service to comply with relevant statutes (see http://www.justice.gov/enrd/3258.htm; accessed on 29 July 2015). The plan's conservation framework and unprecedented monitoring of forest and aquatic conditions along with at-risk species (those with declining populations) offer important lessons for managers interested in large-scale conservation and ecosystem management [1]. Thus, our objectives are to: (1) showcase the plan's fundamental conservation biology and ecosystem management principles as a regional case study for large-scale forest planning; and (2) build on the plan's conservation approach to provide a robust strategy for forest biodiversity in the context of unprecedented climate change, increasing land-use stressors, and new forest and climate science and policies.

At the time of the NWFP development, President Bill Clinton sought to end decades of conflict over old-growth logging by directing 10 federal agencies responsible for forest management, fisheries, wildlife, tribal relations, and national parks to work together and with scientists on a region wide forest plan that would be "scientifically sound, ecologically credible, and legally responsible." The plan was crafted to ensure the long-term viability of "our forests, our wildlife, and our waterways," and to "produce a predictable and sustainable level of timber sales and non-timber resources that will not degrade or destroy the environment." A multi-disciplinary team of scientists known as the Forest Ecosystem Management Assessment Team [2] was tasked with identifying management alternatives that would meet the requirements of applicable laws and regulations, including the Endangered Species Act, the National Forest Management Act, the Federal Land Policy Management Act, the Clean Water Act, and the National Environmental Policy Act.

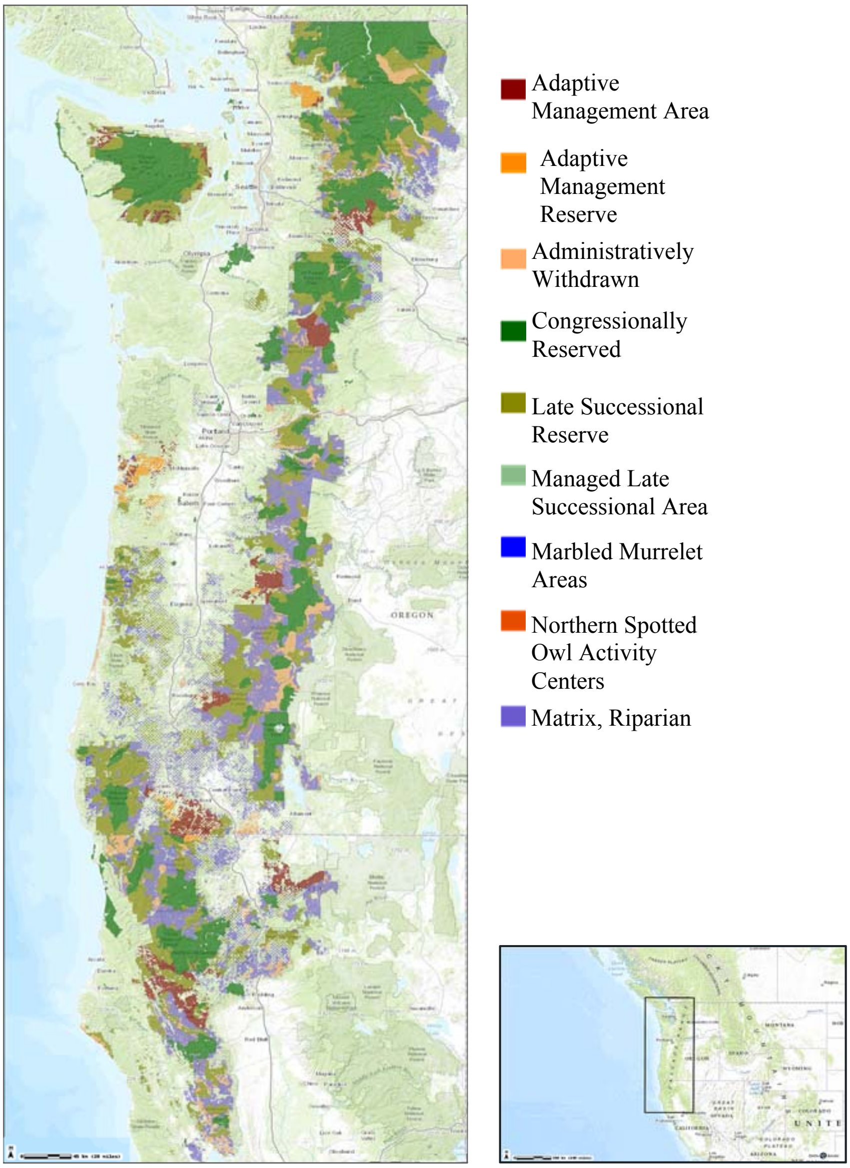

Figure 1. Land-use allocations within the Northwest Forest Plan (NWFP) area: Congressionally reserved—2.93 million ha (30%); Late Successional Reserves (LSRs)—2.96 million ha (30%); Managed Late Successional Reserves—40,880 ha (1%); Adaptive Management Areas—608,720 ha (6%); Administratively Withdrawn 590,840 ha (6%); Riparian Reserves—1.1 million ha (11%); and Matrix—1.6 million ha (16%). Figure created using Data Basin (www.databasin.org; accessed on 29 July 2015) and NWFP data layers [3].

The NWFP amended resource management plans for 19 national forests and seven BLM planning districts with 80% of those lands dedicated to some form of conservation (Figure 1). This increased level of protection and improved management standards were necessary because for many decades federal lands were managed without proper regard for water quality, fish and wildlife viability, and ecosystem integrity. Overcutting of older forests and rapid road expansion were the main factors responsible for the 1990 threatened species listing of the northern spotted owl, 1992 threatened listing of the marbled murrelet (*Brachyramphus marmoratus*), multiple listings of Evolutionary Significant Units (ESUs) of salmonids (*Oncorhynchus* spp.), and pervasive and mounting water quality problems. Prior to the NWFP, ~9.6 million cubic meters of timber was being logged from old-growth forests (>150 years old) annually on federal lands alone—roughly 5 square kilometers per week (assuming stands averaged 300 cubic meters per hectare). USFWS [4] estimated that this rate of logging would have eliminated spotted owl habitat outside remote and protected areas within a few decades. Simultaneously, logging was on the brink of eliminating old-growth forests from surrounding nonfederal lands.

Older forests in the Pacific Northwest are a conservation priority because they harbor exceptional levels of forest biodiversity (e.g., >1000 species have been recognized) and numerous at-risk species [2]. Historically, such forests widely dominated much of the Pacific Northwest landscape, especially in wet areas (coastal) where the intervals between successive fires were centuries long [5].

Older forest communities vary considerably in dominant tree species composition among the southern Cascade Range (Oregon/California), central and northern Cascades (Oregon/Washington), Coast Range (California/Oregon/Washington) and Klamath Mountains (Oregon/California [6]). Forests are generally dominated by Douglas-fir (*Pseudotsuga menziesii*) on sites associated with western hemlock (*Tsuga heterophylla*, sometimes including Pacific and grand fir, *Abies amabalis*, *A. grandis*; western red cedar *Thuja plicata*, bigleaf maple *Acer macrophyllum*); mixed conifers (white fir *A. concolor* and sometimes incense cedar *Calocedrus decurrens*, ponderosa and sugar pine *Pinus ponderosa*, *P. lambertina*); and mixed-evergreens (Pacific madrone *Arbutus menziesii*, tan oak *Lithocarpus densiflorus*, and canyon live oak *Quercus chrysolepis*). Structurally, these forests are characterized by the presence of high densities of large (>100 cm in diameter) conifers (typically 16–23 trees/ha), varied tree sizes and multi-layered canopies, trees with broken and dead tops, high levels of snags and downed wood, and diverse understories [6].

Most forest types in this region generally begin acquiring older forest characteristics at 80 years, depending on site productivity and disturbance history, with full expression of structural diversity at 400+ years [7]. Upper elevation subalpine fir (*Abies lasiocarpa*) and Pacific silver fir are not considered old growth until they are 260–360 years old [8]. Notably, researchers have recently developed an old-growth structure index (OGSI) to represent a successional continuum from young to older forests. The OGSI is a continuous value of 0–100 used to delineate older forests based on four features: (1) large live tree density; (2) large snag density; (3) down wood cover; and (4) tree size diversity at the stand level [9]. Young forests <80 years old that originate from natural disturbance in older forests, known as complex early seral forest, also have high levels of structural complexity (e.g., snags and downed logs) and species richness (especially forbs, shrubs; [10,11]). These younger forests have only recently been recognized as a conservation priority and like old growth have been replaced by structurally simplistic tree plantations [10].

2. NWFP's Long-Term Objectives

FEMAT [2] aptly recognized that even with the plan's protective elements in place, it would take at least a century and possibly two to restore a functional, interconnected late-successional/old growth (LSOG) ecosystem because older forests were reduced to a fraction (<20%) of their historical extent, and 40% of the LSRs were regenerating from prior clearcut harvest that would require decades of restoration to eventually acquire older characteristics [12]. The NWFP also represented a tradeoff between conservation and timber interests with about 1.6 million ha (16%) of older forests placed into the "Matrix" (Figure 1) where the majority of logging would take place pursuant to the plan's management standards and guidelines. As the NWFP was implemented, the volume of timber anticipated for sale (known as the probable sale quantity) was projected at ~234 million cubic meters annually. Since then, the plan has achieved about 80% of the probable sale quantity (on average ~178 million m^3 annually [13]). The apparent shortfall has been variously attributed to protective measures implemented before timber volume can be offered for sale, ongoing public controversy (appeals and lawsuits) around logging of older forests in the Matrix, fluctuations in domestic housing starts and global timber markets. Congressional appropriations to federal agencies for administering timber sales also have contributed to a *de facto* limit on timber offered for sale. Consequently, the plan's timber goals remain controversial. Some contend that socioeconomic considerations tied to timber extraction have not been met [14]. Others contend that rural communities no longer depend on timber in a region where economic sectors are influenced mainly by external factors and local economies have largely diversified [15]. Nonetheless, while it is premature to judge the efficacy of a 100-year plan in just two decades, periodic monitoring has shown that it has put federal forestlands on a trajectory to meet many of its ecosystem management targets [1,9,16,17].

Restoring a functional, interconnected LSOG ecosystem requires protecting existing older forests and growing more of it over time from young-growth tree plantations within the reserves. Restoring LSOG from former tree plantations is an uncertain endeavor that will require many decades to centuries and has never been envisioned before on such a large scale, especially in the face of rapidly changing climate. Thus, periodic monitoring of several of the ecosystem-based components of the NWFP by federal agencies is being used to gauge restoration targets, assess implementation efficacy of the plan, and proactively respond to new stressors. For instance, an unprecedented level of old forest, aquatics, and at-risk species monitoring occurs at regular intervals, depending on factors assessed, in order to achieve compliance with the 1991 Dwyer court ruling and biodiversity requirements of the National Forest Management Act of 1976. Maintaining biodiversity is a fundamental goal of any large conservation effort and the NWFP is instructive for managers considering similar large-scale ecosystem management and conservation efforts.

2.1. Reserves as a Coarse Filter

Conservation scientists have long-recognized that effective conservation planning involves two complementary approaches: a coarse filter consisting of representative reserve networks, and fine filter that includes local protections for species outside reserves [18,19]. FEMAT [2] emphasized the need for a large, interconnected reserve network as fundamental to biodiversity conservation [1,20,21]

(IUCN protected areas categories: http://www.iucn.org/about/work/programmes/gpap_home/gpap_quality/gpap_pacategories/; accessed on 17 September 2015). Thus, the conservation foundation of the NWFP is rooted in a network of reserves (e.g., LSRs and Riparian Reserves) that are widely distributed (Figure 1) throughout the planning area. The reserve network was principally designed to support viability and dispersal of the northern spotted owl in what is otherwise a highly fragmented system (Figure 2).

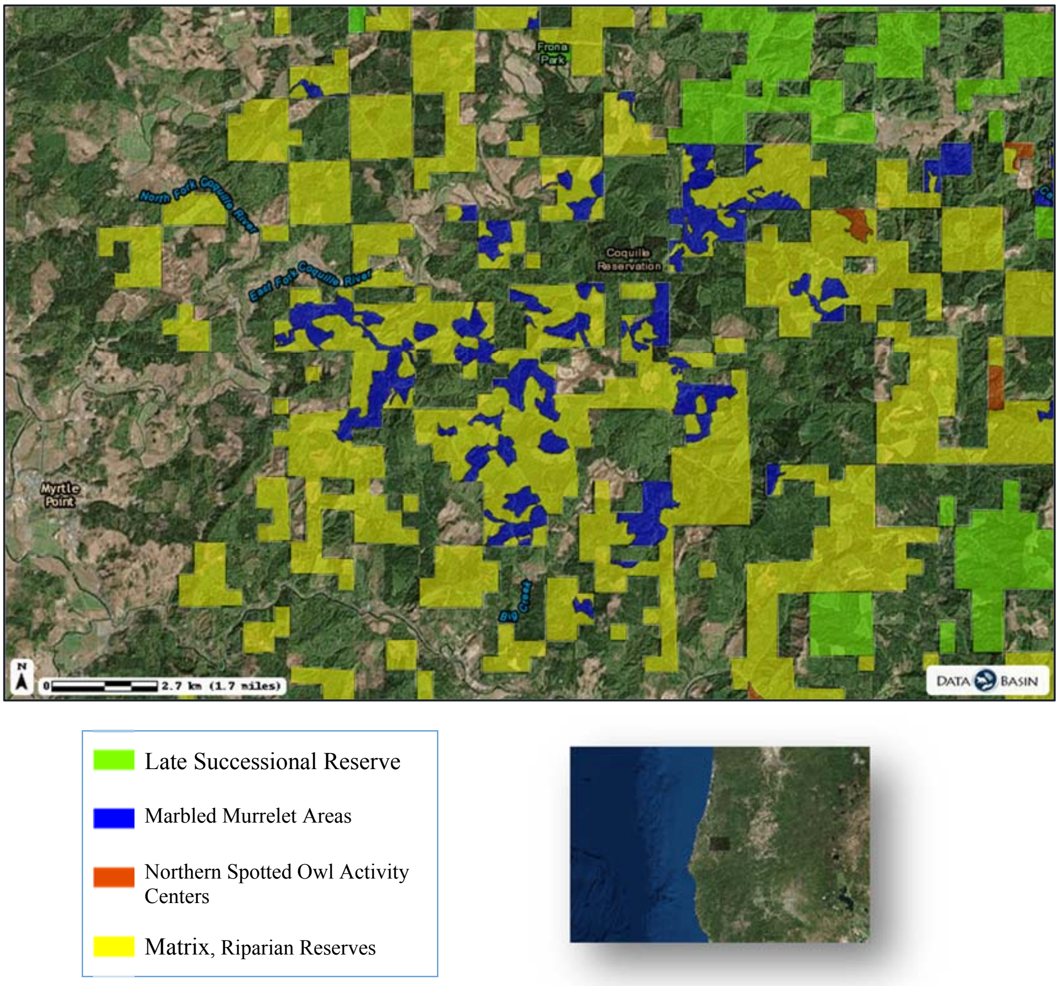

Figure 2. Satellite image of Southwest Oregon showing extensive fragmentation from a "checkerboard" pattern of clearcuts on private and public lands with NWFP land management allocations. Map created using Data Basin (www.databasin.org; accessed on 15 September 2015).

With reserves acting as a coarse filter, ecosystem-based approaches can be implemented to target geographic concentrations—or hotspots—of listed or rare species, thereby increasing conservation efficacy via multiple species benefits. Coarse filters are landscape characteristics of a natural environment that are easily measured, for instance, using satellite images, digital elevation models, and weather station data. Importantly, coarse filters are meant to capture the habitat needs of an entire species assemblage rather than habitat requirements for a particular focal species. For example, a land manager might use dominant vegetation identified through remotely sensed imagery to infer which species potentially occur across the landscape. Thus, the fundamental premise of coarse filters is that measuring the amounts and spatial distribution of biophysical features allows managers to assess the suitability of the landscape for multiple species and to represent key aggregate ecological attributes within a system of designated reserves. Effective coarse-filter reserves need to be defined at appropriate scales so that habitats and populations are sufficiently represented and reserves are distributed in redundant sequences to be robust to prevailing dynamics of natural biophysical disturbance (e.g., forest fires) and external land-management stressors in the surrounding landscape. These considerations were explicitly implemented by FEMAT when scientists designed alternatives that established the conservation architecture of the NWFP.

Three scales are important for estimating the amount and spatial arrangement of habitat needed to recover or conserve at-risk species, particularly those that are indicators of a broader community:

(1) **Species**: habitat needed to provide the resources and physical conditions required for a particular species to survive and reproduce.
(2) **Population**: habitat needed to support a local population of sufficient size to be resilient to background stochastic demographic and environmental events and short-term inbreeding depression.
(3) **Geographic range**: collective habitat required by multiple local populations of a species that are well distributed so that all populations do not respond synchronously to stochastic environmental events.

Central to its biodiversity focus, the NWFP was designed with explicit consideration of resilience, redundancy, and representation across multiple groups of taxa and communities. Resilient populations are those that are large enough, have sufficient genetic variation, and are sufficiently diverse with respect to the age and sex of individuals to persist in the face of periodic threats such as drought, wildfire, disease, and climate change. With respect to redundancy in populations or habitat areas, sufficient numbers of separate populations of a species and areas to support them are needed to provide a margin of safety in case disturbance eliminates some populations or important habitat types. In addition, sufficient genetic variation among populations of a species is necessary to conserve the breadth of the species' genetic makeup and its capacity to evolve and adapt to new environmental conditions. Representation refers to the plan's ability to capture a range of old growth conditions regionally within a reserve network.

2.2. Survey and Manage Program as Fine Filter

As a supplement to the Endangered Species Act, one of the fine-filters of the NWFP is the "survey and manage" program, an unprecedented precautionary approach designed to protect known locations and collect new information to address persistence probabilities and management uncertainties for rare and poorly surveyed species outside the reserve network [22]. Some 400 late-successional species of amphibians, bryophytes, fungi, lichens, mollusks, vascular plants, arthropod functional groups, and one mammal, including many endemics that otherwise may not persist outside the reserve network, were included in the program and given limited protections from logging if found (usually small site-specific buffers).

The survey and manage standards and guidelines for management might not be needed if the coarse filter reserves and older forests were fully functional and, therefore, resilient to short-term disturbance like fires and longer-term climate and land-use changes. However, that is not currently the case. In sum, the survey and manage program resulted in significant gains in knowledge, reduced uncertainty about conservation, and developed useful new inventory methods for rare species [22]. The program, however, remains one of the more controversial aspects of the NWFP, and federal agencies have repeatedly proposed its elimination given the restrictions it can place on the pace and cost of logging.

Thorough documentation of old forest species' distributions and diversity is still needed. In particular, some regions with diverse vegetation types (e.g., Klamath-Siskiyou of southwest Oregon/northern California [23]) have exceptional concentrations of endemic species that remain poorly studied and vulnerable to climate change [24]. Many rare species are inadequately known for development of effective management policies and practices, especially under a rapidly changing climate. The survey and manage program is also needed to ensure that rare species do not become at-risk species due to unforeseen population declines and conservation neglect.

2.3. Northern Spotted Owl Decline Slowed but Not Reversed

Spotted Owl Conservation Strategy—The northern spotted owl is the umbrella species for hundreds of late-successional species in the NWFP area [2]. When developing the conservation strategy for the owl, Thomas *et al.* [25] drew on fundamental principles from population viability analysis [26], island biogeography [27], and conservation biology [28–30] that applied both specifically to the owl and more generally to the community of late-successional associates. Thus, the NWFP is considered a model for conserving at-risk species [1]. Additional conservation biology principles guided the design of the NWFP [2]:

- Species that are widely distributed are less prone to extinction than those with more restricted ranges because local population dynamics are more independent [31].
- Large patches of habitat supporting many individuals are more likely to sustain those populations than small patches because larger populations are less subject to demographic and environmental stochasticity [32,33].
- Populations residing in habitat patches in close proximity are less extinction prone than those in widely separated patches because the processes of dispersal and recolonization are facilitated [34].
- The extent to which the landscape matrix among habitat patches (supporting local populations of the focal species) resembles suitable habitat, the greater the connectivity among local populations leading to lower extinction risks [35].
- Sustaining a species over the long-term requires that demographic processes be evaluated at three key spatial scales: territory, local population, and metapopulation [36].

Spotted Owl Population Trends and the NWFP—Even with the reserve network in place, spotted owl populations on federal lands have continued to show an alarming (3.8%) annual rate of decline [9] that has increased from the 2.8% annual decline reported previously [37]. Spotted owl populations are monitored across 11 large demographic study areas on federal (n = 8) and nonfederal (n = 3) lands where data on owl population dynamics are collected. Based on 2011 monitoring results for demography study areas, four study areas showed marked declines (both the point estimator and 95% confidence intervals) in mean annual rate of owl population change [38]. In 2015, the number of study areas with marked declines in owl populations increased to six (K.M. Dugger, pers. communication). Spotted owl declines were attributed to interference competition with barred owls (*Strix varia*; [39]), logging-related habitat losses (mostly nonfederal lands), and the lack of a fully functional reserve system [12,40].

Notably, total spotted owl detections and the number of previously banded owls was the lowest ever recorded for the demography study areas [41]. Spotted owl detections at historic territories remained unchanged from 2013–2014 at LSRs, whereas, a double-digit decrease in owl detections was noted in the Matrix that well exceeded the slight decrease in detections recorded for Wilderness areas. Anthony *et al.* [42] also reported that the decline in spotted owls was steepest on study areas not managed under the NWFP and therefore the downward trajectory of owl populations might have been much worse without the NWFP.

Spotted Owl Habitat Trends—Before the NWFP, the annual rate of LSOG losses on national forests was ~1% in California and 1.5% in Oregon and Washington [9,40]. Recent monitoring of older forests by federal agencies using multiple inventory methods shows, at the forest plan-scale, a slight reduction in the area of federal older forests (2.8%–2.9% in 2012 compared to 1993 levels Table 1).

Table 1. Total old forest area (hectares x million) for federal (USFS, BLM combined) *vs.* nonfederal lands using three old-forest estimates: an old-growth structure index at 80-years (OGSI-80); old-growth structure index at 200 years (OGSI-200); and Late-Successional/Old Growth (LSOG) [9]. Percent differences between time periods (parentheses) were repeated from Davis *et al.* [9] who used more significant figures in calculations not shown here and rounded to the nearest hundred thousand.

Time Period	Federal OGSI-80	Federal OGSI-200	Federal LSOG	NonFederal OGSI-80	NonFederal OGSI-200	NonFederal LSOG
1993	5.1	2.6	3.0	2.6	0.7	1.6
2012	4.9 (−2.9)	2.5 (−2.8)	2.6 (−2.0)	2.3 (−11.6)	0.6 (−18.1)	1.3 (−14.2)

Based on federal lands monitoring reports, wildfire accounted for 4.2%–5.4% of the gross older forest losses compared to logging, which accounted for 1.2%–1.3% old-forest reductions [9]. Such losses were within the 5% anticipated disturbance level for the NWFP area over this time frame; however, fire-related losses were >5% in some dry forest ecoprovinces (5.5%–7.1% Washington Eastern Cascades; 12.2%–15.3% Klamath Oregon; and 7.0%–13.1% California) [9]. Thus, one primary accomplishment of the plan was to drastically slow old forest losses from logging over the NWFP time period. Exceptions include BLM lands in western Oregon, where the rate of old forest loss was >2 times that of U.S. Forest Service lands over a 10-year period (Table 2).

Table 2. Estimated spotted owl habitat losses due to logging on U.S. Forest Service (USFS) *vs.* Bureau of Land Management (BLM) lands under different time periods. Estimates obtained from USFWS [43] data.

Federal Agency	Pre-Owl Listing (ha) (1981–1990)	Anticipated Rates (ha) (1991–2000)	Calculated Rates (1994–2003) (%)
USFS (WA, OR)	25,910	15,951	4,187 (0.21)
USFS (CA)	NA	1,903	669 (0.14)
BLM (OR)	8,907	9,474	1,988 (0.52)
Regional Total	NA	27,328	6,844 (0.24)

NA = not available.

Notably, extinction rates of spotted owls at the territory scale have been linked to the additive effects of decreased old-forest area and interference competition with barred owls [44]. Wiens *et al.* [39] also reported that the barred owl's competitive advantage over the spotted owl diminishes in spotted owl territories with a greater proportion of late-successional habitat. Thus, conservation of large tracts of contiguous, old-forest habitat is justified in any attempt to maintain northern spotted owls in the landscape.

Spotted Owls and Fires—USFWS [40] assumes that fire is a leading cause of habitat loss to owls on federal lands, However, few empirical studies have actually investigated northern spotted owl response to fire absent post-fire logging in or around owl territories [45,46]. Spotted owls may be resilient to forest fires provided low-moderate severity patches (refugia) are present within large fire complexes to provide nesting and roosting habitat. In the dry portions of the owls' range, where fire is common, owl fitness is associated with a mosaic of older forests (nesting and roosting habitat) and open vegetation patches (foraging areas; [47,48]). Such patch mosaics are produced by mixed-severity fires characteristic of the Klamath and eastern Cascade dry ecoprovinces [49,50] that may have contributed to maintenance of owl habitat historically [51]. However, if fire increases in severity or homogeneity of burn patterns due to climate change [52,53] and if LSOG losses outpace recruitment rates over time, the beneficial habitat effects of fire to owls would diminish. Currently, a deficit in high-severity fire exists in most of western North America compared to historical levels [49,54]. Recruitment of older forests in dry ecoprovinces of the region is projected to outpace fire losses for the next several decades [55].

Despite uncertainties about owl use of post-fire landscapes, federal managers in dry ecoprovinces have employed widespread forest thinning with the intent to reduce fire severity perceived as a threat to owl habitat. However, forest thinning may lead to cumulative losses in owl habitat that exceed those from severe fires. Using state transition models that accounted for recruitment of owl habitat over time *vs.* presumed habitat losses from severe fires, Odion *et al.* [55] concluded that thinning of suitable owl habitat at intensities (22% to 45% of dry forest provinces) recommended by USFWS [40] would reduce LSOG three to seven times more than loss attributed to high-severity fires. Projected thinning losses were consistent with empirically based studies of habitat loss from thinning that reduced overstory canopy below minimum thresholds for owl prey species [56]. The tradeoff between fire risk reduction and owl persistence in thinned forests has seldom if ever been systematically evaluated by the federal agencies.

2.4. Marbled Murrelet Continues to Decline but at a Slower Rate

Murrelet Population Trends—This federally threatened coastal seabird, nests in older-aged forests usually within 80-km of the coast from northern California to Alaska. The murrelet was listed as threatened in the Pacific Northwest due to habitat fragmentation from roads and clearcuts that expose murrelets to increased levels of nest predation [57–59]. Murrelet distribution and population trends are determined by the amount of suitable nesting habitat within five coastal "conservation zones" from Washington to California [60]. In general, as nesting habitat decreases murrelet abundance goes down, although abundance is also related to near-shore marine conditions (e.g., fish-prey abundance). Over the NWFP area, the trend estimate for the 2001–2013 period was slightly negative (~1.2%) (confidence intervals overlapped with zero [60]). At the scale of conservation zones, there was strong evidence of a linear decline in murrelet nesting populations in two of the five conservation zones both in Washington State. Trends were downward (but not significant) in other NWFP states; declines in murrelets likely would have been worse without the NWFP [60,61].

Murrelet Habitat Trends—About 1 million ha of potential suitable nesting habitat for murrelets remained on all lands within the range of the murrelet at the start of the NWFP (estimate based on satellite imagery [60]). Of this, only ~186,000 ha was estimated as high quality nesting habitat based on murrelet nest site locations. Over the NWFP baseline (1993–2012), net loss of potential nesting habitat was 2% and 27% on federal and nonfederal lands, respectively [60]. Losses on federal lands were mostly due to fire (66%) and logging (16%); on nonfederal lands logging (98%) was the primary cause of habitat loss [60]. In sum, loss and degradation of murrelet habitat resulted from: (1) logging on nonfederal lands (*i.e.*, State and private); (2) logging and thinning in suitable habitat and in habitat buffers on federal lands, including within LSRs; and (3) a variety of natural and anthropogenic causes including fire, windthrow, disturbance, and development [62].

Given that the availability of higher-quality nesting habitat is related to the carrying capacity of murrelets, forest management should focus on conserving and restoring remaining nesting habitat. The conservation strategy for murrelets, therefore, should include protecting remaining large patches of older-aged forests with minimal edge, buffering nest sites from windthrow and predators, and maintaining habitat connectivity. Maintaining the system of LSRs continues to be critical to murrelet conservation as is balancing the short- and long-term management of forests within LSRs [60,61]. For example, thinning that accelerates creation of older forest conditions in forest plantations that eventually become suitable to murrelet nesting can have short-term negative impacts, including increasing access of predators (e.g., corvids) to murrelet nest sites, blowdown and unraveling of suitable habitat, and changing the microclimate critical to temperature regulation and habitat availability [61]. Increased edge resulting from forest fragmentation can lower moss abundance needed for murrelet nesting [63,64], and increase nest depredation rates by corvids, especially at the juxtaposition of large openings and forests and in areas with berry producing plants such as elderberry (*Sambucus* sp. [65–67]. These factors underscore the need to maintain suitable buffers (suggested minimum widths of 91–183 m [57]) to minimize fragmentation and edge effects, and reduce windthrow and predation risk within LSRs and adjacent to suitable murrelet habitat [60]. Landscape condition, juxtaposition of occupied murrelet habitat, and ownership should all be considered in thinning operations within LSRs or adjacent to older-aged forests.

Impacts to murrelets would increase if fire frequency and severity were to increase due to climate change. Greater storm intensity associated with climate change also may cause more windthrow, especially in fragmented landscapes. Because murrelet nesting and foraging habitat appear sensitive to climate variability [68], forest management for murrelets should consider the potential additive effects of climate change and habitat fragmentation. Maintaining the LSR network, protecting all occupied sites outside LSRs, and, in the long term, protecting all remaining habitat and minimizing fragmentation and edge effects are essential conservation measures [60–62].

2.5. The Aquatic Conservation Strategy Has Improved Watershed Conditions

The Aquatic Conservation Strategy of the NWFP established Riparian Reserves and Key Watersheds to restore and maintain ecological processes and the structural components of aquatic and riparian areas [69]. Protective stream buffers in Riparian Reserves preclude most logging and Key Watersheds are managed for water quality and habitat improvements for at-risk salmonids. Stream conditions across 214 watersheds are being evaluated on federal lands in two eight-year sampling periods (2002–2009 and 2010–2017, incomplete) [70].

At the regional scale, broad-scale improvements in pools (*i.e.*, deep water pockets that provide cover, food, thermal refuge for aquatic species), stream substrate, and aquatic macroinvertebrates were observed between sampling periods, but no trend was detected in physical habitat features in riparian area canopy cover condition or stream temperature (Table 3).

Table 3. Summary of aquatic trend analysis testing for linear relationship between sampling periods (2002–2009 and 2010–2013, incomplete) [69]. Macroinvertebrates were based on an observed to expected index (O/E) calculated by Miller *et al.* [69]. Pool scores were estimated by using the amount of fine (<2 mm) sediments that accumulate in the downstream portion of pools.

Aquatic Indicator	Trend Estimate	F-Test *	*p*-Value
Physical habitat	+0.1	0.33	0.59
Pools	−0.21	6.22	**0.03**
Wood	+0.09	3.14	0.11
Substrate	+0.10	9.90	**0.02**
Macro-invertebrates O/E	+0.01	10.84	**0.02**
Temperature	−0.09	1.19	0.31

* Includes Kenward-Roger approximation. $p < 0.05$ is significant as described in Miller *et al.* [69]

At the NWFP level, moderate gains in upslope/riparian conditions occurred due to forest ingrowth and road decommissioning; however, they were largely offset by declines in riparian forest cover following large fires, particularly in reserve areas [69]. Notably, the Aquatic Conservation Strategy anticipated that improvements in stream and habitat conditions would take place over many decades; repeated monitoring confirms short-term benefits as noted but long-term goals have yet to be realized [68,69,71]. With available data, watershed condition appeared best in Congressionally Reserved lands (primarily designated Wilderness Areas), followed by LSRs, and the Matrix, although statistical analysis could not be performed due to incomplete sampling [69]. Key Watersheds and roadless areas encompass many of the remaining areas of high-quality habitat and represent refugia for aquatic and riparian species [72]. Therefore, improved protection and restoration actions in those areas are critically important to conserving aquatic biodiversity. We note that in the smaller number of watersheds where riparian conditions have measurably declined in the past 25 years, largely due to wildfire, we can expect a pulsed, very rapid improvement of instream conditions in the coming decades. This is because of anticipated post-fire recruitment of large wood coupled with vigorous regrowth of vegetation in riparian areas and erosion-prone slopes—at least where these natural recovery processes have not been disrupted and delayed by post-fire logging.

In a recent review of the NWFP's Aquatic Conservation Strategy Frissell *et al* [73] documented a host of reasons to recommend expansion of Riparian Reserves, and reduction in logging compared to the original (baseline) NWFP. They recommended that Key Watersheds and LSRs receive more stringent protection to ensure their contribution to aquatic conservation and salmon recovery. They also called for more limits on or an end to post-fire logging, and more aggressive and strategically focused reduction of road density and storm proofing improvements in roads that remain. The BLM and the Forest Service, however, have increased logging in Riparian Reserves, are now proposing or suggesting reductions in the width and extent of Riparian Reserves, and have pressed for increasing road system density to provide access to more land for logging purposes. These agency recommendations do not explicitly consider ongoing stressors from land management in the surrounding nonfederal lands or increasing likelihood of climate-change-driven stress from drought, floods, and wildfire. Nor do they deal with the adverse watershed impacts from thinning projects relative to their putative but highly uncertain benefits for reducing the severity of future fire or insect outbreaks.

2.6. Climate Change and the NWFP

Climate change was not fully anticipated during development of the NWFP and thus represents a new broad-scale stressor that would exacerbate earlier projected and realized cumulative impacts to aquatic and terrestrial species and ecosystems throughout the region. Temperatures already have increased by 0.7 °C from 1895–2011 [53] and are anticipated to rise another 2 °C–6 °C by late century with warming most extreme during the summer [53,74]. Greater uncertainty exists in precipitation projections due to variability in emissions scenarios and climate models; however, summertime drying by the end of the century has higher certainty [53]. Summer drying coupled with increasing temperatures will likely impact timing of salmonid migrations in snow-fed streams [53,75] and increase future fire events [52,75].

Notably, a key characteristic of widely distributed species is that the dynamics of their multiple local populations experience environmental variation asynchronously. This decoupling of the dynamics of local populations within a metapopulation greatly increases overall persistence likelihood given inevitable large-scale disturbances [76]. Persistence is achieved because the spatial distribution of the species exceeds the spatial extent of most stochastic environmental events. Persistence may be compromised, however, when climate change operates as a top-down driver over very large spatial scales, increasing the synchrony of metapopulation dynamics and extinction probabilities for late-successional species. Persistence likelihood in the face of disturbances was addressed in the

NWFP via redundancy and distribution of the reserve network but it is unclear whether the reserves can accommodate unprecedented climate-related shifts. This does not mean that the reserves are ineffective, just that they may not be as effective as hoped, and increasing the number and size of LSRs would make the network more effective.

Environmental uncertainty caused by climate change also has implications for restoration objectives of the NWFP. The NWFP assumed that young plantations can be restored to an older forest condition, but this may be less certain as forest succession comes under the influence of novel climatic conditions and perhaps increasingly altered disturbance regimes [52]. Thus, as forest conditions are altered by climate change, this may impact the climate preferences of late-successional species (e.g., mesic species are expected to decline near coastal areas due to drying [24]). One important way to reduce this uncertainty is to conserve more LSOG along north-facing slopes as potential micro-refugia and a hedge against further losses [24].

2.7. Ecosystem Services and the NWFP

Older forests and intact watersheds generally provide a myriad of ecosystem services associated with high levels of biodiversity [77,78]. Some examples of ecosystem services that have benefited from the NWFP include net primary productivity, water quality, recreation such as camping and hunting, salmon productivity, and carbon storage and sequestration. Older forests with high biomass (>200 mg carbon/ha, live above ground biomass of trees) most abundantly provide these services in aggregate primarily on federal lands [79].

The storage of carbon on federal lands is especially noteworthy because the region's high-biomass forests are among the world's most carbon dense forest ecosystems [80,81]. When cut down, these forests quickly release about half their carbon stores as CO_2 [82]. Reduced logging levels and increased regrowth under the NWFP has resulted in the regional forests shifting from a net source of CO_2 prior to the NWFP to a net sink for carbon during the NWFP time period [83]. While most of the carbon losses on federal lands are the result of forest fires, logging (mostly on nonfederal lands) remains the leading cause of land-use related CO_2 emissions [84]. Forests regenerating from natural disturbances including fire also rapidly sequester carbon and can then store it for long periods via succession if undisturbed. By comparison, logging places forests on short-rotation harvests, thereby precluding long-periods of carbon accumulation [82,83].

3. Building on the NWFP

The NWFP was founded on the best available science of the time, and the plan's reserve network and ecosystem management approach remain fundamentally sound [1,16,40,61,85,86] (also see http://www.fws.gov/oregonfwo/species/data/northernspottedowl/recovery/Plan/; accessed on 29 July 2015). If federal agencies wish to retain the protective elements of the NWFP, then forest plan revisions need to be based first and foremost on an adaptive approach to long-term goals as informed by monitoring. Increases in conservation measures are warranted to accommodate new scientific knowledge and unprecedented challenges from climate change and land-use stressors.

More recent climate change policies have been enacted since the NWFP that should be incorporated into forest planning. Examples include President Barack Obama's November 2013 Climate Change

Executive Order directing federal agencies to include forest carbon sequestration in forest management, the Council on Environmental Quality's draft guidelines on reducing greenhouse gas emissions from land-used activities (Federal Register Vol. 80, No. 35/Monday, 23 February 2015), and emphasis on forest carbon and ecosystem integrity in forest planning on national forests [87]. Improvements to the NWFP's ecosystem and conservation focus are especially relevant today given: (1) the spotted owls' precarious status, including increased competition with barred owls; (2) continuing declines in murrelet populations; (3) other at-risk species recently proposed for listing (e.g., Pacific fisher *Martes pennanti*, North Oregon Coast Range distinct population segment of the red tree vole *Arborimus longicaudus*); (4) numerous forest associated invertebrates and lesser known species with restricted ranges that are vulnerable to extinction as a result of climate change [24]; and (5) additional ESU's of Pacific salmon that have been listed with none recovered to the point of delisting. Recent and ongoing land-use stressors acting alone or in concert, especially on nonfederal lands, also need to be reduced along with improved forest management practices and stepped up conservation efforts (Table 4).

Table 4. Land use stressors, the Northwest Forest Plan (current), and suggested additions based on adaptive management approaches.

Land Use Stressor	NWFP Current	Suggested NWFP Improvements
Climate-forced wildlife migrations	LSRs, landscape connectivity via riparian and other reserves	Enlarge LSR and riparian reserve network by protecting remaining older and high-biomass forests in the reserve system, increase connectivity for climate-forced wildlife displacement, reduce management stressors, shift older forests to the reserves and forest management to restoration of degraded areas, and identify and protect climate refugia [24], especially for rare and endemic species (continue the survey and manage program).
Livestock grazing	Aquatic Conservation Strategy standards and guidelines provide some protections for riparian and other sensitive areas	Remove cattle from riparian areas and reduce overall grazing pressure via large no-grazing zones given cumulative effects of grazing and climate change [88].
Wildfire	Thinning for fuels reduction and post-fire logging allowed in dry province reserves (trees <80 years) and Matrix	Prohibit post-fire logging in reserves, maintain all large snags in the Matrix (other than legitimate road side hazards), continue to protect older trees >80 years and maintain canopy closure at ≥60% in spotted owl habitat in thinning operations [55]. Plan for wildland fire to achieve ecosystem integrity objectives. Focus on flammable tree plantations and work cooperatively with private landowners on fire risk reduction.
Forest carbon loss	Not recognized other than if they overlap with reserves	Optimize carbon storage by protecting high-biomass forests from logging and by reducing logging frequency and intensity to sequester more carbon. Choose management alternatives with low emissions from forestry by making use of new assessment tools [89] (also see http://landcarb.forestry.oregonstate.edu/summary.aspx; accessed on 29 July 2015).
Aquatic ecosystem degradation	Riparian Reserves, Key Watersheds, LSRs, watershed restoration, watershed assessments/monitoring	Maintain or increase riparian buffer widths to ameliorate winter erosion, sedimentation, and flooding, restore floodplain connectivity and sinuosity, retain runoff and natural summer storage, increase efforts to improve and decommission failing roads, identify cold water refugia for increased protections [73,90], update watershed and LSR assessments to incorporate carbon and climate change. Where possible, support a closed forest canopy over perennial and intermittent streams and fully restore recruitment of large downed wood, including by prohibiting or severely limiting forest thinning in riparian reserves.

BLM Western Oregon Plan Revisions

A key contribution of the NWFP was its unprecedented emphasis on coordination among federal agencies via an overarching ecosystem management approach. In particular, the BLM manages ~1 million ha within the NWFP area (http://www.blm.gov/or/plans/wopr/oclands.php; accessed on 29 July 2015). BLM lands collectively provide irreplaceable ecosystem benefits to people and wildlife in western Oregon where there are relatively fewer national forest lands near the coast. Benefits include some 480,000 ha of watersheds that overlap with Surface Water Source Areas that produce clean drinking water for >1.5 million people from Medford to Portland, Oregon (State of Oregon water quality datasets; http://www.deq.state.or.us/wq/dwp/results.htm; accessed on 29 July 2015), connectivity and dispersal functions for wildlife linking the Coast and Cascade ranges (east-west, north-south linkages) [91], and habitat for at-risk species (Table 5). Unfortunately, the BLM has signaled its intent to move away from the Aquatic Conservation Strategy stream buffers and the survey and manage protections (http://www.blm.gov/or/plans/wopr/oclands.php; accessed on 29 July 2015).

Table 5. Summary of important ecological attributes of a subset of BLM lands in western Oregon essential to the coordinated management of the Northwest Forest Plan (summarized from Staus *et al.* [91]).

Attribute	BLM Lands
Late-successional forests	360,000 ha of old growth (>150 years, 22% of BLM Land), 236,000 ha mature (80–150 years, 15% of totals for western OR)
Northern spotted owl critical habitat	400,000 ha (27% of BLM land); LSRs: 240,000 ha
Marbled murrelet critical habitat	~192,000 ha, 32% of total critical habitat in western OR, 83% of which is within BLM LSRs
Evolutionary Significant Units of coho (*Oncorhynchus kisutch*)	~720,000 ha of coho ESU area, 260,000 ha of coho ESU's in BLM LSRs—35% of ESU area on BLM land. Of the 10,075 km of spawning and rearing habitat within western Oregon, 12% is located on BLM lands, 100% in Riparian Reserves, and 44% of which is within LSRs.
Evolutionary Significant Units of chinook (*O. tshawytscha*)	~148,000 ha of ESU habitat, 16% of BLM land in western Oregon; 25,200 ha of chinook ESU habitat in BLM LSRs—17% of the total ESU area on BLM land.
Evolutionary Significant Units of steelhead (*O. mykiss*)	87,200 ha of steelhead ESU habitat, all of which is found in the Salem and Eugene districts. Nine percent of BLM land in western Oregon contains steelhead ESU habitat with 14,000 ha of steelhead ESU habitat in BLM LSRs—16% of the total ESU area across BLM land.
Key Watersheds	Western Oregon contains ~1.6 million ha of Key Watersheds, 61,600 ha (4%) of which are located within BLM LSRs. In the Coast Range, LSRs protect 9% of Key Watersheds overall, over 25% of 10 of the 38 key watersheds in this area.
Survey and Manage Species	Of the 404 survey and manage species (primarily rare species at risk of local extirpation) recognized in the NWFP, 149 species are found on BLM land and 93 are found within BLM LSRs. LSRs in the Salem BLM District contain the highest concentration of these species (54), followed by Roseburg (39), and Coos Bay (35). Species include red tree vole (*Arborimus longicaudus*, an important food source for spotted owls), and many species of vascular plant, aquatic mollusk, lichen, fungi, and bryophyte.

4. Robust Conservation Additions to the NWFP

The NWFP provided a much-needed starting-place for a robust conservation strategy on federal forests in the face of climate change. For clarity, we organize our recommendations to improve the plan based on widely recognized principles of conservation biology and ecosystem management that also apply more broadly to large-landscape conservation planning.

4.1. Reserves

The large, well distributed, and redundant system of reserves was chosen based on specific requirements for the northern spotted owl that are still supported by the best available science [1,16,17,40–42,85]. At a minimum, we recommend continuation of the reserve network as a foundation for at-risk species in a changing climate and with increased stressors in the surrounding nonfederal lands. The NWFP reserves along with the survey and manage program function together as precautionary measures for species that are less mobile (e.g., many endemics) due to increasing stressors in the surroundings and climate change [19,24]. Given the redundancy and spacing requirements of the reserve system to address owl viability requirements, the network is likely to maintain older forest conditions over time by accommodating temporary losses from fire and other natural disturbances without compromising the integrity of the network [2,9], unless disturbances increase dramatically due to climate change [53]. The reserve system also is arranged along north-south gradients, including the Coast and Cascade ranges, elevation gradients, and topographically diverse areas, presumably allowing for climate-forced wildlife dispersal and climate refugia [24]. Large, contiguous federal ownerships and coordinated management of federal agencies under the standards and guidelines of the NWFP should continue to allow for adaptive responses to climatic change. Blocks of federal ownership also provide opportunities for wildland fire needed to restore and maintain ecosystem processes across a successional gradient [10,92,93].

The NWFPs' combination of coarse- and fine-filter approaches should continue to provide time for many wildlife to adjust and adapt to changing climatic conditions. Any effort to scale-back the reserves (as is currently being considered by federal agencies) must acknowledge that the NWFP architects aptly recognized that LSRs, Riparian Reserves, and Key Watersheds fit together in a cohesive manner to maintain long-term benefits to terrestrial and aquatic ecosystems. Reducing protections to reserves would create cumulative impacts across ecosystems. With new stressors like climate change and ongoing land-uses, reserve synergies and integrated strategies are even more important.

4.2. Forest Carbon

Regional carbon storage capacity can be increased if managers both protect carbon stores in older high biomass forests and allow young forests to re-grow for longer periods [83,84]. Managing for high-biomass forests is also associated with the multifunctionality of ecosystems because carbon dense forests are associated with high levels of biodiversity and numerous other ecosystem services [79]. Prudent management should integrate forest carbon policies with multiple use management objectives of federal agencies by optimizing carbon stored in older forests and extending timber harvest rotations to allow for longer periods of carbon sequestration and storage. Thus, forest managers can select management alternatives to minimize carbon flux from logging and land-uses by evaluating alternatives based on new carbon assessment tools (Table 4).

4.3. Aquatic Conservation

The variety of requirements for watershed analysis, reserve assessments, and monitoring under the NWFP has provided a foundation for tracking the plan's implementation objectives for aquatic ecosystems, at least at a regional scale. With improvements, aquatic ecosystem monitoring could provide integrated and sensitive indicators of ecosystem changes associated with climate shifts. Current Aquatic Conservation Strategy provisions, therefore, could be strengthened to help make aquatic ecosystems more resilient to climate change by (1) lessening cumulative watershed impacts particularly from the extensive road network on federal lands; (2) reducing the imprint of management disturbance on relatively high-integrity watersheds and roadless areas; (3) emphasizing maintenance of riparian areas, shade, floodplain processes, and recruitment of large wood from both near stream areas and unstable slopes; and (4) restoring migratory connectivity and fish passage to allow cold-water fisheries a better chance to occupy refugia less stressed by climate change.

4.4. At-Risk Species Recovery

Our understanding of threats to at-risk species has greatly advanced since passage of the Endangered Species Act (ESA) in 1973 and the NWFP in 1994. Specifically, the recognition that avoiding extinction is different than achieving recovery when it addresses the original ESA goal of "… preserving the ecosystems upon which threatened and endangered species depend." Hence, implementation of the NWFP and enforcement of the ESA are linked objectives that together provide for the ecosystem and population needs of at-risk species among a host of other benefits.

To build on the complementarity of the NWFP and ESA, we recommend that at-risk species recovery (e.g., spotted owl, marbled murrelet, Pacific salmon) on federal lands include more habitat protections to reduce interactions with their competitors (e.g., spotted owls *vs.* barred owls), maintain genetic diversity [94], provide for resilient populations, and enable multiple local populations to be well-distributed throughout the NWFP area. Additionally, at least until land-use stressors are reduced, the survey and manage program should be continued to avoid the need for listing future at-risk species and expanded to include species that require complex early seral forests [10]. Managers can then select a broad suite of focal species that depend on all segments of successional gradient.

4.5. Adopting New Policies and Approaches

The foundation of the NWFP can be easily amended to accommodate new scientific information and elevated and novel stressors by building on its foundational elements (e.g., reserves, stream buffers, survey and manage). This can best be accomplished by incorporating recent national forest policies that emphasize ecosystem integrity [87] and climate change planning on federal lands (President Barack Obama's 2013 Climate Change Executive Order), reducing land-use stressors, and maintaining or restoring landscape connectivity to enable climate-forced wildlife migrations (Figure 3).

Additionally, recent mapping of high-biomass forests [84] and carbon accounting in forestry practices (http://landcarb.forestry.oregonstate.edu/summary.aspx; accessed on 29 July 2015) provide new opportunities for retaining carbon in older forests while reducing forestry related CO_2 emissions.

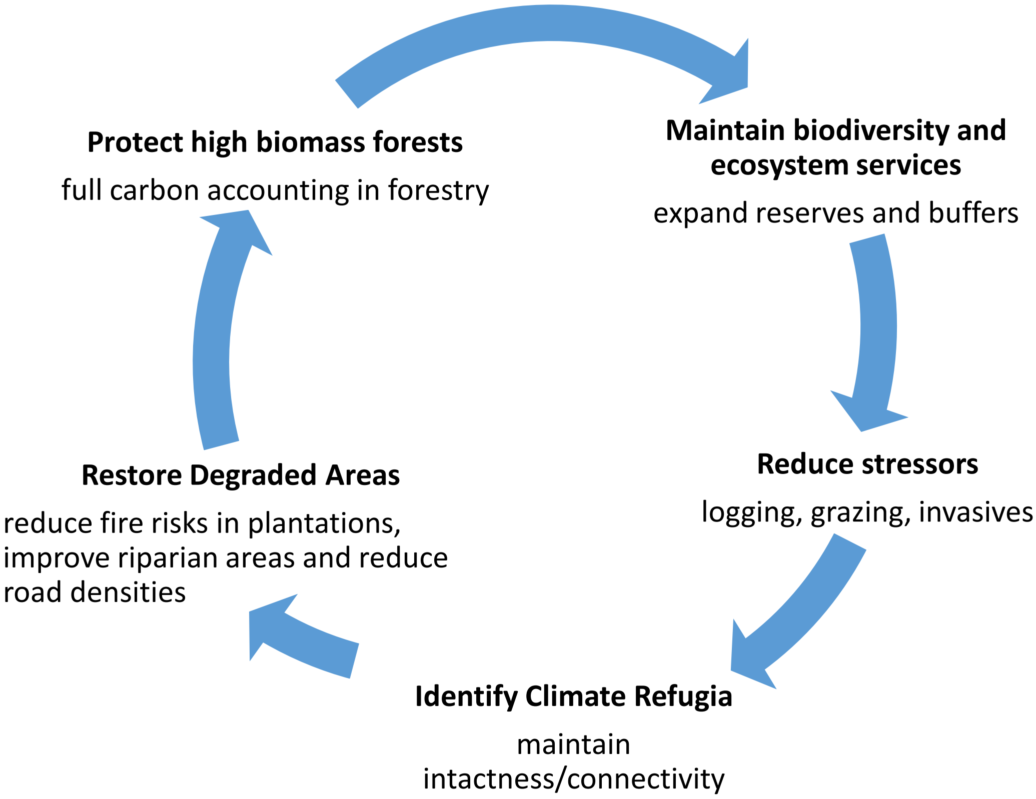

Figure 3. Integrating ecosystem management and conservation biology with recent forest policies related to climate change (e.g., President Barack Obama's 2013 Climate Change Executive Order), forest carbon, and ecosystem integrity in forest planning [87].

5. Conclusions

The foundation of the NWFP is its reliance on best available science for conserving, restoring, and responsibly managing federal lands within the range of the northern spotted owl and, for the first time ever, an entire ecosystem, which is why it is considered a global model [1]. Although the plan is only two decades into its century-long implementation, its key conservation goals and species recovery mandates are far more likely to be met with the plan's management and conservation measures intact.

As forest plan revisions go forward in the region, the reserve network needs to be expanded in response to increasing land-use stressors to ecosystems and at-risk species, and to provide for a more robust conservation framework in response to climate change. Climate change may trigger more forest fires in places and, correspondingly, more logging and livestock grazing as these practices almost always follow forest fires on federal lands. Notably, burned forests successionally link complex early seral forests [10,11] to future old-forest development [92] and are not ecological disasters as often claimed. Depending on fire severity, burned forests provide nesting and roosting (low-moderate severity) or foraging (high severity) habitat for spotted owls [45,46,51]. Federal managers, however, have increasingly proposed massive post-fire logging projects that degrade complex early seral forests [95] and spotted owl habitat [45,46], and that can elevate fuel hazards and re-burn potential [96,97]. Post-fire logging over large landscapes may cause type conversions whereby fires burn intensely in logged areas only to be replanted in densely stocked and flammable tree plantations to burn intensely again in the next fire and so on [98]. Livestock grazing in combination with climate change is also now the biggest impact to biodiversity on federal lands that needs to be offset by new protections such as large blocks of ungrazed areas [88].

In sum, changes in ecosystem management practices on federal lands, triggered by the NWFP, have for the most part arrested an approaching ecosystem-wide collapse set in motion by decades of large-scale logging and mounting land-use stressors. Implementation of the plan has been challenging due, in large part, to socio-economic pressures to increase logging without full consideration of the environmental consequences and understanding of the science and conservation principles underpinning the NWFP. Moreover, despite substantive improvements in federal land management practices compared to those previous to the NWFP, amendments that respond to emerging contemporary threats are clearly needed. Scientific information and robust conservation principles can provide federal managers with the knowledge needed to adapt the next generation of forest plans. Improvements should be grounded in careful evaluation of the effects of past actions along with ongoing and future stressors as they pertain to the region's underlying ecological fabric and its link to sustainable economies. Science-based revisions of the plan should seek to improve its implementation in an adaptive context by addition rather than subtraction. Unfortunately, attempts to revise the plan have been bogged down by ongoing controversy over timber *vs.* biodiversity values that has led to a perpetual tug-of-war between decision makers that either support or seek to dismantle the NWFP. If this trend continues, federal land management may regress and recreate many of the problems the NWFP was implemented to correct, including re-inflamed social conflict, a cascade of endangered species listings, permanently increased conservation burdens on private landowners due to additional endangered species listings, and loss of ecological integrity that underpins the region's ecosystem services and their adaptive capacity to climate change.

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Conflicts of Interest

The authors declare no conflict of interest.

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